Course 5:Linear modulation

Agenda

- Introduction
- Amplitude modulation principles
- Types of amplitude modulation
- Demodulation of the amplitude modulated signals
- Errors in amplitude modulation

Introduction

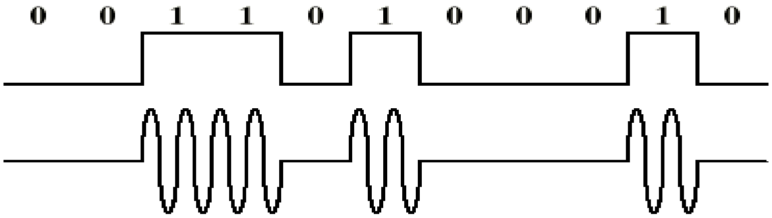
- Modulation…Why?
  - We need to transmit baseband data (digital or analog) through a channel
  - The channel “behaves better” to other frequencies than the base-band
  - For the radio transmission, the antennas size is directly proportional with the wavelength
  - Signal needs to be translated to another frequency than the original central frequency of its spectrum
- Modulation…How?
  - A carrier signal (sine wave) is “modulated” (=modified, =shaped) by the useful signal
  - AM, FM, PM

Modulation’s key terms

- Modulator (modulating) signal: the signal to be transmitted
  - The signal can be analog or digital
  - Especially in the digital signal context, the modulator signal can be referred to as message
- Carrier signal: used to “transport” the message signal
  - Carrier signal is a sine wave (continuous wave modulation) or a periodic rectangular wave

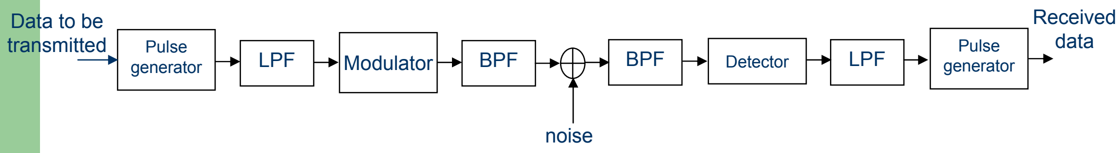
Amplitude modulation

- AM is referred to as linear modulation
- The amplitude of the carrier is changed by the signal to be transmitted
- When the modulating signal is digital, the Amplitude Shift Keying (ASK) case is obtained
- The simplest form of ASK is called On/Off Keying (OOK)



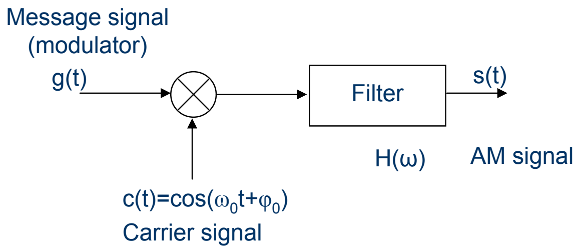
(a) Amplitude-shift keying

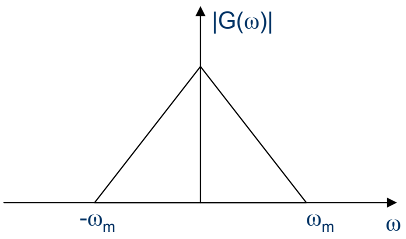
AM transmission chain



- Transmitter
  - The pulse generator produces rectangular pulses to represent data (baseband signal, usually two voltage levels)
  - LPF (Low-Pass filter): shapes (in time and frequency) the signal
  - Modulator: performs AM
  - BPF (Band-Pass Filter): fits the signal to its dedicated band (to avoid interferences with the adjacent bands)
- Receiver
  - BPF: eliminates out-of-band noises and interference
  - Detector: retrieves the baseband signal (complementary block for modulator)
  - LPF: eliminates unusefull components
  - Pulse shaper: issues voltage levels to represent data

AM Frequency domain view [1]





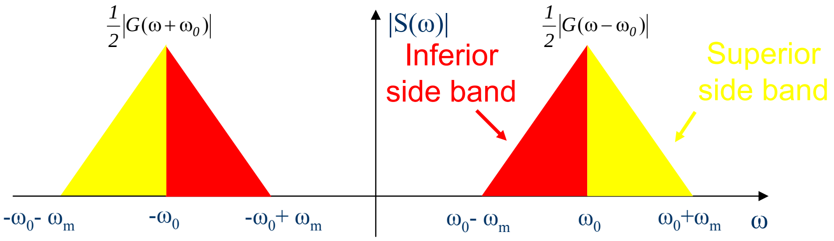
- As a result of the modulation, the spectrum of the message signal is shifted from “0” to ω_0 (carrier frequency)
- Thus, the signal transmitted through the channel has a spectrum located to the carrier frequency
- Example: “Radio Romania can be listened to at 567 KHz” refers to the carrier frequency used
- Most of the spectrum of the modulator signal (audio) in this example is below 0-20KHz (or -20 to 20 KHz for bi-dimensional Power Spectral Density)

AM Frequency domain view [2]

- The spectrum of the modulated signal is:

$$S(\omega) = H(\omega)\left[\frac{1}{2}G(\omega+\omega_0)+\frac{1}{2}G(\omega-\omega_0)\right] \quad (1)$$

- The filter H selects the type of modulation:



Suppressing…and un-suppressing the carrier

- If the carrier has a DC component:

$$c(t) = c_0 + \cos(\omega_0 t + \varphi_0) \quad (2)$$

- The modulated signal is:

$$s_a(t) = (s(t) + c_0)\cos(\omega_0 t + \phi_0) \quad (3)$$

- In the spectrum, we will retrieve the Dirac pulses corresponding to the sine carrier

$$S(\omega) = H(\omega)\left\{\pi c_0[\delta(\omega+\omega_0)+\delta(\omega-\omega_0)] + \left[\frac{1}{2}G(\omega+\omega_0)+\frac{1}{2}G(\omega-\omega_0)\right]\right\} \quad (4)$$

Remarks

- If $c_0=0$, then we have AM with suppressed carrier
  - The figures from the next slide correspond to the above case
- The later is also called product modulation, because it consists on a simple multiplication
- All the information of the AM signal is carried by EACH side-band
- From effectiveness reasons, one side-band can be suppressed

Graphical illustration

- The filter selects the lower (inferior) or the upper (superior) side-band, leading to Single Side Band (SSB) AM

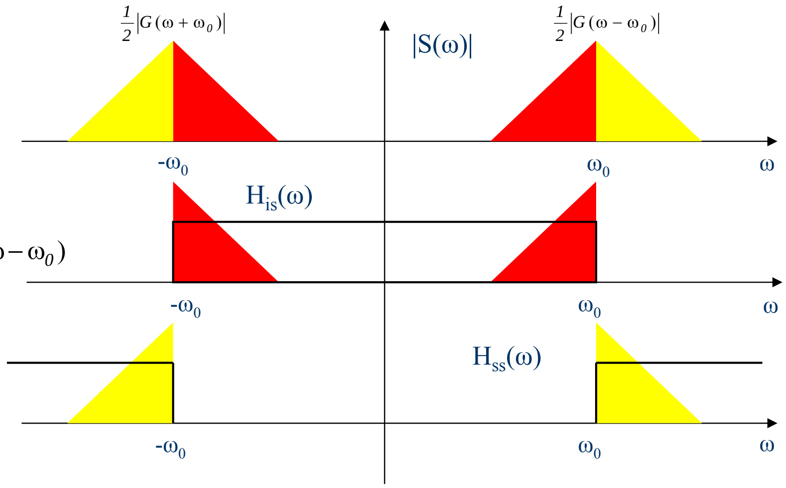
a. Double side-band AM

b. Inferior SB AM

$H_{IS}(\omega) = \sigma(\omega+\omega_0) - \sigma(\omega-\omega_0)$

c. Superior SB AM

$H_{ss}(\omega) = 1 - H_{IS}(\omega)$



SSB-AM

- SSB signal can be expressed as:

$$s_{si}(t) = \frac{1}{2} g(t)\cos(\omega_0 t) + \frac{1}{2} \hbar\{g(t)\}\sin(\omega_0 t) \quad (5)$$

- $\hbar\{g(t)\}$ is the Hilbert transform of g, which can be obtain by passing g(t) through the filter:

$$F(\omega) = -j\,\mathrm{sgn}(\omega) \quad (6)$$

- SSB-AM is spectrally efficient
- Difficult to implement in practice: the filters which separate the side-band must be very selective

AM with Vestigial Side-Band (VSB)

- Only part of the side-bands is suppressed
- Lower frequencies transmitted with both Side-Bands, upper frequencies with one side-band
- This allows easier filtering to separate the bands (frequencies near the carrier must not be filtered)
- 25% more bandwidth required than in SSB, but easier to implement
- Example: NTSC TV system: all upper sideband of bandwidth W2 = 4 MHz, but only W1 = 1.25 MHz of the lower sideband are transmitted

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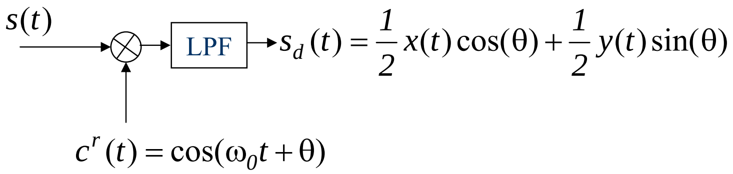
AM signals demodulation

- AM modulation with suppressed carrier is discussed
- Two types of detection for AM: coherent and non-coherent
- Even if simpler, the non-coherent detection is very sensitive to noise
- Coherent detection is oftentimes preferred

Coherent demodulation [1]



$s(t)$

$$s_d(t)=\frac{1}{2}x(t)\cos(\theta)+\frac{1}{2}y(t)\sin(\theta)$$

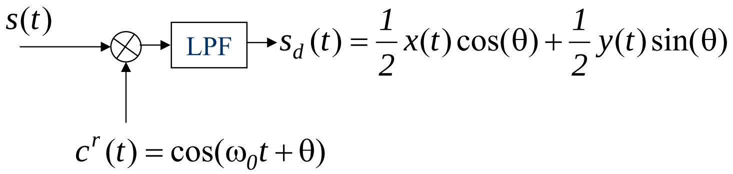
$$c^r(t)=\cos(\omega_0 t+\theta)$$

- Principle: locally generated carrier must be used in receiver
- This carrier must be synchronized (frequency, phase) with the one used for transmission
- The modulated signal can be expressed as:

$$s(t)=x(t)\cos(\omega_0 t)+y(t)\sin(\omega_0 t) \quad (7)$$

- The LPF cuts-off the 2 ω_0 component, and r(t) is obtained

Coherent demodulation [2]



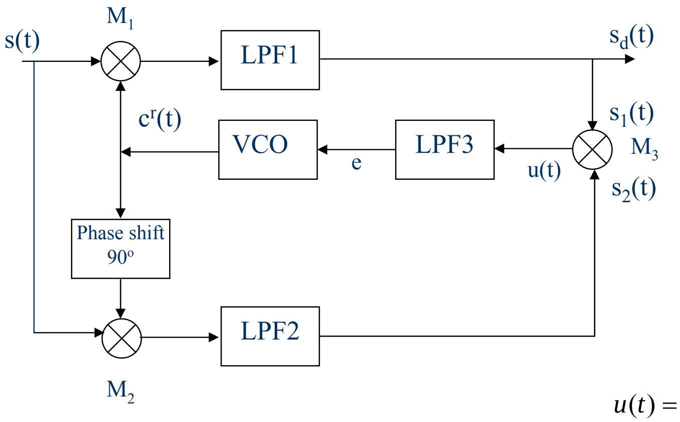
$s(t)$

$$s_d(t)=\frac{1}{2}x(t)\cos(\theta)+\frac{1}{2}y(t)\sin(\theta)$$

$$c^r(t)=\cos(\omega_0 t+\theta)$$

- Θ affects the in-phase component and introduces an in-quadrature component (for double Side Band signals)
- Θ must be 0!!! (phase synchronization)
- Two choices to regenerate the carrier at receiver:
  - Based on the received signal
  - Based on special pilot signals

Costas Loop



$$s(t) = x(t)\cos(\omega_0 t) \qquad (7)$$

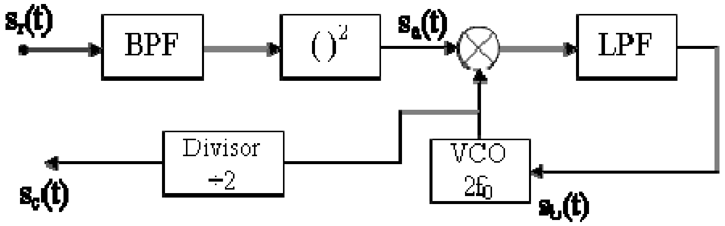
$$s_1(t) = \frac{1}{2}x(t)\cos(\theta) \qquad (8)$$

$$s_2(t) = \frac{1}{2}x(t)\sin(\theta) \qquad (9)$$

$$u(t) = \frac{1}{8}x^2(t)\cdot\sin(2\theta) \cong \frac{\theta}{4}x^2(t) \qquad (10)$$

- Final result: VCO is tuned by an “error” signal (effective value of $x^2(t)$)
- Calibration/testing done using white noise as an input

Squared loop



$$s_a(t) = x^2(t)\cos^2(\omega_0 t) = \frac{x^2(t)}{2} + \frac{x^2(t)}{2}\cos(2\omega_0 t) \qquad (11)$$

- After LPF, a signal which is proportional with θ is obtained, tuning the VCO:

$$s_b(t) = \frac{1}{4}\langle x(t)\rangle^2 \sin\theta \cong \frac{\theta}{4}\langle x(t)\rangle^2 \qquad (12)$$

- The divisor brings the signal back to the carrier frequency

Squared loop’s shortcomings

- Squared loop uses the data (modulated) signal to tune the local receiver’s oscillator
- After the divisor, a signal of the carrier frequency is generated
- The signal after the divisor is affected by a phase ambiguity:

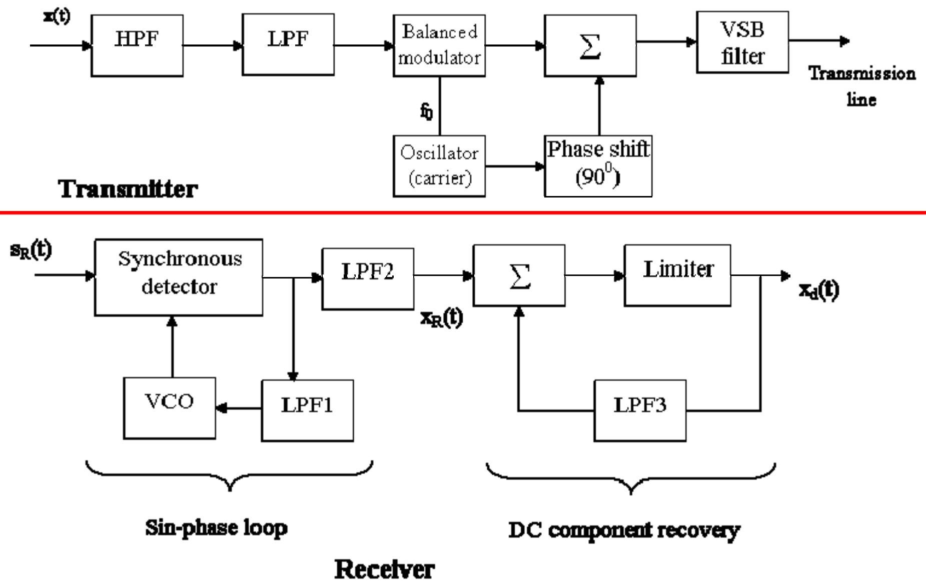
$$s_c(t) = \cos\frac{2\omega_0 t + 2k\pi}{2} = \cos(2\omega_0 t + k\pi) \quad (13)$$

- Special signals are used in this case to ease carrier recovery
- These signals are either in-band or out of band “pilots”

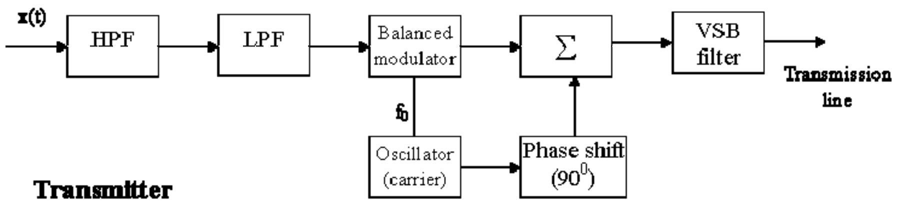
Synchronization challenges

- In the coherent AM, the receiver must dispose of a carrier which is synchronized with the one used by the transmitter
- Synchronization is, generally, a challenging task
- The local receiver’s oscillator synchronization may be eased by using some special signals (pilots) transmitted along with the AM signal
  - In-band pilots: pilots are transmitted within the bandwidth of the AM signal
  - Out-of-band: pilots are transmitted outside the AM dedicated band

Pilot based synchronization approach

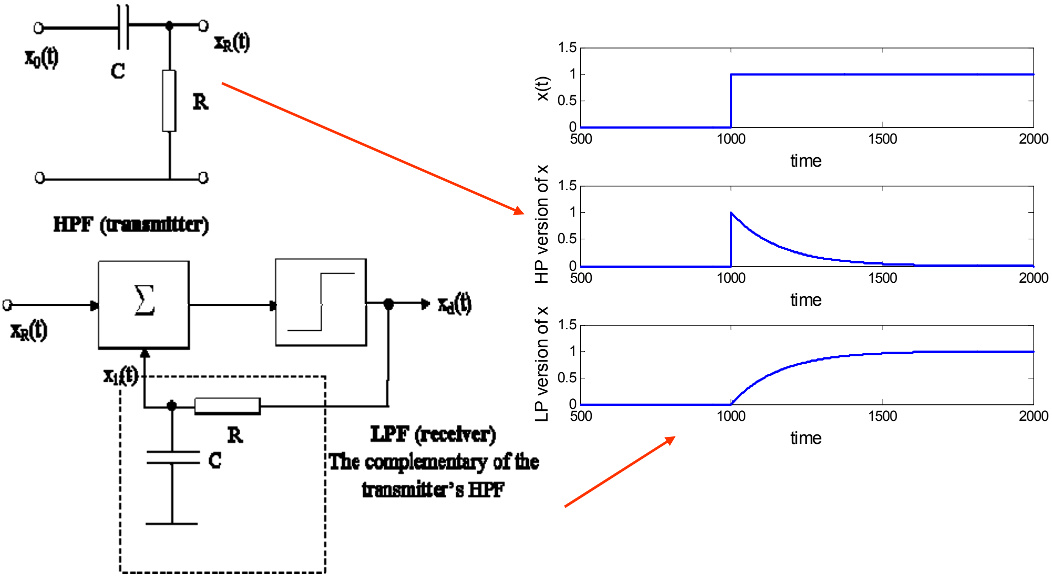


The transmitter



- HPF: eliminates components around DC
- Balanced modulator: implements a AM with suppressed carrier
- A low-power carrier (in-quadrature) is added to the input signal

Quantized loop principle

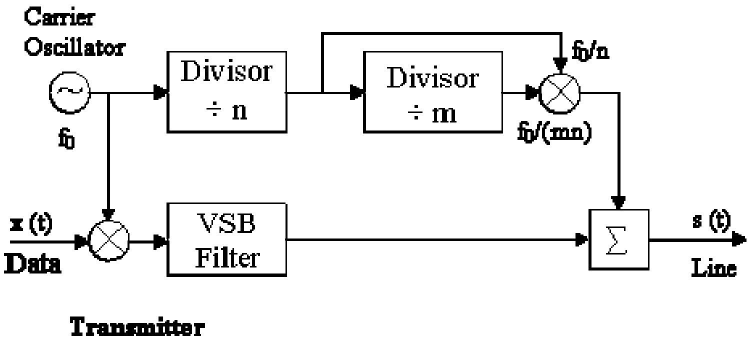


Remarks on the quantized loop

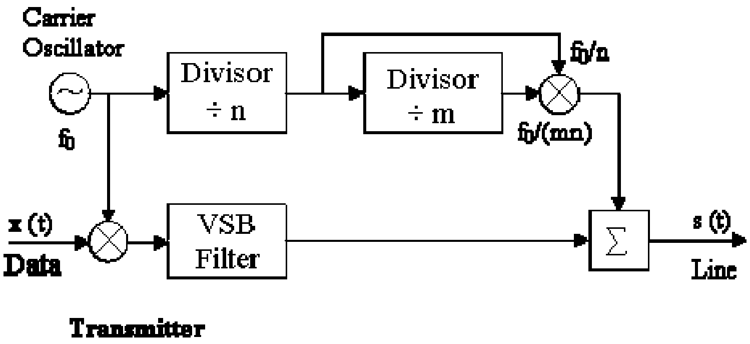
- High sensitivity to the channel distortions
- This sensitivity can be reduced if lower cut-off frequency will be used by the HPF of the transmitter
- But, carrier's neighbor components will re-occur in the spectrum
- Consequently, the synchronization loop (the left-hand part of the receiver) will be affected

Out-of-band pilot based synchronization

- Principle: out-of band pilot is transmitted
- This way, there are no perturbations in the useful bandwidth
- The pilot frequency is a ratio of the carrier frequency

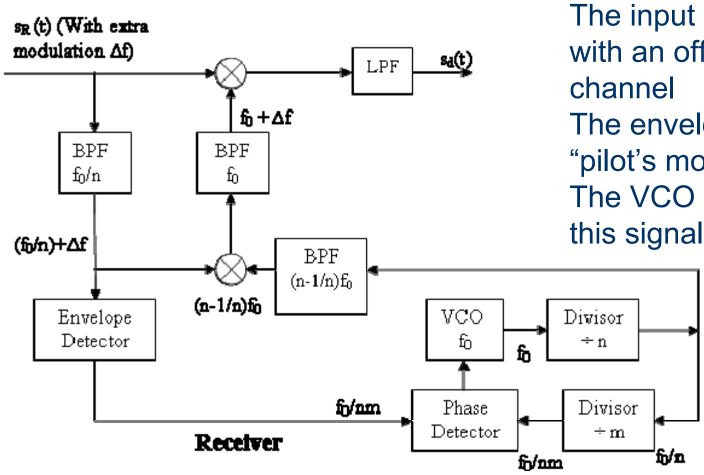


Transmitter basics



- A classical VSB is performed
- One sine wave of frequency f_0/(nm) modulates a “pseudo-carrier” f_0/n
- The two signals are added and transmitted

Receiver’s scheme



The input BPF separates the pilot f0/N, with an offset introduced by the channel

The envelope detector extracts the “pilot’s modulator”, $f_0/(nm)$

The VCO (f_0 frequency) is tuned by this signal

After passing the signal to the BPF, a modulation (multiplication between this signal and the modulated pilot) is applied

The output of the f_0 centered BPF is a shofted carrier

Out-of-band pilot synchronization: pro and cons

- Because the pilots are transmitted out-of band, they do not influence carrier retrieval at reception
- The frequency selectivity of the channel may influence differently the pilot f_0/n and the carrier f_0
- Equalization needed in this case