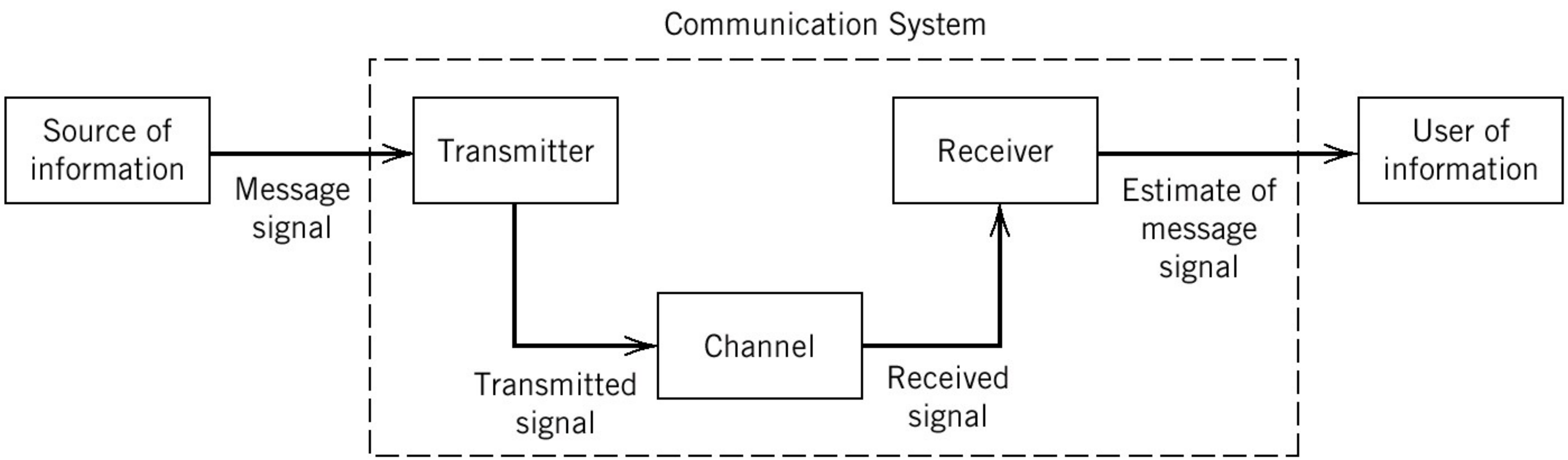
What is Communication?

- **Communication**: transmission of information from one point to another.
- **Four Basic Elements**
  - **Information source:** voice, music, picture, video, …
  - **Transmitter**: converts information in the source into a form suitable for transmission over the channel
  - **Channel**: the physical medium, introduces distortion, noise, interference
  - **Receiver**: reconstruct a recognizable form of the source signal



Energy, Average Power, Bandwidth

Energy:

$$\boxed{E = \int_{-\infty}^{+\infty} |s(t)|^2\, dt = \int_{-\infty}^{+\infty} |S(f)|^2\, df}$$

Average Power = time average of energy, computed over a large interval

$$P = \frac{1}{T} \int_{-T/2}^{+T/2} |s(t)|^2\, dt$$

Average Power of a Random Signal: Assemble average as following

$$P = E\left\{s^2(t)\right\} = \int_{-\infty}^{\infty} x^2 f_{s(t)}(x,t)\,dx$$

Average Power of a Signal consisting of random and deterministic components:
Both time and assemble average

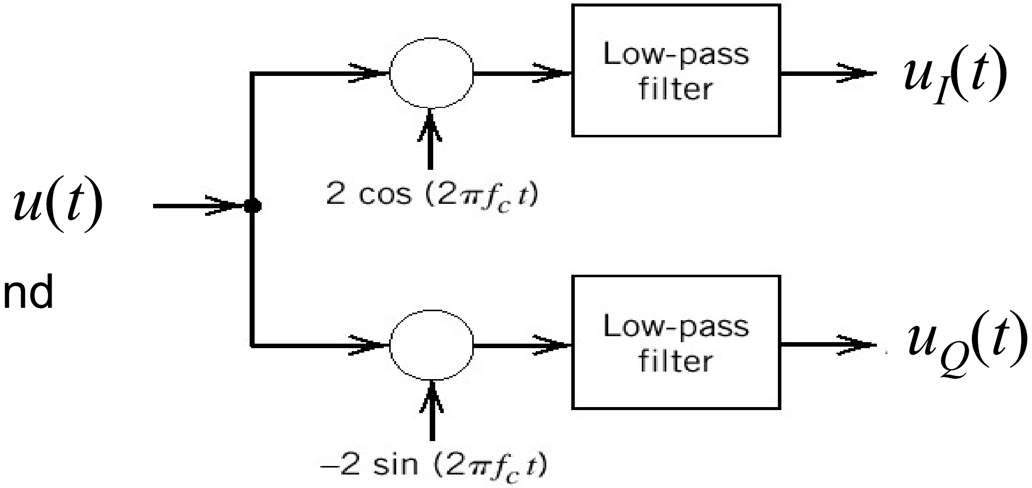
One-sided bandwidth: only consider positive frequencies when computing bandwidth for ***physical*** **(real) signals**

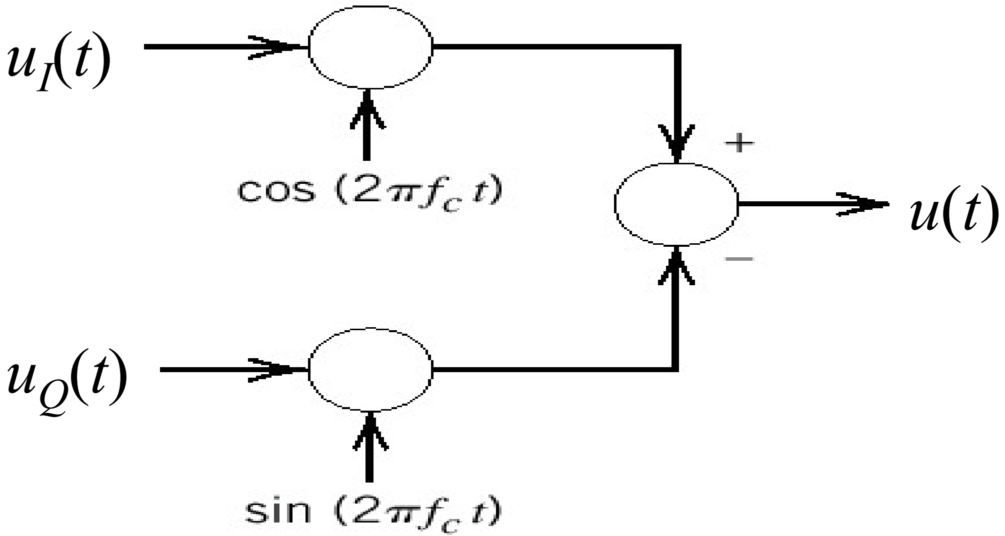
Complex-valued (in the time domain) signals: Complex envelope of a real-valued passband signal. The two-sided bandwidth of the complex envelope equals the physical (one-sided) bandwidth of the passband signal

Baseband and Passband Signals/Channels

Up-Conversion:

baseband → passband



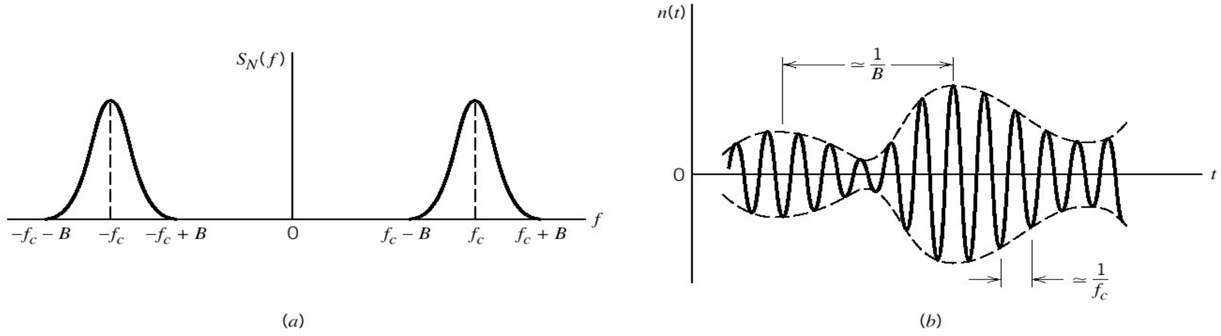


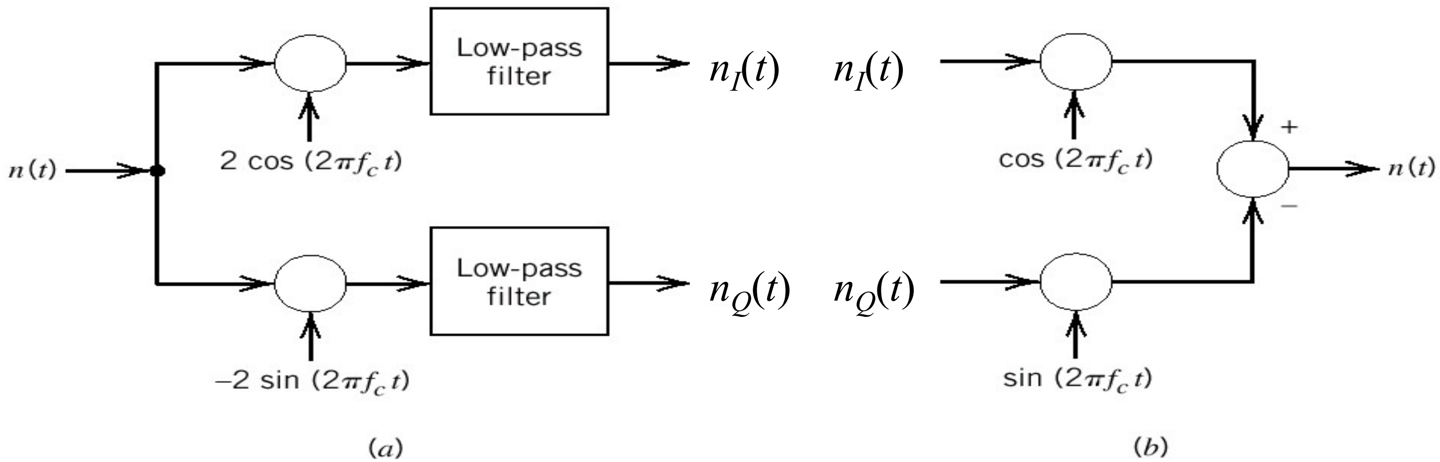
Down-Conversion:

passband → baseband

Band-pass Noise

- n(t) in canonical form: $n(t) = n_I(t)\cos(2\pi f_c t) - n_Q(t)\sin(2\pi f_c t)$
- $n_I(t)$ and $n_Q(t)$ are fully representative of the band-pass noise.
  - Given band-pass noise, one may extract in-phase and quadrature components (using LPF of bandwidth *B*).
  - Given the two components, one may generate band-pass noise. This is useful in computer simulation.





Properties of Baseband Noise

- Usually noise $n(t)$ has zero mean, then so do $n_I(t)$ and $n_Q(t)$.

- $n_I(t)$ and $n_Q(t)$ have the same variance (i.e., same power) as $n(t)$

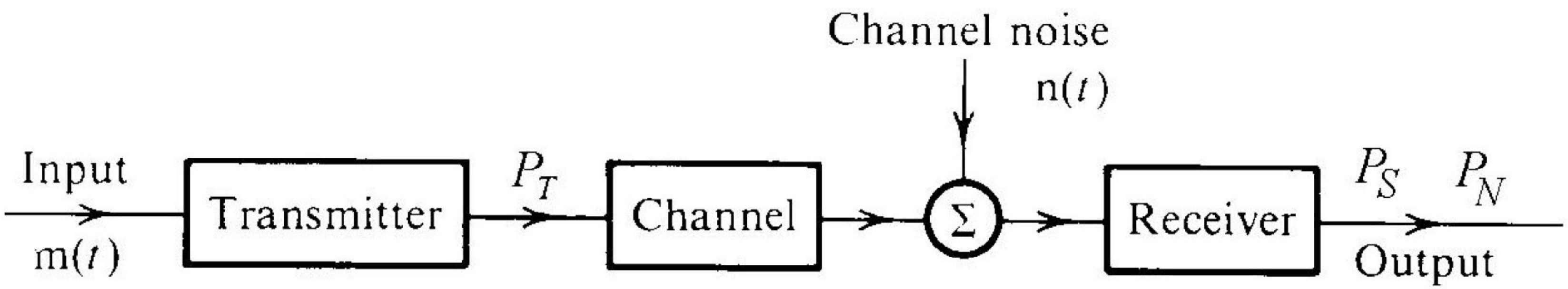
- If noise $n(t)$ is Gaussian, then so are $n_I(t)$ and $n_Q(t)$ and

  the envelope $r(t) = \sqrt{n_I^2(t) + n_Q^2(t)}$ is Rayleigh distribution.

- Both in-phase and quadrature components have the same PSD:

$$S_{N_I}(f) = S_{N_Q}(f) = \begin{cases} S_N(f - f_c) + S_N(f + f_c), & |f| \le B \\ 0, & \text{otherwise} \end{cases}$$

Analog Communication Systems



Model of an analog communication system

Signal-to-Noise Ratio (SNR) at the output of the receiver:

$$SNR_o \equiv \frac{\text{average power of message signal at the receiver output}}{\text{average power of noise at the receiver output}} = \frac{P_S}{P_N}$$

Normally expressed in decibels (dB): SNR (dB) = 10 $\log_{10}$(SNR)

A Baseband Communication System

- It does not use modulation
- Transmit power is identical to message power:

$$P_T = P$$

- If the unit channel gain or no propagation loss, then

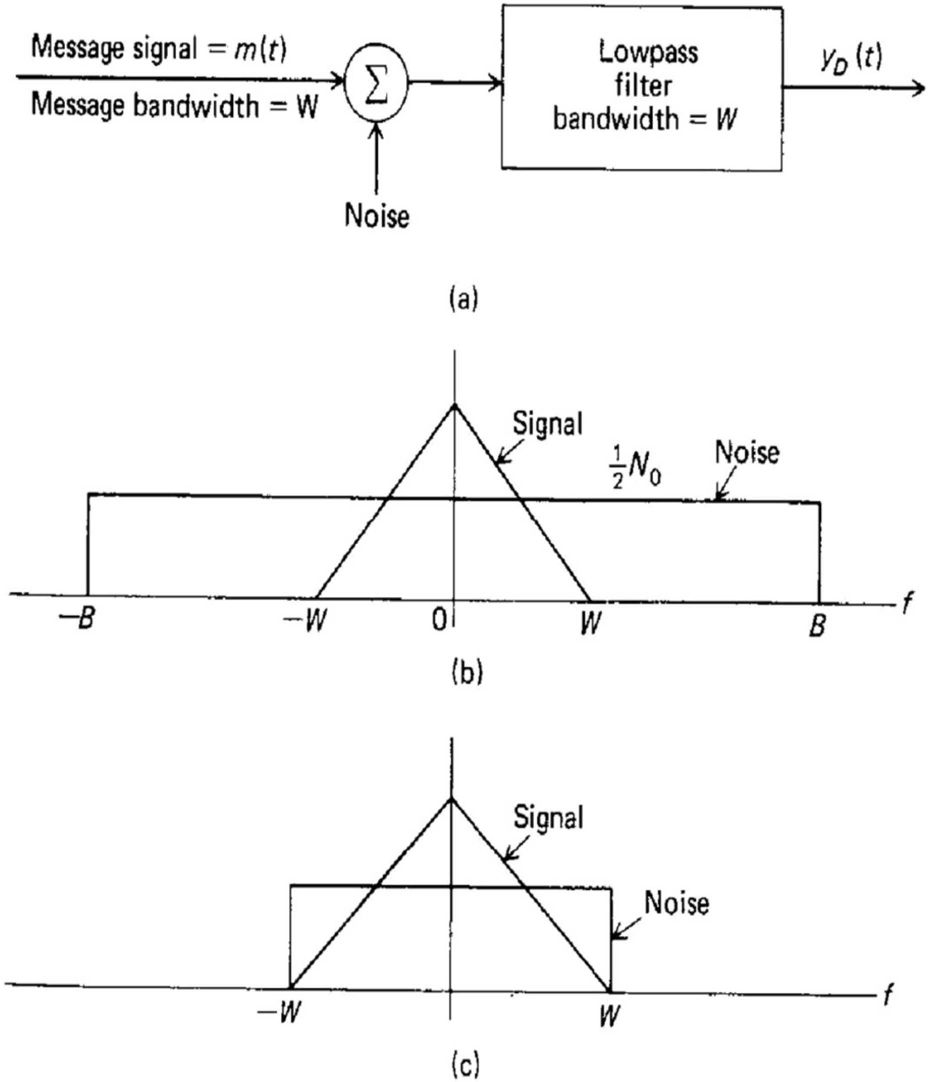
$$P_S = P_T = P$$

- Average noise power at receiver

$$P_N = 2W \times N_0/2 = WN_0$$

- SNR at receiver output:

$$\boxed{SNR_{\text{baseband}} = \frac{P_T}{N_0 W}}$$

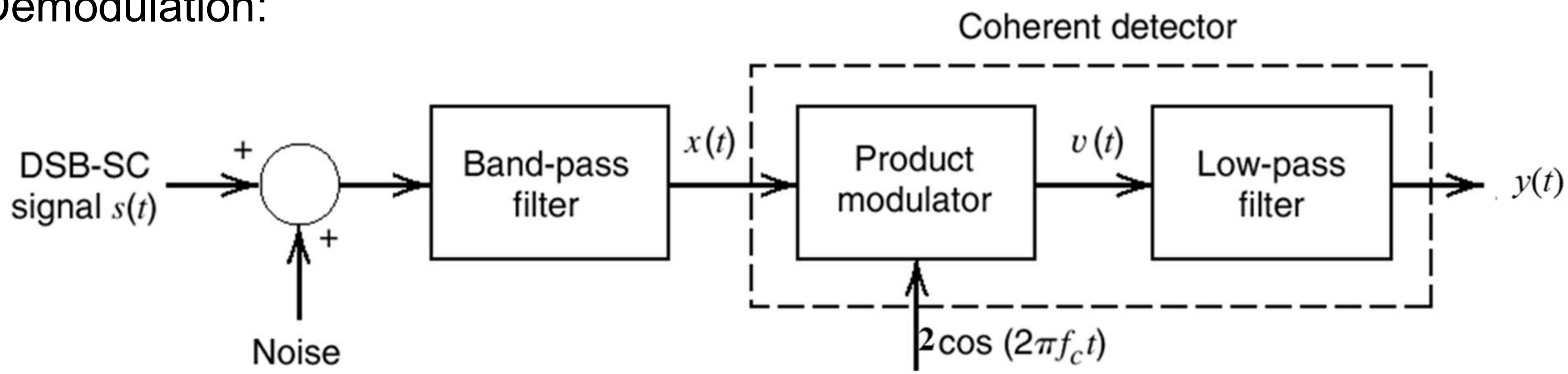


Double Sideband-Suppressed Carrier (DSB-SC) Modulation

- General form of a DSB-SC signal (suppressed carrier AM):

$$s(t) = m(t)A\cos(2\pi f_c t)$$

  - A: amplitude of the carrier; f_c: carrier frequency
  - $m(t)$: message signal with bandwidth W and average power, P
  - s(t): DSB modulated signal: bandwidth 2W, average power $P_T = \frac{1}{2}A^2 P$
- Demodulation:



  - Bandwidth of band-pass filter: 2W
  - Bandwidth of the low-pass filter: W
  - SNR at the receiver output:

$$SNR_{baseband} = \frac{P_T}{N_0 W} \quad \Rightarrow \quad SNR_{DSB-SC} = SNR_{baseband}$$

Single Sideband (SSB) Modulation

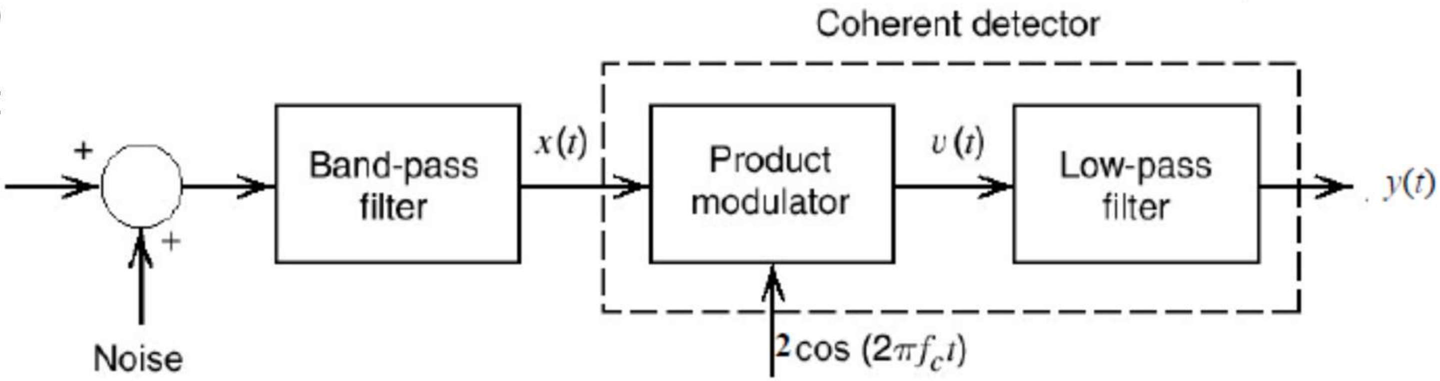
- General form of a SSB-SC signal:

$$s(t) = \frac{A}{2} m(t)\cos(2\pi f_c t) - \frac{A}{2} \hat{m}(t)\sin(2\pi f_c t)$$

  - A: amplitude of the carrier; f_c: carrier frequency
  - $m(t)$: message signal with bandwidth W and average power, P
  - s(t): SSB modulated signal: bandwidth W and average power $P_T = \frac{1}{4} A^2 P$
- Demodulatio

SSB Modulat

Signal s(t)



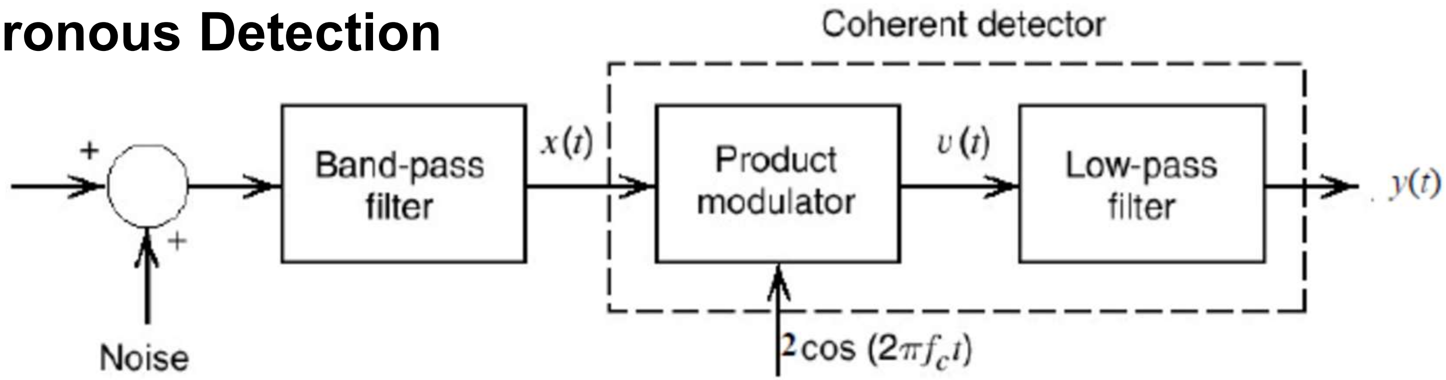
  - Bandwidth of band-pass filter: W
  - Bandwidth of the low-pass filter: W
  - SNR at the receiver output:

$$SNR_{SSB} = SNR_{baseband} = SNR_{DSB-SC}$$

Standard AM

- **Standard AM**: $s_{AM}(t) = [A + m(t)]\cos(2\pi f_c t)$
  - Usually $A \geq \mathrm{m_p} = \max|m(t)|$, modulation index $\mu = \frac{m_p}{A} \leq 1$
  - *m*(*t*): message signal with bandwidth W and average power, P
  - AM modulated signal: bandwidth $2\mathrm{W}$ and average power $\dfrac{A^2 + P}{2}$

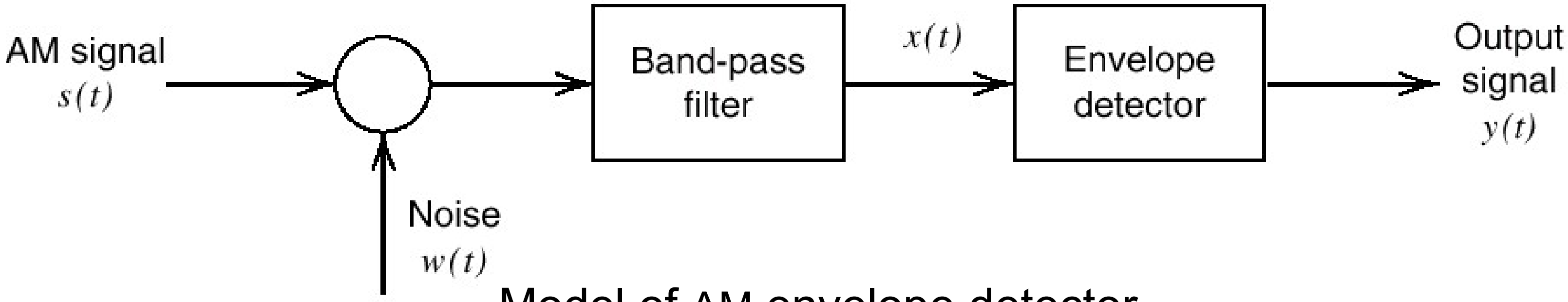
- **Synchronous Detection**



  - Bandwidth of band-pass filter: $2\mathrm{W}$
  - Bandwidth of the low-pass filter: W
  - SNR at the receiver output: $SNR_{AM} = \dfrac{P}{A^2 + P} SNR_{baseband}$

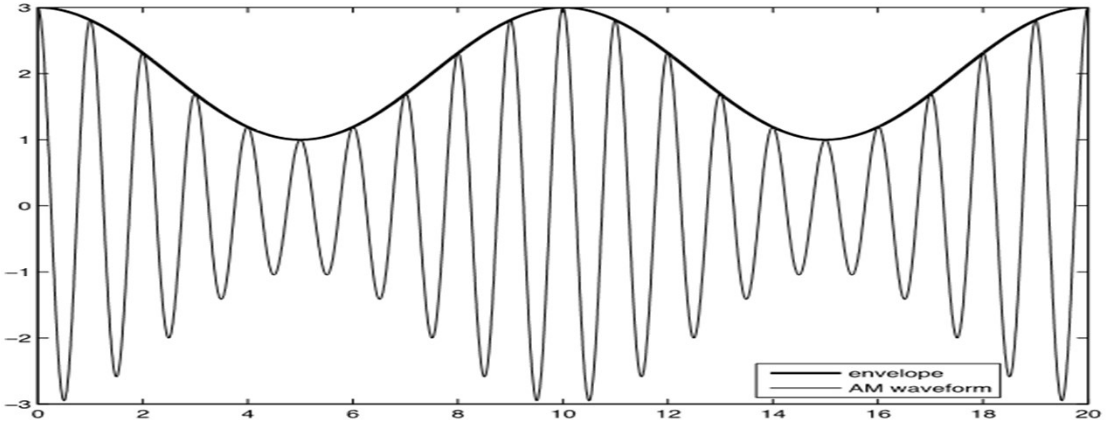
Non-coherent Receiver

- Receiver:



Model of AM envelope detector

  - Bandwidth of band-pass filter: 2W
  - $\mu = \frac{m_p}{A} \leq 1$, or $m_p \leq A$
  - SNR at the receiver output for small noise case: $SNR_{env} \approx \dfrac{P}{A^2 + P} SNR_{baseband}$



Frequency Modulation

- Instantaneous frequency is varied linearly with message:

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

  - k_f is the frequency sensitivity of the modulator.
  - frequency deviation: $\Delta f = k_f\, m_p$
  - deviation ratio/modulation index:

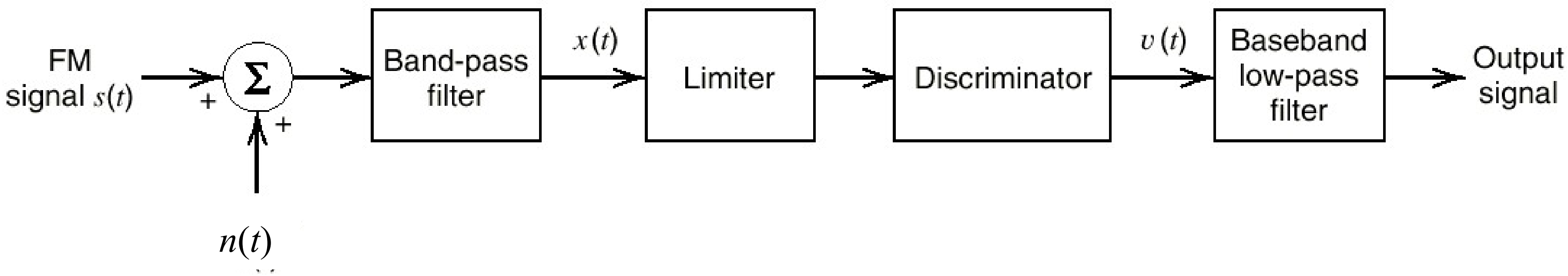
    $\beta = \Delta f / W$, W: message bandwidth

- Modulated signal:

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

  - The envelope is constant
  - Signal s(t) is a non-linear function of the message signal m(t)
  - Bandwidth using Carson's rule of thumb: $B_T = 2W(\beta+1) = 2(\Delta f + W)$

FM Receiver

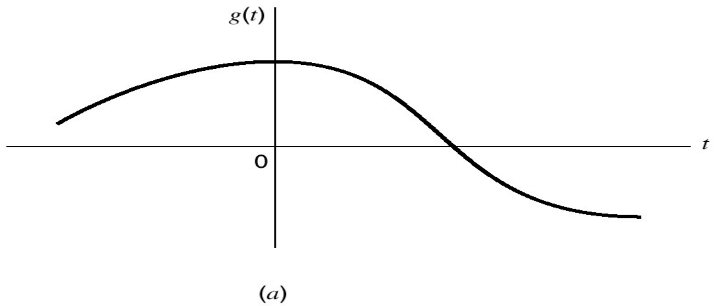


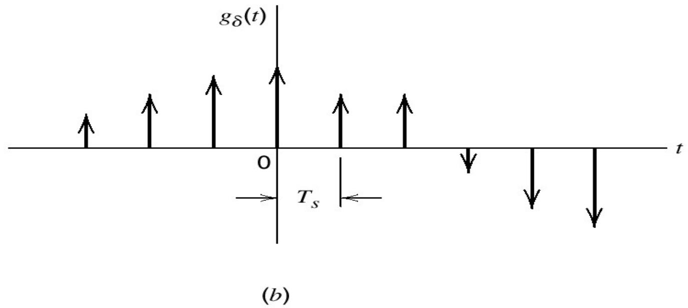
- Bandwidth of bandpass filter: $B_T = 2W(\beta+1) = 2(\Delta f + W)$
- Discriminator: instantaneous amplitude is proportional to instantaneous frequency
- Bandwidth of baseband low-pass filter: W
- SNR at the receiver output:

$$SNR_{FM} = 3\beta^2 \frac{P}{m_p^2} SNR_{baseband}$$

Sampling, Quantization, PCM

- Sampling Theorem: A signal whose spectrum is band-limited to W Hz, can be reconstructed exactly from its samples if they are taken uniformly at a rate of $R \geq 2W$ Hz.
- Nyquist frequency: $f_s = 2W$ Hz





- Quantization
  - Uniform quantization: $SNR_o(\text{dB}) = 6n + 10\log_{10}\left(\dfrac{3P}{m_p^2}\right)$ (dB)
  - Non-uniform quantization: improving SNR
- PCM: Pulse code modulation
- Grey Mapping
- Line Code