Subject Evaluations

Your feedback is important to us!

Please give feedback to the staff and future 6.003 students:  
http://registrar.mit.edu/subjectevaluation

Evaluations are open until Monday, December 17 at 9 am.

You will be able to view quantitative results at 
http://web.mit.edu/subjectevaluation/results.html
and student-written summaries at
http://hkn.mit.edu/ug_sel.php
Communications Systems

Some of largest and fastest growing applications of signal processing.

Examples:

- cellular communications
- wifi
- broadband
- cable
- bluetooth
- GPS (the Global Positioning System)
- private networks: fire departments, police
- radar and navigation systems
- IOT (the Internet of Things)
  - smart house / smart appliances
  - smart car
  - medical devices
- many more
Telephone

Indications of the popular thirst for communications are evident from the growth of telephone networks.

Patented by Alexander Graham Bell (1876) this technology flourished first as a network of copper wires and later as optical fibers (“long-distance” network) connecting virtually every household in the US by the 1980’s.

Bell Labs became a premier research facility, developing information theory and a host of wired and wireless communications technologies that built on that theory, as well as hardware innovations such as the transistor and the laser.
Cellular Communication

First demonstrated by Motorola in 1973, cellular communications quickly revolutionized the field. There are now more cell phones than people in the world.

Much of the popularity and convenience of cellular communications is that the communication is **wireless** (at least to the local tower).
Wireless signals are transmitted via electromagnetic (E/M) waves.

For energy-efficient transmission and reception, the length of the antenna should be on the order of the wavelength.

Telephone-quality speech contains frequencies from 200 to 3000 Hz. How long should the antenna be?
Check Yourself

For energy-efficient transmission and reception, the length of the antenna should be on the order of the wavelength.

Telephone-quality speech contains frequencies between 200 Hz and 3000 Hz.

How long should the antenna be?

1. < 1 mm
2. ~ cm
3. ~ m
4. ~ km
5. > 100 km
Check Yourself

Wavelength is $\lambda = \frac{c}{f}$.

The lowest frequencies (200 Hz) produce the longest wavelengths

$$\lambda = \frac{c}{f} = \frac{3 \times 10^8 \text{ m/s}}{200 \text{ Hz}} = 1.5 \times 10^6 \text{ m} = 1500 \text{ km}.$$  

and highest frequencies (3000 Hz) produce the shortest wavelengths

$$\lambda = \frac{c}{f} = \frac{3 \times 10^8 \text{ m/s}}{3000 \text{ Hz}} = 10^5 \text{ m} = 100 \text{ km}.$$  

The size of the antenna should be on the order of 900 miles!
For energy-efficient transmission and reception, the length of the antenna should be on the order of the wavelength.

Telephone-quality speech contains frequencies between 200 Hz and 3000 Hz.

How long should the antenna be?  5

1. < 1 mm
2. ~ cm
3. ~ m
4. ~ km
5. > 100 km
Check Yourself

What frequency E/M wave is well matched to an antenna with a length of 10 cm (about 4 inches)?

1. < 100 kHz
2. 1 MHz
3. 10 MHz
4. 100 MHz
5. > 1 GHz
Check Yourself

A wavelength of 10 cm corresponds to a frequency of

\[ f = \frac{c}{\lambda} \sim \frac{3 \times 10^8 \text{ m/s}}{10 \text{ cm}} \approx 3 \text{ GHz}. \]

Modern cell phones use frequencies near 2 GHz.
Check Yourself

What frequency E/M wave is well matched to an antenna with a length of 10 cm (about 4 inches)?

1. < 100 kHz
2. 1 MHz
3. 10 MHz
4. 100 MHz
5. > 1 GHz
Speech is not well matched to the wireless medium.

Matching the message to the medium is important in all communications systems.

Example media:

- radio (E/M) waves
- cable (coaxial wires)
- fiber optics

Today we will introduce simple matching strategies based on modulation, which underlie virtually all communication schemes.
Check Yourself

Construct a signal $Y$ that codes the audio frequency information in $X$ using frequency components near 2 GHz.

$$|X(\omega)|$$

$$|Y(\omega)|$$

Determine an expression for $Y$ in terms of $X$.

1. $y(t) = x(t) e^{j\omega ct}$
2. $y(t) = x(t) * e^{j\omega ct}$
3. $y(t) = x(t) \cos(\omega_c t)$
4. $y(t) = x(t) * \cos(\omega_c t)$

5. none of the above
Check Yourself

Construct a signal $Y$ that codes the audio frequency information in $X$ using frequency components near 2 GHz.

\[ Y(\omega) = X(\omega - \omega_c) \]

\[
y(t) = \frac{1}{2\pi} \int Y(\omega) e^{j\omega t} d\omega = \frac{1}{2\pi} \int X(\omega - \omega_c) e^{j\omega t} d\omega
\]

\[
= \frac{1}{2\pi} \int X(\lambda) e^{j(\lambda+\omega_c)t} d\lambda \quad \text{where } \lambda = \omega - \omega_c
\]

\[
= e^{j\omega_c t} \left( \frac{1}{2\pi} \int X(\lambda) e^{j\lambda t} d\lambda \right) = e^{j\omega_c t} x(t)
\]
Construct a signal $Y$ that codes the audio frequency information in $X$ using frequency components near 2 GHz.

$|X(\omega)|$

$Y(\omega)$

$\omega_{c}$

Determine an expression for $Y$ in terms of $X$.  

1. $y(t) = x(t) e^{j\omega_c t}$
2. $y(t) = x(t) \ast e^{j\omega_c t}$
3. $y(t) = x(t) \cos(\omega_c t)$
4. $y(t) = x(t) \ast \cos(\omega_c t)$

5. none of the above
Amplitude Modulation (Frequency Domain)

Multiplying a signal by a sinusoidal carrier signal is called amplitude modulation (AM). AM shifts the frequency components of $X$ by $\pm \omega_c$.

$$x(t) \times \cos \omega_c t \rightarrow y(t)$$

$$|X(\omega)|$$

$$|Y(\omega)|$$
Amplitude Modulation (Time Domain)

Multiplying a signal by a sinusoidal carrier signal is called amplitude modulation. The signal “modulates” the amplitude of the carrier.

\[ x(t) \times \cos \omega_c t \rightarrow y(t) \]

\[ x(t) \cos \omega_c t \]
Amplitude Modulation

How could you recover $x(t)$ from $y(t)$?

$x(t) \times \cos \omega_c t \rightarrow y(t)$
Synchronous Demodulation

$X$ can be recovered by multiplying by the carrier and then low-pass filtering. This process is called **synchronous demodulation**.

\[
y(t) = x(t) \cos \omega_c t
\]

\[
z(t) = y(t) \cos \omega_c t = x(t) \times \cos \omega_c t \times \cos \omega_c t = x(t) \left( \frac{1}{2} + \frac{1}{2} \cos(2\omega_c t) \right)
\]
Synchronous Demodulation

Synchronous demodulation: convolution in frequency.

\[ |Y(\omega)| \]

\[ Y(\omega) = \omega \cdot c - \omega \cdot c \]

\[ |Z(\omega)| \]

\[ Z(\omega) = 2\omega \cdot c - 2\omega \cdot c \]
Synchronous Demodulation

We can recover $X$ by low-pass filtering.

\[ |Y(\omega)| \]

\[ |Z(\omega)|^2 \]

\[ \omega \]

\[ -\omega_c \]

\[ \omega_c \]

\[ -2\omega_c \]

\[ 2\omega_c \]
Frequency-Division Multiplexing

Multiple transmitters can co-exist, as long as the frequencies that they transmit do not overlap.

\[ x_1(t) \times \cos \omega_1 t \rightarrow z_1(t) \]
\[ x_2(t) \times \cos \omega_2 t \rightarrow z_2(t) \]
\[ x_3(t) \times \cos \omega_3 t \rightarrow z_3(t) \]

\[ z_1(t) + z_2(t) + z_3(t) \rightarrow y(t) \]

\[ \text{LPF} \]
Frequency-Division Multiplexing

Multiple transmitters simply sum (to first order).
Multiple transmitters can co-exist, as long as the frequencies that they transmit do not overlap.
Multiple transmitters can co-exist, as long as the frequencies that they transmit do not overlap.

\[ Z_1(\omega) \]

\[ Z_2(\omega) \]

\[ Z_3(\omega) \]
Frequency-Division Multiplexing

Multiple transmitters can co-exist, as long as the frequencies that they transmit do not overlap.

\[ Z_1(\omega) \quad Z_2(\omega) \quad Z_3(\omega) \quad Z(\omega) \]
“Broadcast” radio was championed by David Sarnoff, who previously worked at Marconi Wireless Telegraphy Company (point-to-point).

- envisioned “radio music boxes”
- analogous to newspaper, but at speed of light
- receiver must be cheap (as with newsprint)
- transmitter can be expensive (as with printing press)

Sarnoff (left) and Marconi (right)
Inexpensive Radio Receiver

The problem with making an inexpensive radio receiver is that you must know the carrier signal exactly!
The problem with making an inexpensive radio receiver is that you must know the carrier signal exactly!

What happens if there is a phase shift $\phi$ between the signal used to modulate and that used to demodulate?
Check Yourself

\[ y(t) = x(t) \times \cos(\omega_c t) \times \cos(\omega_c t + \phi) \]

\[ = x(t) \times \left( \frac{1}{2} \cos \phi + \frac{1}{2} \cos(2\omega_c t + \phi) \right) \]

Passing \( y(t) \) through a low pass filter yields \( \frac{1}{2} x(t) \cos \phi \).

If \( \phi = \pi/2 \), the output is zero!

If \( \phi \) changes with time, then the signal “fades.”
AM with Carrier

One way to synchronize the sender and receiver is to send the carrier along with the message.

\[ z(t) = x(t) \cos \omega_c t + C \cos \omega_c t = (x(t) + C) \cos \omega_c t \]

Adding carrier is equivalent to shifting the DC value of \( x(t) \). If we shift the DC value sufficiently, the message is easy to decode: it is just the envelope (minus the DC shift).
Inexpensive Radio Receiver

If the carrier frequency is much greater than the highest frequency in the message, AM with carrier can be demodulated with a peak detector.

\[ z(t) \overset{+}{\rightarrow} R \overset{C}{\rightarrow} y(t) \]

In AM radio, the highest frequency in the message is 5 kHz and the carrier frequency is between 500 kHz and 1500 kHz.

This circuit is simple and inexpensive.

But there is a problem.
Inexpensive Radio Receiver

AM with carrier requires more power to transmit the carrier than to transmit the message!

\[
x(t) \quad x_p > 35 \times x_{\text{rms}}
\]

Speech sounds have high crest factors (peak value divided by rms value). The DC offset \( C \) must be larger than \( x_p \) for simple envelope detection to work.

The power needed to transmit the carrier can be \( 35^2 \approx 1000 \times \) that needed to transmit the message.

Okay for broadcast radio (WBZ: 50 kwatts).

Not for point-to-point (cell phone batteries wouldn’t last long!).
Inexpensive Radio Receiver

Envelope detection also cannot separate multiple senders.
Edwin Howard Armstrong invented the superheterodyne receiver, which made broadcast AM practical.

Edwin Howard Armstrong also invented and patented the “regenerative” (positive feedback) circuit for amplifying radio signals (while he was a junior at Columbia University). He also invented wide-band FM.
Could we implement a radio with digital electronics?

Commercial AM radio
- 106 channels
- each channel is allocated 10 kHz bandwidth
- center frequencies from 540 to 1600 kHz
Determine $T$ to decode commercial AM radio.

Commercial AM radio
- 106 channels
- each channel is allocated 10 kHz bandwidth
- center frequencies from 540 to 1600 kHz

The maximum value of $T$ is approximately
1. 0.3 fs
2. 0.3 ns
3. 0.3 µs
4. 0.3 ms
5. none of these
Check Yourself

Determine $T$ to decode commercial AM radio.  3.

Commercial AM radio
- 106 channels
- each channel is allocated 10 kHz bandwidth
- center frequencies from 540 to 1600 kHz

The maximum value of $T$ is approximately
1. 0.3 fs  
2. 0.3 ns  
3. 0.3 µs  
4. 0.3 ms  
5. none of these
Today’s Lab

Implement a software radio.