

Ve 216: Introduction to Signals and Systems

Yong Long

The University of Michigan- Shanghai Jiao Tong University Joint Institute
Shanghai Jiao Tong University

April 10, 2018

Based on Lecture Notes by Prof. Jeffrey A. Fessler

Outline

- 1 8. Communications
 - Introduction
 - Sinusoidal amplitude modulation (8.1)
 - Demodulation (8.2)
 - Frequency-division multiplexing (8.3)

Outline

- 1 8. Communications
 - Introduction
 - Sinusoidal amplitude modulation (8.1)
 - Demodulation (8.2)
 - Synchronous Demodulation
 - Asynchronous Demodulation
 - Frequency-division multiplexing (8.3)

Introduction

This chapter applied FT principles and tools to the analysis of **communications systems** (AM radios, FM radios, wireless phones, video, etc.)

All of it is based on the **modulation property** of the FT.

Overview

- Amplitude Modulation (AM radio, digital comm (modems))
- Synchronous demodulation
- Asynchronous demodulation
- Heterodyning tuner

We will only cover 8.1, 8.2, 8.3

Introduction

This chapter applied FT principles and tools to the analysis of **communications systems** (AM radios, FM radios, wireless phones, video, etc.)

All of it is based on the **modulation property** of the FT.

Overview

- Amplitude Modulation (AM radio, digital comm (modems))
- Synchronous demodulation
- Asynchronous demodulation
- Heterodyning tuner

We will only cover 8.1, 8.2, 8.3

Introduction

This chapter applied FT principles and tools to the analysis of **communications systems** (AM radios, FM radios, wireless phones, video, etc.)

All of it is based on the **modulation property** of the FT.

Overview

- Amplitude Modulation (AM radio, digital comm (modems))
- Synchronous demodulation
- Asynchronous demodulation
- Heterodyning tuner

We will only cover 8.1, 8.2, 8.3

Introduction

This chapter applied FT principles and tools to the analysis of **communications systems** (AM radios, FM radios, wireless phones, video, etc.)

All of it is based on the **modulation property** of the FT.

Overview

- Amplitude Modulation (AM radio, digital comm (modems))
- Synchronous demodulation
- Asynchronous demodulation
- Heterodyning tuner

We will only cover 8.1, 8.2, 8.3

Modulation Property

Modulation Property:

$$\begin{aligned} e^{j\omega_0 t} f(t) &\xleftrightarrow{\mathcal{F}} F(\omega - \omega_0) \\ f(t) \cos \omega_0 t &\xleftrightarrow{\mathcal{F}} \frac{F(\omega - \omega_0) + F(\omega + \omega_0)}{2} \end{aligned}$$

Question

Why modulate signals in communication systems?

Modulation Property

Modulation Property:

$$\begin{aligned} e^{j\omega_0 t} f(t) &\xleftrightarrow{\mathcal{F}} F(\omega - \omega_0) \\ f(t) \cos \omega_0 t &\xleftrightarrow{\mathcal{F}} \frac{F(\omega - \omega_0) + F(\omega + \omega_0)}{2} \end{aligned}$$

Question

Why modulate signals in communication systems?

Modulation Property

Modulation Property:

$$\begin{aligned} e^{j\omega_0 t} f(t) &\xleftrightarrow{\mathcal{F}} F(\omega - \omega_0) \\ f(t) \cos \omega_0 t &\xleftrightarrow{\mathcal{F}} \frac{F(\omega - \omega_0) + F(\omega + \omega_0)}{2} \end{aligned}$$

Question

Why modulate signals in communication systems?

Definition

Modulation is the process used to shift the frequency of an information signal so that the resulting signal is the desired frequency band.

Importance of modulation

- 1 *Ear can hear from about 20Hz to 20kHz. For such audio signals, electrical transmission over copper wire works fine (and is used in all audio systems). So there is no need to modulate.*
- 2 *Human voice is dominated by frequency components of less than 1kHz. If we were attempt to transmit a human voice signal by the propagation of electromagnetic (radio) waves, we could encounter the several problems. Two of the more obvious problems are as follows.*

Importance of modulation

- 1 *Ear can hear from about 20Hz to 20kHz. For such audio signals, electrical transmission over copper wire works fine (and is used in all audio systems). So there is no need to modulate.*
- 2 *Human voice is dominated by frequency components of less than 1kHz. If we were attempt to transmit a human voice signal by the propagation of electromagnetic (radio) waves, we could encounter the several problems. Two of the more obvious problems are as follows.*

Antenna length requirement (1)

1. Antenna length requirement.

For efficient radiation, antenna lengths should be longer than $\lambda/10$, where λ is the wavelength of the signal to be radiated, given by

$$\lambda = \frac{c}{f_c}$$

where c is the speed of the light and f_c is the frequency of the signal.

Example

For a 30Hz frequency component, the wavelength is

$$\lambda = \frac{c}{f_c} = \frac{3 \cdot 10^8 \text{ m/s}}{30 \text{ s}^{-1}} = 10,000 \text{ km},$$

so $\lambda/10 = 1000 \text{ km}$. Obviously impractical.

Antenna length requirement (1)

1. Antenna length requirement.

For efficient radiation, antenna lengths should be **longer than $\lambda/10$** , where λ is the wavelength of the signal to be radiated, given by

$$\lambda = \frac{c}{f_c}$$

where c is the speed of the light and f_c is the frequency of the signal.

Example

For a **30Hz** frequency component, the wavelength is

$$\lambda = \frac{c}{f_c} = \frac{3 \cdot 10^8 m/s}{30 s^{-1}} = 10,000 km,$$

so $\lambda/10 = 1000 km$. Obviously impractical.

Antenna length requirement (2)

1. Antenna length requirement.

After considering the wavelength formula,

$$\lambda = \frac{c}{f_c}$$

it becomes apparent that by **increasing the frequency** of the signal, we can **decrease the antenna length** required.

Question

OK, so let's say we forget antennas and stick to copper wire (like the cable company does). Now why should we modulate?

Antenna length requirement (2)

1. Antenna length requirement.

After considering the wavelength formula,

$$\lambda = \frac{c}{f_c}$$

it becomes apparent that by **increasing the frequency** of the signal, we can **decrease the antenna length** required.

Question

OK, so let's say we forget antennas and stick to copper wire (like the cable company does). Now why should we modulate?

Interference from other signals

2. Interference from other signals.

- If all radio stations transmitted baseband 20Hz-20kHz signals (over a cable for example), the receivers would receive all of those signals **superimposed**, and would have **no way of separating them**.
- The solution to these problems is to **modulate signals** to **different parts of the frequency spectrum**.

Interference from other signals

2. Interference from other signals.

- If all radio stations transmitted baseband 20Hz-20kHz signals (over a cable for example), the receivers would receive all of those signals **superimposed**, and would have **no way of separating them**.
- The solution to these problems is to **modulate signals** to different parts of the frequency spectrum.

Interference from other signals

2. Interference from other signals.

- If all radio stations transmitted baseband 20Hz-20kHz signals (over a cable for example), the receivers would receive all of those signals **superimposed**, and would have **no way of separating them**.
- The solution to these problems is to **modulate signals** to **different parts of the frequency spectrum**.

FCC regulation

In the U.S., the **frequency band allocation** is controlled by the Federal Communications Commission (FCC).

- **AM radio**: 540-1600kHz
- **FM radio**: 88-108MHz

Note: lots of room for many non-overlapping channels each $\pm 20\text{kHz}$ wide.

(Human voice about 1kHz bandwidth)

FCC regulation

In the U.S., the **frequency band allocation** is controlled by the Federal Communications Commission (FCC).

- **AM radio**: 540-1600kHz
- **FM radio**: 88-108MHz

Note: lots of room for many non-overlapping channels each **$\pm 20\text{kHz}$ wide**.

(Human voice about 1kHz bandwidth)

Outline

- 1 8. Communications
 - Introduction
 - Sinusoidal amplitude modulation (8.1)
 - Demodulation (8.2)
 - Synchronous Demodulation
 - Asynchronous Demodulation
 - Frequency-division multiplexing (8.3)

DSB/SC-AM

- So we need to shift the audio signal from baseband to something much higher.
- We have already seen that the **modulation property** of the FT provides a mechanism for this.
- There are **many variations** on how to do this (see Ve 353 Introduction to Communication Systems).
- The simplest method is called **double sideband, suppressed carrier, amplitude modulation** or **DSB/SC-AM**.

DSB/SC-AM

- So we need to shift the audio signal from baseband to something much higher.
- We have already seen that the **modulation property** of the FT provides a mechanism for this.
- There are **many variations** on how to do this (see Ve 353 Introduction to Communication Systems).
- The simplest method is called **double sideband, suppressed carrier, amplitude modulation** or **DSB/SC-AM**.

DSB/SC-AM

- So we need to shift the audio signal from baseband to something much higher.
- We have already seen that the **modulation property** of the FT provides a mechanism for this.
- There are **many variations** on how to do this (see Ve 353 Introduction to Communication Systems).
- The simplest method is called **double sideband, suppressed carrier**, **amplitude modulation** or **DSB/SC-AM**.

DSB/SC-AM

- So we need to shift the audio signal from baseband to something much higher.
- We have already seen that the **modulation property** of the FT provides a mechanism for this.
- There are **many variations** on how to do this (see Ve 353 Introduction to Communication Systems).
- The simplest method is called **double sideband, suppressed carrier, amplitude modulation** or **DSB/SC-AM**.

Sinusoidal amplitude modulation (1)

Let $x(t)$ be the **modulating signal** (the audio signal) and let $c(t)$ be the **carrier signal** (a high-frequency cosinusoid). Specifically

$$c(t) = \cos(\omega_c t + \theta_c)$$

where ω_c is called the **carrier frequency**.

The transmitted signal is

$$y(t) = x(t)c(t) = x(t)\cos(\omega_c t + \theta_c)$$
$$\xleftrightarrow{\mathcal{F}} Y(\omega) = \frac{1}{2}[e^{j\theta_c}X(\omega - \omega_c) + e^{-j\theta_c}X(\omega + \omega_c)]$$

Sinusoidal amplitude modulation (1)

Let $x(t)$ be the **modulating signal** (the audio signal) and let $c(t)$ be the **carrier signal** (a high-frequency cosinusoid). Specifically

$$c(t) = \cos(\omega_c t + \theta_c)$$

where ω_c is called the **carrier frequency**.

The transmitted signal is

$$y(t) = x(t)c(t) = x(t)\cos(\omega_c t + \theta_c)$$
$$\xleftrightarrow{\mathcal{F}} Y(\omega) = \frac{1}{2}[e^{j\theta_c}X(\omega - \omega_c) + e^{-j\theta_c}X(\omega + \omega_c)]$$

Sinusoidal amplitude modulation (2)

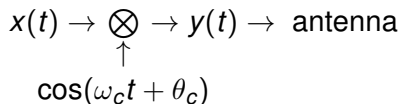
Block diagram of modulation system:

$$x(t) \rightarrow \begin{array}{c} \otimes \\ \uparrow \\ \cos(\omega_c t + \theta_c) \end{array} \rightarrow y(t) \rightarrow \text{antenna}$$

(Picture) in frequency domain (MIT, Lecture 13.9) (textbook, Figure 8.4, p. 586) This multiplication is also sometimes called **mixing**. Note that graphically it appears that **all of the audio signal information is retained**, it is just **moved to a different part of the spectrum**.

Sinusoidal amplitude modulation (2)

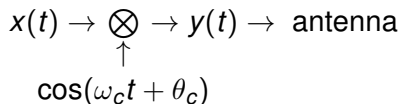
Block diagram of modulation system:



(Picture) in frequency domain (MIT, Lecture 13.9) (textbook, Figure 8.4, p. 586) This multiplication is also sometimes called **mixing**. Note that graphically it appears that all of the audio signal information is retained, it is just moved to a different part of the spectrum.

Sinusoidal amplitude modulation (2)

Block diagram of modulation system:



(Picture) in frequency domain (MIT, Lecture 13.9) (textbook, Figure 8.4, p. 586) This multiplication is also sometimes called **mixing**. Note that graphically it appears that **all of the audio signal information is retained**, it is just **moved to a different part of the spectrum**.

Sinusoidal amplitude modulation (3)

Since it is now a **high frequency** signal, it can be transmitted by a **practical antenna**, and **different radio stations can use different ω_c 's**.

Question

How much should the carrier frequencies (the ω_c 's) of different stations be separated?

Sinusoidal amplitude modulation (3)

Since it is now a **high frequency** signal, it can be transmitted by a **practical antenna**, and **different radio stations can use different ω_c 's**.

Question

How much should the carrier frequencies (the ω_c 's) of different stations be separated?

Sinusoidal amplitude modulation (3)

Since it is now a **high frequency** signal, it can be transmitted by a **practical antenna**, and **different radio stations can use different ω_c 's**.

Question

How much should the carrier frequencies (the ω_c 's) of different stations be separated?

*40kHz would be a **bare minimum**, but that would require an **ideal filter** to separate the different channels. So somewhat **wider separation** desirable.*

Sinusoidal amplitude modulation (4)

Question

The carriers of AM radio stations are spaced by 10kHz! How?

Sinusoidal amplitude modulation (4)

Question

The carriers of AM radio stations are spaced by 10kHz! How?

Smaller bandwidth, so lower audio quality.

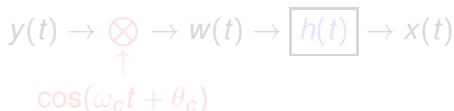
Outline

- 1 8. Communications
 - Introduction
 - Sinusoidal amplitude modulation (8.1)
 - Demodulation (8.2)
 - Synchronous Demodulation
 - Asynchronous Demodulation
 - Frequency-division multiplexing (8.3)

Synchronous Demodulation

- The signal must be **restored to baseband** for our **ears** to hear it.
- Conceptually, this can be done by **another multiplication** by a $\cos(\omega_c t + \theta_c)$ signal, followed by **lowpass filtering**.

Block diagram of demodulation system

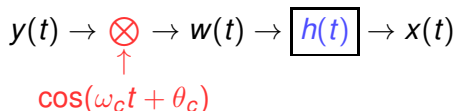


$$w(t) = y(t) \cos(\omega_c t + \theta_c)$$

Synchronous Demodulation

- The signal must be **restored to baseband** for our **ears** to hear it.
- Conceptually, this can be done by **another multiplication** by a $\cos(\omega_c t + \theta_c)$ signal, followed by **lowpass filtering**.

Block diagram of demodulation system



$$w(t) = y(t) \cos(\omega_c t + \theta_c)$$

Frequency response and lowpass filtering

$$w(t) = y(t) \cos(\omega_c t + \theta_c)$$

$$W(\omega) = \frac{1}{2} [e^{j\theta_c} Y(\omega - \omega_c) + e^{-j\theta_c} Y(\omega + \omega_c)]$$

$$= \frac{1}{4} e^{2j\theta_c} X(\omega - 2\omega_c) + \frac{1}{2} X(\omega) + \frac{1}{4} e^{-2j\theta_c} X(\omega + 2\omega_c)$$

$$Y(\omega) = \frac{1}{2} [e^{j\theta_c} X(\omega - \omega_c) + e^{-j\theta_c} X(\omega + \omega_c)]$$

Now pass through a **lowpass filter** to extract the baseband signal. (**Picture**)(MIT, Lecture 13.10 and 13.11)

Frequency response and lowpass filtering

$$w(t) = y(t) \cos(\omega_c t + \theta_c)$$

$$W(\omega) = \frac{1}{2} [e^{j\theta_c} Y(\omega - \omega_c) + e^{-j\theta_c} Y(\omega + \omega_c)]$$

$$= \frac{1}{4} e^{2j\theta_c} X(\omega - 2\omega_c) + \frac{1}{2} X(\omega) + \frac{1}{4} e^{-2j\theta_c} X(\omega + 2\omega_c)$$

$$Y(\omega) = \frac{1}{2} [e^{j\theta_c} X(\omega - \omega_c) + e^{-j\theta_c} X(\omega + \omega_c)]$$

Now pass through a **lowpass filter** to extract the baseband signal. (**Picture**)(MIT, Lecture 13.10 and 13.11)

Frequency response and lowpass filtering

$$w(t) = y(t) \cos(\omega_c t + \theta_c)$$

$$W(\omega) = \frac{1}{2} [e^{j\theta_c} Y(\omega - \omega_c) + e^{-j\theta_c} Y(\omega + \omega_c)]$$

$$= \frac{1}{4} e^{2j\theta_c} X(\omega - 2\omega_c) + \frac{1}{2} X(\omega) + \frac{1}{4} e^{-2j\theta_c} X(\omega + 2\omega_c)$$

$$Y(\omega) = \frac{1}{2} [e^{j\theta_c} X(\omega - \omega_c) + e^{-j\theta_c} X(\omega + \omega_c)]$$

Now pass through a **lowpass filter** to extract the baseband signal. (**Picture**)(MIT, Lecture 13.10 and 13.11)

Frequency response and lowpass filtering

$$w(t) = y(t) \cos(\omega_c t + \theta_c)$$

$$W(\omega) = \frac{1}{2} [e^{j\theta_c} Y(\omega - \omega_c) + e^{-j\theta_c} Y(\omega + \omega_c)]$$

$$= \frac{1}{4} e^{2j\theta_c} X(\omega - 2\omega_c) + \frac{1}{2} X(\omega) + \frac{1}{4} e^{-2j\theta_c} X(\omega + 2\omega_c)$$

$$Y(\omega) = \frac{1}{2} [e^{j\theta_c} X(\omega - \omega_c) + e^{-j\theta_c} X(\omega + \omega_c)]$$

Now pass through a **lowpass filter** to extract the baseband signal. **(Picture)**(MIT, Lecture 13.10 and 13.11)

Practical problem

Question

Any practical problems?

Practical problem

Question

Any practical problems?

*Yes! At your receiver you do not have the modulation signal $\cos(\omega_c t + \theta_c)$ available. Specifically, the **phase θ_c** is not available.*

Loss of synchronization in phase (1)

Effect of loss of synchronization in phase. (Picture)(MIT, Lecture 13.16) (textbook, Figure 8.9)

- 1 If the phase difference is $\pi/2$, the output will be *zero*.
- 2 If the amplitude is small and there exists noise in the system, the *signal to noise ratio is small*.
- 3 If the phase relation between θ_c and ϕ_c is not maintained over time, the *amplitude factor* $\cos(\theta_c - \phi_c)$ *varies*.

Loss of synchronization in phase (1)

Effect of loss of synchronization in phase. (Picture)(MIT, Lecture 13.16) (textbook, Figure 8.9)

- 1 If the phase difference is $\pi/2$, the output will be **zero**.
- 2 If the amplitude is small and there exists noise in the system, the **signal to noise ratio is small**.
- 3 If the phase relation between θ_c and ϕ_c is not maintained over time, the **amplitude factor** $\cos(\theta_c - \phi_c)$ **varies**.

Loss of synchronization in phase (1)

Effect of loss of synchronization in phase. (Picture)(MIT, Lecture 13.16) (textbook, Figure 8.9)

- 1 If the phase difference is $\pi/2$, the output will be **zero**.
- 2 If the amplitude is small and there exists noise in the system, the **signal to noise ratio is small**.
- 3 If the phase relation between θ_c and ϕ_c is not maintained over time, the **amplitude factor** $\cos(\theta_c - \phi_c)$ **varies**.

Loss of synchronization in phase (1)

Effect of loss of synchronization in phase. (Picture)(MIT, Lecture 13.16) (textbook, Figure 8.9)

- ❶ *If the phase difference is $\pi/2$, the output will be zero.*
- ❷ *If the amplitude is small and there exists noise in the system, the signal to noise ratio is small.*
- ❸ *If the phase relation between θ_c and ϕ_c is not maintained over time, the amplitude factor $\cos(\theta_c - \phi_c)$ varies.*

Loss of synchronization in phase (2)

Synchronous demodulation requires a sophisticated phase-tracking receiver.

- *An expensive receiver is reasonable in some applications like satellite communications where transmit power is limited, so an expensive base station is acceptable.*
- *But in applications like commercial AM radio, one would like the receivers to be inexpensive, even if that means a more complicated and power-inefficient transmitter.*

Loss of synchronization in phase (2)

Synchronous demodulation requires a sophisticated phase-tracking receiver.

- *An expensive receiver is reasonable in some applications like satellite communications where transmit power is limited, so an expensive base station is acceptable.*
- *But in applications like commercial AM radio, one would like the receivers to be inexpensive, even if that means a more complicated and power-inefficient transmitter.*

Loss of synchronization in phase (2)

Synchronous demodulation requires a sophisticated phase-tracking receiver.

- *An expensive receiver is reasonable in some applications like satellite communications where transmit power is limited, so an expensive base station is acceptable.*
- *But in applications like commercial AM radio, one would like the receivers to be inexpensive, even if that means a more complicated and power-inefficient transmitter.*

Outline

- 1 8. Communications
 - Introduction
 - Sinusoidal amplitude modulation (8.1)
 - Demodulation (8.2)
 - Synchronous Demodulation
 - Asynchronous Demodulation
 - Frequency-division multiplexing (8.3)

Asynchronous Demodulation

A simple system and associated waveform for an **asynchronous demodulation** system. **(Picture)**(MIT, Lecture 13.17)

- The **envelop** of $y(t)$ (a smooth curve connecting the peaks) is a reasonable approximation of $x(t)$.
- $x(t)$ could be approximately recovered through the use of the **envelop detector** that tracks these peaks to extract the envelop.

Asynchronous Demodulation

A simple system and associated waveform for an **asynchronous demodulation** system. (**Picture**)(MIT, Lecture 13.17)

- The **envelop** of $y(t)$ (a smooth curve connecting the peaks) is a reasonable approximation of $x(t)$.
- $x(t)$ could be approximately recovered through the use of the **envelop detector** that tracks these peaks to extract the envelop.

Asynchronous Demodulation

A simple system and associated waveform for an **asynchronous demodulation** system. (**Picture**)(MIT, Lecture 13.17)

- The **envelop** of $y(t)$ (a smooth curve connecting the peaks) is a reasonable approximation of $x(t)$.
- $x(t)$ could be approximately recovered through the use of the **envelop detector** that tracks these peaks to extract the envelop.

Asynchronous Demodulation

A simple system and associated waveform for an **asynchronous demodulation** system. (**Picture**)(MIT, Lecture 13.17)

- The **envelop** of $y(t)$ (a smooth curve connecting the peaks) is a reasonable approximation of $x(t)$.
- $x(t)$ could be approximately recovered through the use of the **envelop detector** that tracks these peaks to extract the envelop.

Two basic assumptions

Two basic assumptions are required, so that the envelop is easily tracked.

- 1 $x(t)$ be positive. Solution: $x(t) + A > 0$.
- 2 $x(t)$ vary slowly compared to ω_c .

Example

- $x(t)$: 15-20 kHz
- $\omega_c/2\pi \in [500K, 2M]\text{Hz}$.

Two basic assumptions

Two basic assumptions are required, so that the envelop is easily tracked.

- 1 $x(t)$ be positive. Solution: $x(t) + A > 0$.
- 2 $x(t)$ vary slowly compared to ω_c .

Example

- $x(t)$: 15-20 kHz
- $\omega_c/2\pi \in [500K, 2M]\text{Hz}$.

DSB/WC-AM

Definition

Transmitting some of the modulation signal too (uses power) is called **double sideband, with carrier, amplitude modulation** or **DSB/WC-AM**.

Now the modulated signal (transmitted) is:

$$y(t) = (A + x(t)) \cos(\omega_c t)$$

(**Picture**) of block diagram (MIT, Lecture 13.18) (textbook, Figure 8.12) Spectrum of the DSB/WC signal:

$$Y(\omega) = A\pi[\delta(\omega - \omega_c) + \delta(\omega + \omega_c)] + \frac{1}{2}[X(\omega - \omega_c) + X(\omega + \omega_c)]$$

(**Picture**) of $Y(\omega)$ spectrum (MIT, Lecture 13.19) (textbook, Figure 8.14)

DSB/WC-AM

Definition

Transmitting some of the modulation signal too (uses power) is called **double sideband, with carrier, amplitude modulation** or **DSB/WC-AM**.

Now the modulated signal (transmitted) is:

$$y(t) = (A + x(t)) \cos(\omega_c t)$$

(Picture) of block diagram (MIT, Lecture 13.18) (textbook, Figure 8.12) Spectrum of the DSB/WC signal:

$$Y(\omega) = A\pi[\delta(\omega - \omega_c) + \delta(\omega + \omega_c)] + \frac{1}{2}[X(\omega - \omega_c) + X(\omega + \omega_c)]$$

(Picture) of $Y(\omega)$ spectrum (MIT, Lecture 13.19) (textbook, Figure 8.14)

DSB/WC-AM

Definition

Transmitting some of the modulation signal too (uses power) is called **double sideband, with carrier, amplitude modulation** or **DSB/WC-AM**.

Now the modulated signal (transmitted) is:

$$y(t) = (A + x(t)) \cos(\omega_c t)$$

(Picture) of block diagram (MIT, Lecture 13.18) (textbook, Figure 8.12) Spectrum of the DSB/WC signal:

$$Y(\omega) = A\pi[\delta(\omega - \omega_c) + \delta(\omega + \omega_c)] + \frac{1}{2}[X(\omega - \omega_c) + X(\omega + \omega_c)]$$

(Picture) of $Y(\omega)$ spectrum (MIT, Lecture 13.19) (textbook, Figure 8.14)

Issues associated with the value of A

Positive and negative issues associated with the value of A.

As A is increased

- The relative amount of carrier present in the modulated output increases, which results in easier demodulation for the envelop tractor. (**Picture**)(MIT, Lecture 13.18)
- Inefficiency of the system in terms of the power because A dose not carry any information about the signal.

Issues associated with the value of A

Positive and negative issues associated with the value of A .

As A is increased

- The relative amount of carrier present in the modulated output increases, which results in easier demodulation for the envelop tractor. (**Picture**)(MIT, Lecture 13.18)
- Inefficiency of the system in terms of the power because A dose not carry any information about the signal.

Single crystal receiver

- Since the envelope of the DSB/WC signal describes the original audio signal, an envelop detector (**(Picture)**, MIT, Lecture 13.17) will recover the envelope.

$$y(t) = (A + x(t)) \cos(\omega_c t)$$

$$m(t) = A + \hat{x}(t)$$

- Just eliminate the DC component and you recover the original signal.

$$y(t) \rightarrow \boxed{\text{Envelop detector}} \rightarrow m(t) \rightarrow \boxed{\text{DC blocking filter}} \rightarrow \hat{x}(t)$$

Single crystal receiver

- Since the envelope of the DSB/WC signal describes the original audio signal, an envelop detector (**(Picture)**, MIT, Lecture 13.17) will recover the envelope.

$$y(t) = (A + x(t)) \cos(\omega_c t)$$

$$m(t) = A + \hat{x}(t)$$

- Just eliminate the DC component and you recover the original signal.

$$y(t) \rightarrow \boxed{\text{Envelop detector}} \rightarrow m(t) \rightarrow \boxed{\text{DC blocking filter}} \rightarrow \hat{x}(t)$$

Single crystal receiver

- Since the envelope of the DSB/WC signal describes the original audio signal, an envelop detector (**(Picture)**, MIT, Lecture 13.17) will recover the envelope.

$$y(t) = (A + x(t)) \cos(\omega_c t)$$

$$m(t) = A + \hat{x}(t)$$

- Just eliminate the DC component and you recover the original signal.

$$y(t) \rightarrow \boxed{\text{Envelop detector}} \rightarrow m(t) \rightarrow \boxed{\text{DC blocking filter}} \rightarrow \hat{x}(t)$$

Outline

- 1 8. Communications
 - Introduction
 - Sinusoidal amplitude modulation (8.1)
 - Demodulation (8.2)
 - Synchronous Demodulation
 - Asynchronous Demodulation
 - Frequency-division multiplexing (8.3)

Frequency-division multiplexing (1)

- Different stations are allocated different carrier frequencies, separated by (at least) the allowed bandwidth of each station.
- Commercial AM: 10KHz spacing between carriers.
- The transmitted spectrum of the k th station occupies $\omega_k \pm \omega_B$.

Example

- **(Picture)** of block diagram multiple transmitters (MIT, Lecture 13.12)
- **(Picture)** of spectra illustrating (MIT, Lecture 13.13)
- The three signals appear simultaneously in time, but are separated in frequency.

Frequency-division multiplexing (1)

- Different stations are allocated different carrier frequencies, separated by (at least) the allowed bandwidth of each station.
- Commercial AM: 10KHz spacing between carriers.
- The transmitted spectrum of the k th station occupies $\omega_k \pm \omega_B$.

Example

- **(Picture)** of block diagram multiple transmitters (MIT, Lecture 13.12)
- **(Picture)** of spectra illustrating (MIT, Lecture 13.13)
- The three signals appear simultaneously in time, but are separated in frequency.

Frequency-division multiplexing (1)

- Different stations are allocated different carrier frequencies, separated by (at least) the allowed bandwidth of each station.
- Commercial AM: 10KHz spacing between carriers.
- The transmitted spectrum of the k th station occupies $\omega_k \pm \omega_B$.

Example

- **(Picture)** of block diagram multiple transmitters (MIT, Lecture 13.12)
- **(Picture)** of spectra illustrating (MIT, Lecture 13.13)
- The three signals appear simultaneously in time, but are separated in frequency.

Frequency-division multiplexing (1)

- Different stations are allocated different carrier frequencies, separated by (at least) the allowed bandwidth of each station.
- Commercial AM: 10KHz spacing between carriers.
- The transmitted spectrum of the k th station occupies $\omega_k \pm \omega_B$.

Example

- **(Picture)** of block diagram multiple transmitters (MIT, Lecture 13.12)
- **(Picture)** of spectra illustrating (MIT, Lecture 13.13)
- The three signals appear simultaneously in time, but are separated in frequency.

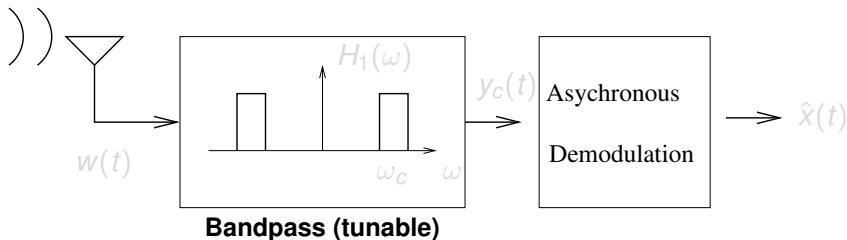
Tunable bandpass filter (1)

Question

How can we “tune in” to our favorite station?

Design 1: a tunable bandpass filter.

Tuning (Design #1)



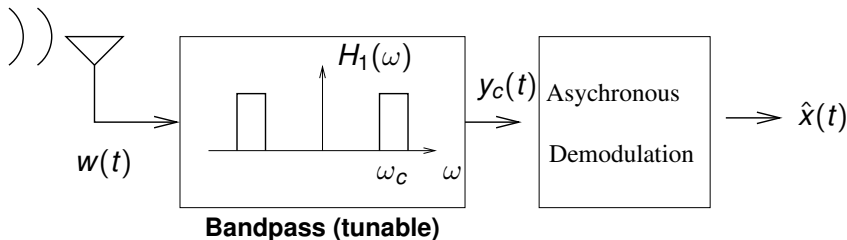
Tunable bandpass filter (1)

Question

How can we “tune in” to our favorite station?

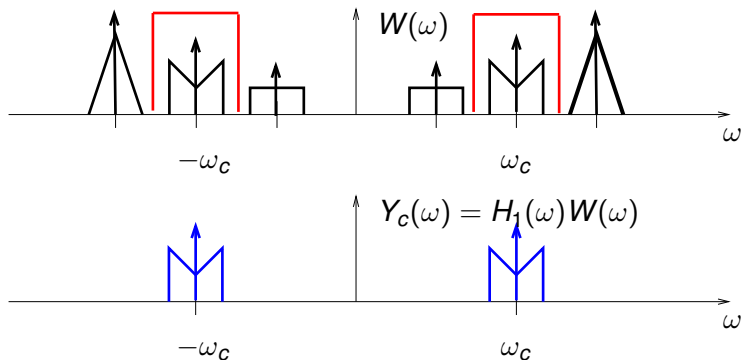
Design 1: **a tunable bandpass filter.**

Tuning (Design #1)



Tunable bandpass filter (2)

(Frequency Division Multiplexing)



Tunable bandpass filter (3)

Question

What are the practical requirements on the bandpass filter of this design?

Tunable bandpass filter (3)

Question

What are the practical requirements on the bandpass filter of this design?

- 1 narrowband (± 5 kHz)
- 2 high center frequency (540 to 1600 kHz)
- 3 tunable
- 4 stable
- 5 sharp cutoff (to avoid interference from neighboring channels)

Tunable bandpass filter (3)

Question

What are the practical requirements on the bandpass filter of this design?

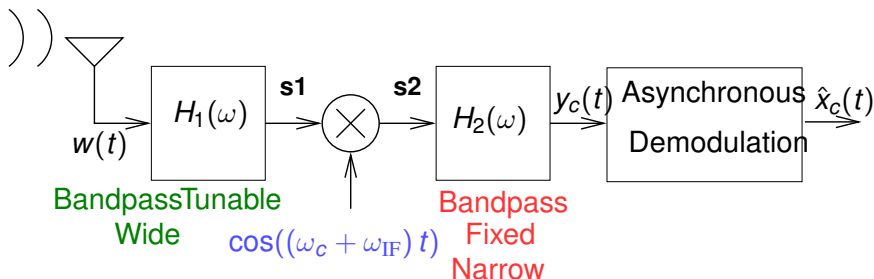
- 1 narrowband (± 5 kHz)
- 2 high center frequency (540 to 1600 kHz)
- 3 tunable
- 4 stable
- 5 sharp cutoff (to avoid interference from neighboring channels)

*These concurrent requirements are difficult to achieve in practice, so **commercial AM radios are not built this way.***

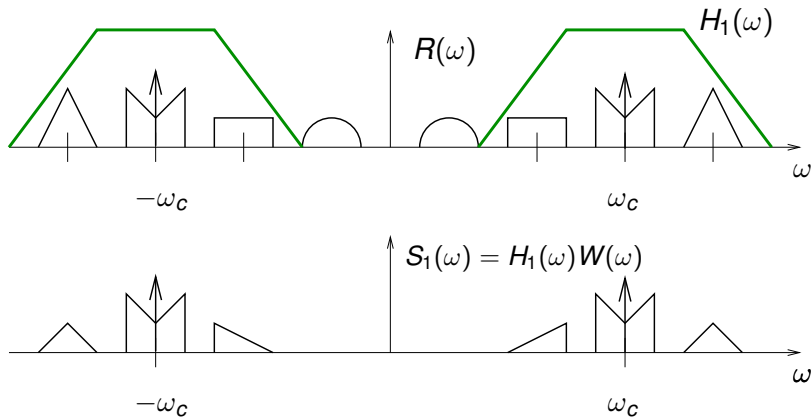
Superheterodyning receiver

Design 2: **superheterodyning receiver** (avoids a tunable narrow bandpass filter)

Superheterodyning Tuner



Bandpass tunable wide



IF filter and mixing frequency

Definition

The fixed frequency bandpass filter called the **IF filter** for “intermediate frequency.”

In commercial AM this is $\omega_{\text{IF}}/2\pi = 455\text{kHz}$.

Modulate the received RF signal by $\omega_0 = \omega_c + \omega_{\text{IF}}$ to move the spectrum of the desired signal to be centered at ω_{IF} .

$$s_1(t) \rightarrow \begin{array}{c} \otimes \\ \uparrow \\ \cos(\omega_c + \omega_{\text{IF}}) t \end{array} \rightarrow s_2(t)$$

When you “tune in” you are actually controlling the **mixing frequency** ω_0 .

IF filter and mixing frequency

Definition

The fixed frequency bandpass filter called the **IF filter** for “intermediate frequency.”

In commercial AM this is $\omega_{\text{IF}}/2\pi = 455\text{kHz}$.

Modulate the received RF signal by $\omega_0 = \omega_c + \omega_{\text{IF}}$ to move the spectrum of the desired signal to be centered at ω_{IF} .

$$s_1(t) \rightarrow \begin{array}{c} \otimes \\ \uparrow \\ \cos(\omega_c + \omega_{\text{IF}}) t \end{array} \rightarrow s_2(t)$$

When you “tune in” you are actually controlling the **mixing frequency** ω_0 .

IF filter and mixing frequency

Definition

The fixed frequency bandpass filter called the **IF filter** for “intermediate frequency.”

In commercial AM this is $\omega_{\text{IF}}/2\pi = 455\text{kHz}$.

Modulate the received RF signal by $\omega_0 = \omega_c + \omega_{\text{IF}}$ to move the spectrum of the desired signal to be centered at ω_{IF} .

$$s_1(t) \rightarrow \begin{array}{c} \otimes \\ \uparrow \\ \cos(\omega_c + \omega_{\text{IF}}) t \end{array} \rightarrow s_2(t)$$

When you “tune in” you are actually controlling the **mixing frequency** ω_0 .

IF filter and mixing frequency

Definition

The fixed frequency bandpass filter called the **IF filter** for “intermediate frequency.”

In commercial AM this is $\omega_{\text{IF}}/2\pi = 455\text{kHz}$.

Modulate the received RF signal by $\omega_0 = \omega_c + \omega_{\text{IF}}$ to move the spectrum of the desired signal to be centered at ω_{IF} .

$$s_1(t) \rightarrow \begin{array}{c} \otimes \\ \uparrow \\ \cos(\omega_c + \omega_{\text{IF}}) t \end{array} \rightarrow s_2(t)$$

When you “tune in” you are actually controlling the **mixing frequency** ω_0 .

Mixing frequency: example

Example

If we want to tune in to the station at

$$\omega_c/2\pi = 1060\text{kHz}$$

then use

$$\omega_0/2\pi = (\omega_c + \omega_{\text{IF}})/2\pi = 1060 + 455 = 1515\text{kHz}.$$

Before mixing, centered at $\pm 1060\text{kHz}$.

After mixing by 1515kHz , centers at

$$\pm\omega_c \pm \omega_0 \implies \pm\omega_{\text{IF}} \text{ and } \pm(2\omega_c + \omega_{\text{IF}})$$

$$\pm 1060 \pm 1515\text{kHz} \implies \pm 455\text{kHz} \text{ and } \pm 2575\text{kHz}$$

Mixing frequency: example

Example

If we want to tune in to the station at

$$\omega_c/2\pi = 1060\text{kHz}$$

then use

$$\omega_0/2\pi = (\omega_c + \omega_{\text{IF}})/2\pi = 1060 + 455 = 1515\text{kHz}.$$

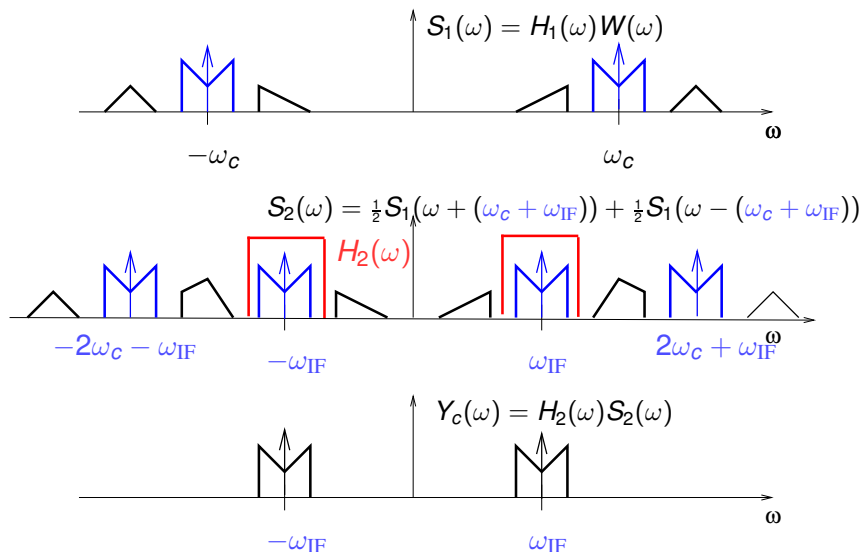
Before mixing, centered at $\pm 1060\text{kHz}$.

After mixing by 1515kHz , centers at

$$\pm\omega_c \pm \omega_0 \implies \pm\omega_{\text{IF}} \text{ and } \pm(2\omega_c + \omega_{\text{IF}})$$

$$\pm 1060 \pm 1515\text{kHz} \implies \pm 455\text{kHz} \text{ and } \pm 2575\text{kHz}$$

Modulation and IF filter



Recovering the original signal

- After mixing with $\cos((\omega_c + \omega_{IF}) t)$, the desired station is centered in the **passband** of the **IF** filter.
- After the IF filter, **asynchronous demodulation** can be used to recover the original audio signal.

Question

One point we have omitted though. In the above example, what happens to the part of the received signal spectrum centered at

$$\omega_0/2\pi + \omega_{IF}/2\pi = 1515 + 455 = 1970\text{kHz?}$$

Recovering the original signal

- After mixing with $\cos((\omega_c + \omega_{IF}) t)$, the desired station is centered in the **passband** of the **IF** filter.
- After the IF filter, **asynchronous demodulation** can be used to recover the original audio signal.

Question

One point we have omitted though. In the above example, what happens to the part of the received signal spectrum centered at

$$\omega_0/2\pi + \omega_{IF}/2\pi = 1515 + 455 = 1970\text{kHz?}$$

Recovering the original signal

- After mixing with $\cos((\omega_c + \omega_{IF}) t)$, the desired station is centered in the **passband** of the **IF** filter.
- After the IF filter, **asynchronous demodulation** can be used to recover the original audio signal.

Question

One point we have omitted though. In the above example, what happens to the part of the received signal spectrum centered at

$$\omega_0/2\pi + \omega_{IF}/2\pi = 1515 + 455 = 1970\text{kHz?}$$

Interfering spectrum components

After mixing by 1515kHz, this part gets moved to

$$\pm 1970 \pm 1515\text{kHz} \implies \pm 455 \text{ and } \pm 3485\text{kHz}.$$

So that signal also would leak through the IF filter and interfere with the desired signal.

Question

How to solve this problem?

Interfering spectrum components

After mixing by 1515kHz, this part gets moved to

$$\pm 1970 \pm 1515\text{kHz} \implies \pm 455 \text{ and } \pm 3485\text{kHz}.$$

So that signal also would leak through the IF filter and interfere with the desired signal.

Question

How to solve this problem?

Interfering spectrum components

After mixing by 1515kHz, this part gets moved to

$$\pm 1970 \pm 1515\text{kHz} \implies \pm 455 \text{ and } \pm 3485\text{kHz}.$$

So that signal also would leak through the IF filter and interfere with the desired signal.

Question

How to solve this problem?

Tunable bandpass filter

The desired signal, centered at 1060kHz, and the interfering signal, centered at 1970kHz, are separated by

$$1970\text{kHz} - 1060\text{kHz} = 910\text{kHz} = 455\text{kHz} + 455\text{kHz} = 2\omega_{\text{IF}}/2\pi.$$

*We just need a **tunable bandpass filter** that is **centered at ω_c** , but with a passband that is about **900kHz wide**. It is fairly easy to build such a tunable bandpass filter.*

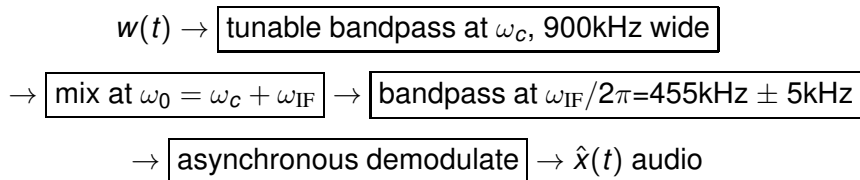
Tunable bandpass filter

The desired signal, centered at 1060kHz, and the interfering signal, centered at 1970kHz, are separated by

$$1970\text{kHz} - 1060\text{kHz} = 910\text{kHz} = 455\text{kHz} + 455\text{kHz} = 2\omega_{\text{IF}}/2\pi.$$

*We just need a **tunable bandpass filter** that is **centered at ω_c** , but with a passband that is about **900kHz wide**. It is fairly easy to build such a tunable bandpass filter.*

Superheterodyning receiver



A better approach?

Question

Is the following a better approach?

$$w(t) \rightarrow \boxed{\text{mix at } \omega_0 = \omega_c + \omega_{\text{IF}} \text{ with } \omega_{\text{IF}} = 0}$$

$$\rightarrow \boxed{\text{lowpass with } \pm 5\text{kHz}} \rightarrow \hat{x}(t) \text{ audio}$$

A better approach?

Question

Is the following a better approach?

$$w(t) \rightarrow \boxed{\text{mix at } \omega_0 = \omega_c + \omega_{\text{IF}} \text{ with } \omega_{\text{IF}} = 0}$$

$$\rightarrow \boxed{\text{lowpass with } \pm 5\text{kHz}} \rightarrow \hat{x}(t) \text{ audio}$$

Consider the effects of loss of synchronization in phase between the carrier signal and the mixing signal.

A better approach? (2)

To simplify the analysis, let's consider one station only. The modulated (transmitted) signal is

$$y(t) = (A + x(t)) \cos(\omega_c t + \theta_c)$$

After mixing at the receiver

$$\begin{aligned} s_2(t) &= y(t) \cos((\omega_c + \omega_{IF}) t + \phi_c) \\ &= \frac{1}{2}(A + x(t)) \cos((2\omega_c + \omega_{IF}) t + \theta_c + \phi_c) \\ &\quad + \frac{1}{2}(A + x(t)) \cos(\omega_{IF} t + \theta_c - \phi_c) \end{aligned}$$

If $\omega_{IF} = 0$, then after passing a lowpass filter,

$$\hat{x}_c(t) = \frac{1}{2}(A + x(t)) \cos(\theta_c - \phi_c)$$

See the effects of the additional term $\cos(\theta_c - \phi_c)$ on Chap. 8, p.49.

A better approach? (2)

To simplify the analysis, let's consider one station only. The modulated (transmitted) signal is

$$y(t) = (A + x(t)) \cos(\omega_c t + \theta_c)$$

After mixing at the receiver

$$\begin{aligned} s_2(t) &= y(t) \cos((\omega_c + \omega_{IF}) t + \phi_c) \\ &= \frac{1}{2}(A + x(t)) \cos((2\omega_c + \omega_{IF}) t + \theta_c + \phi_c) \\ &\quad + \frac{1}{2}(A + x(t)) \cos(\omega_{IF} t + \theta_c - \phi_c) \end{aligned}$$

If $\omega_{IF} = 0$, then after passing a lowpass filter,

$$\hat{x}_c(t) = \frac{1}{2}(A + x(t)) \cos(\theta_c - \phi_c)$$

See the effects of the additional term $\cos(\theta_c - \phi_c)$ on Chap. 8, p.49.

A better approach? (2)

To simplify the analysis, let's consider one station only. The modulated (transmitted) signal is

$$y(t) = (A + x(t)) \cos(\omega_c t + \theta_c)$$

After mixing at the receiver

$$\begin{aligned} s_2(t) &= y(t) \cos((\omega_c + \omega_{IF}) t + \phi_c) \\ &= \frac{1}{2}(A + x(t)) \cos((2\omega_c + \omega_{IF}) t + \theta_c + \phi_c) \\ &\quad + \frac{1}{2}(A + x(t)) \cos(\omega_{IF} t + \theta_c - \phi_c) \end{aligned}$$

If $\omega_{IF} = 0$, then after passing a lowpass filter,

$$\hat{x}_c(t) = \frac{1}{2}(A + x(t)) \cos(\theta_c - \phi_c)$$

See the effects of the additional term $\cos(\theta_c - \phi_c)$ on Chap. 8, p.49.

Summary

- double sideband, suppressed carrier, amplitude modulation (DSB/SC-AM)
- double sideband, with carrier, amplitude modulation (DSB/WC-AM)
- synchronous demodulation
- asynchronous demodulation
- Frequency-division multiplexing (superheterodyning receiver)
- Systems-level analysis of communication system