EE3: Introduction to Electrical Engineering

Lecture 7: Telecommunications Networks

Greg Pottie

pottie@ee.ucla.edu

+1.310.825.8150

Outline

- Historical milestones
- Telephone network
- Internet
- Broadcast networks
- Cellular systems

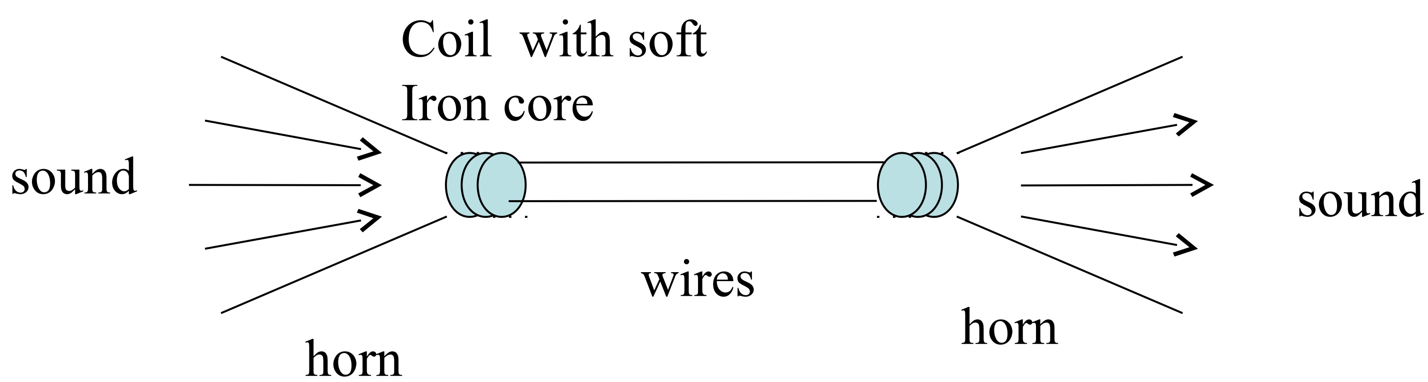
History of Telecommunications

1840's: Telegraph
1860's: Transatlantic cable
1870's: Telephone
1900's: Wireless Telegraphy
1910's: AM broadcast
1920's: Nyquist's theory of digital communications
1930's: FM
1940's: TV, transistor, Shannon's theory of communications
1960's: digital transition begins, ARPAnet, color TV
1970's: Dial-up modems, satellite communications
1980's: Cellular radio
1990's: DSL, cable modems, fiber optic network expansion, www, GPS public use
2010's: Wireless internet; age of apps

Telephone

Success has many fathers, failure is an orphan

In the case of the telephone, patent and commercial success were claimed by Bell. An early telephone pair is shown below.



The core vibrates in response to sound waves, within a permanent magnetic field. This induces an undulating current in the coil, which is reproduced at the far end. The vibration of the core produces sound. There was no amplification.

Telephone Development

By 1876 signals could be conveyed 10 miles over telegraph wire.

Edison developed the carbon microphone, which produces much stronger signals; still used in telephones now.

The modern 4-wire system brings power to the handset; amplifiers were installed soon after their invention

A single point to point connection is near useless; Metcalf's Law states that the value of network grows as n^2 where n is the number of connected nodes in the network.

Bell adapted plug-in connectors from telegraphy exchanges for the first telephone exchanges; human operators were alerted when the phone went off hook to ask for the connection.

Long Distance Transport

Local transport is over a twisted pair of wires; by the mid-20th century, long distance was mainly by means of microwave stations or coaxial cable, with analog repeaters.

Signal quality was measured in terms of signal to noise ratio

$$SNR = (signal\ power)/(noise\ power)$$

Once below some SNR threshold, signal quality is unacceptable. This leads to a problem with multiple repeaters. Each transmission line has power loss L, followed by amplification by a factor G with noise figure F:

$$\rightarrow \boxed{\text{Loss } L} \rightarrow \boxed{G,\ F} \rightarrow \boxed{\text{Loss } L} \rightarrow \boxed{G,\ F} \rightarrow$$

Noise figure $F = (SNR_{in})/(SNR_{out})$

Noise Figure for Repeaters

For a transmission line, $F=L$, where L is the power loss

For n stages, the composite noise figure is

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \ldots \frac{F_n - 1}{G_1 G_2 \ldots G_{n-1}}$$

Suppose there is one line with L=10 and amplifier with G=10 and F_2=8.

$$F = L + \frac{F_2 - 1}{1/L} = 10 + \frac{8 - 1}{1/10} = 80$$

EFTS: What happens with a second loss/amplify section?

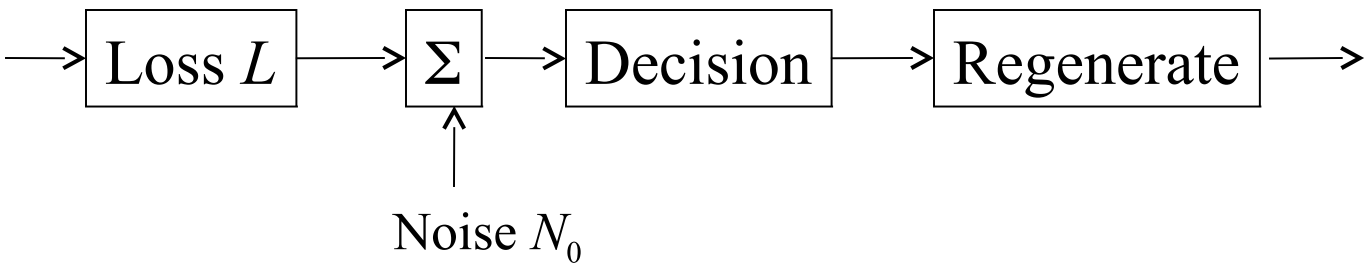
It is easiest to treat each loss/amplify section as one unit:

$$F_1 = F_2 = 80, G_1 = G_2 = 0.1(10) = 1; F = 80 + \frac{80 - 1}{1} = 159$$

Thus for n sections, the noise is approximately n times bigger.

Repeaters in Digital System

Digital repeaters take the following form



For binary signals, the optimal receiver has error probability

$$p = Q\left(\sqrt{\frac{2E_b}{N_0}}\right), \; E_b = \text{energy/bit}$$

If the ratio E_b/N_0 is high enough, p is tiny.

What is the error probability with n repeaters?

$$\text{Solution: } np$$

This motivated digital long distance transport in the 1960's.

The Internet

A side benefit of the digital network interior was more convenient transport of data. Data typically moves in packets

Header	Payload

Long messages are divided into short chunks. The packet header gives source/destination addresses, sequence number, etc. Packets can be sent by a variety of routes and reassembled at the destination

Internet protocols deal with how the packets are to be handled by the network, including dealing with congestion, varying priority, error control, and routing.

The first message of the ARPAnet was “LO”, between UCLA and SRI

Broadcast AM Radio

The invention of the vacuum tube (deForest) and regenerative circuit (Armstrong) enabled radio use without headphones

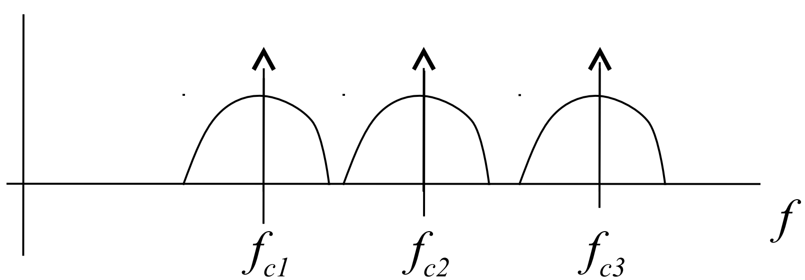
AM radio also spurred many revolutionary developments, completely changing the architecture of radio systems

Timeline:
1906: Fessenden makes first AM radio broadcast
1909: Herrold has first radio station, in San Jose; now KCBS San Francisco
1916: Power in Boston makes first daily broadcast schedule
1919-20: wide deployment
1931: 2/5 of American homes have radios
1938: 4/5 of American homes have radios

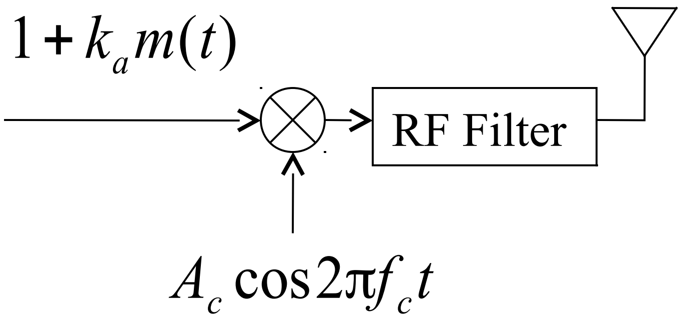
How AM Works

We describe the modern system, reflecting Armstrong's invention of the superheterodyne receiver.

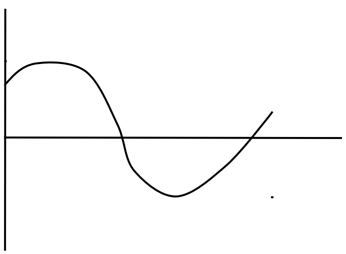
Wireless telegraphy used a broad band of spectrum; one of the ideas in AM was to perform narrowband transmission: bandwidth is equal to message bandwidth and small compared to the carrier frequency f_c. This allows many stations to share the spectrum on closely spaced carriers but required improved filters.



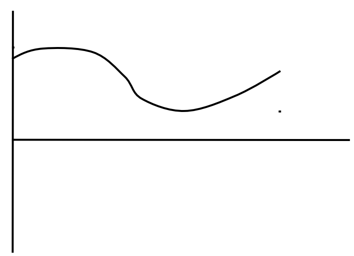
AM System: Transmitter



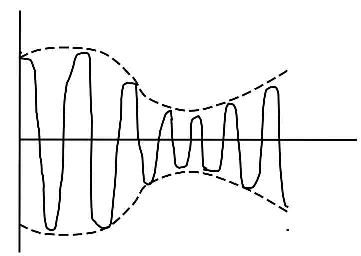
message signal $m(t)$

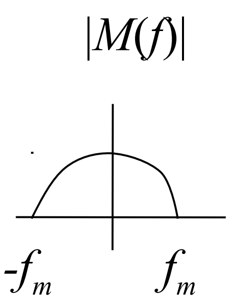


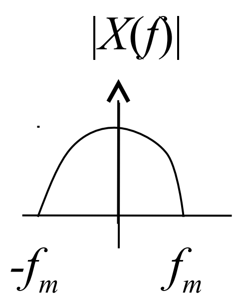
$x(t) = 1 + k_a m(t)$

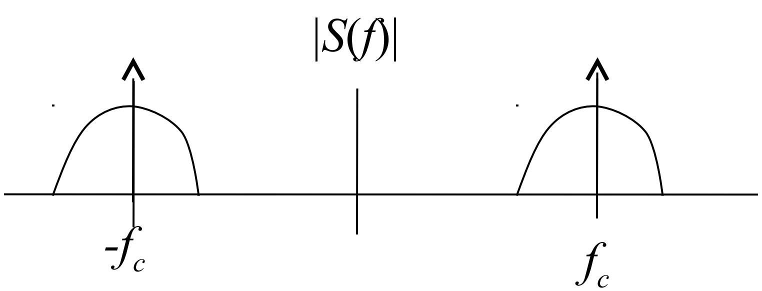


$s(t) = A_c \left[1 + k_a m(t) \right] \cos 2\pi f_c t$

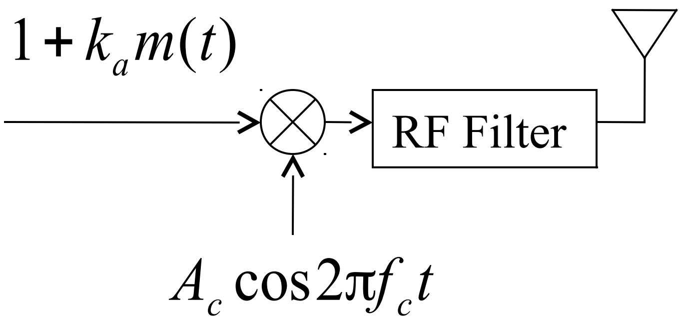








Transmitter Notes



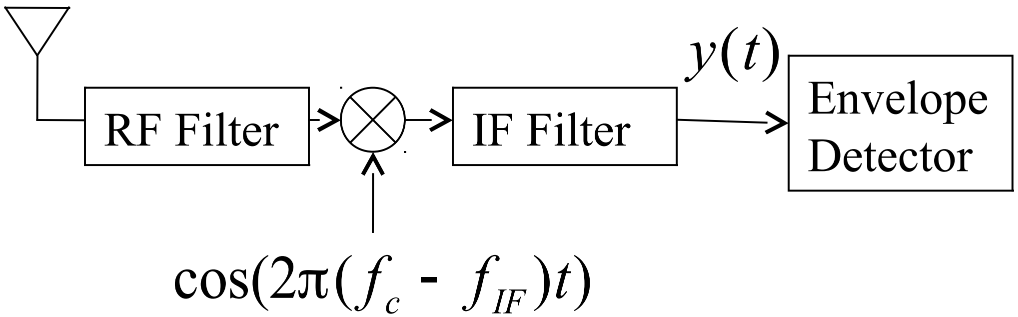
Mixers are non-linear devices; they produce not only the desired signal (attenuated) but also harmonics

A power amplifier is required after mixing (not shown)

The RF filter (centered at f_c) does not have to be high Q since it only has to remove components at $2f_c$ and above.

Matching the impedance to that of the antenna (75 Ohms, resistive for dipoles) improves energy transfer

AM System: Superheterodyne Receiver



With this structure, the (tunable) RF filter can have a low Q. The local oscillator signal that is mixed in comes from a tunable circuit called a voltage controlled oscillator. The IF filter can then be moderate Q and fixed to reject the neighboring channels.

There are also amplifiers prior to the mixer and envelope detector to improve the noise figure and boost the signal. They are controlled by a feedback loop ("automatic gain control") so that all circuits operate in the linear region.

EFTS

The commercial AM broadcast band extends from 520 to 1.6 MHz, with channel bandwidths of approximately 10 kHz (30 kHz in the early days). Receivers now use an IF frequency of 455 kHz. What would be the worst case (highest) *Q* required for the RF filter for a single stage conversion? What is the *Q* required of the IF filter in a superheterodyne receiver?

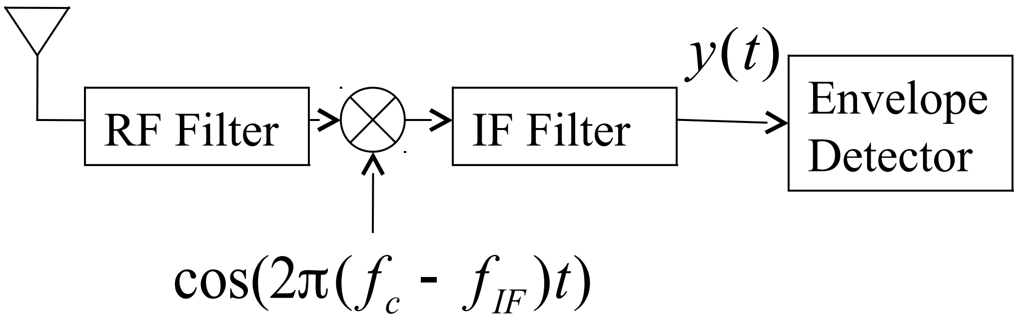
$$Q = \omega_0 / \omega_{BW}$$

The worst case is f_c=1.6 MHz; $\omega_0=10^7$. $\omega_{BW}=6.3\text{x}10^4$; Q=159.

For the superheterodyne system, f_{IF}=455kHz; $\omega_0=2.86\text{x}10^6$. $\omega_{BW}=6.3\text{x}10^4$; Q=45.

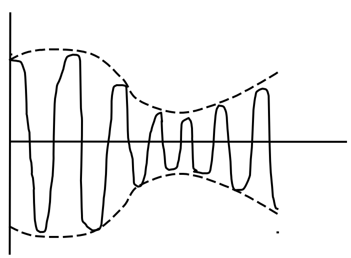
As a practical matter, it is much easier to get high *Q* in a fixed filter than in a highly tunable one.

AM System: Envelope Detector



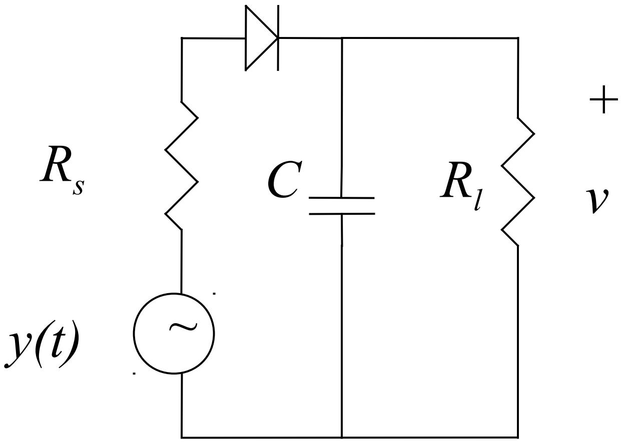
The envelope detector recovers $m(t)$ from $y(t)$:

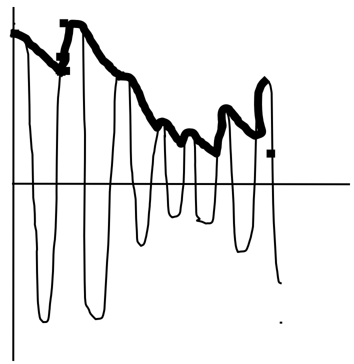
$$y(t) = A_c\left[1 + k_a m(t)\right]\cos 2\pi f_c t + noise$$



The goal is to follow the upper dotted line; the DC can then be removed by capacitive coupling. How is this done?

Envelope Detector Operation II





The condition for following the waveform on the way up is

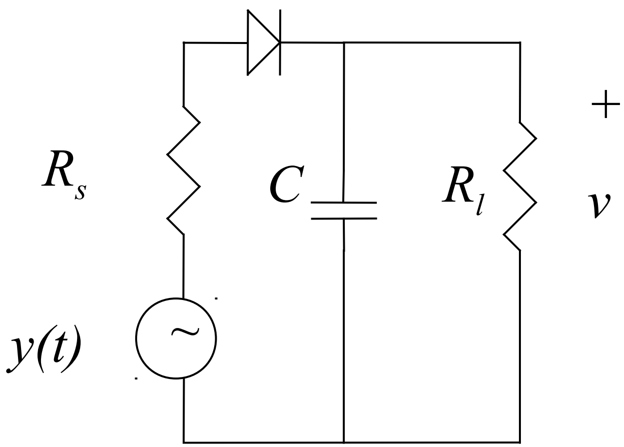
$$R_s C << \frac{1}{f_{IF}}$$

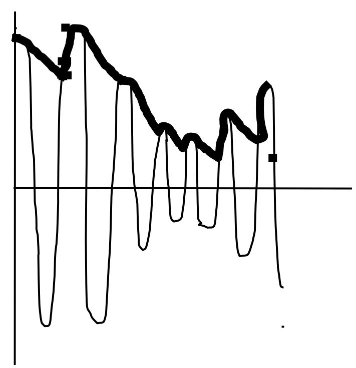
So that we are certain to track the message, if the maximum message frequency is f_m, then for the capacitor discharge we require $R_l C < 1/f_m$; but this must also be much greater than $1/f_{IF}$

The ripple is removed with a low pass filter.

Envelope Detector Operation

The circuit employs a diode, which ideally becomes perfectly conducting when the voltage across it is positive, and non-conducting when the voltage is negative.





When the waveform rises above the voltage of the capacitor, the diode conducts. If R_s is small the capacitor charges quickly and v follows the rising waveform. When the waveform drops the diode blocks current, and voltage exponentially decays.

EFTS

A bandwidth of 10 kHz implies a maximum message frequency of 5 kHz. Given f_{IF}=455 kHz, suggest suitable ratios for R_l/R_s.

Solution: We must satisfy:

$$R_s C << \frac{1}{f_{IF}}; \frac{1}{f_{IF}} << R_l C < \frac{1}{f_m}$$

For example, set $R_l C = \dfrac{1}{4 f_m} = 2e-4 >> 2e-6 = 1/f_{IF}$

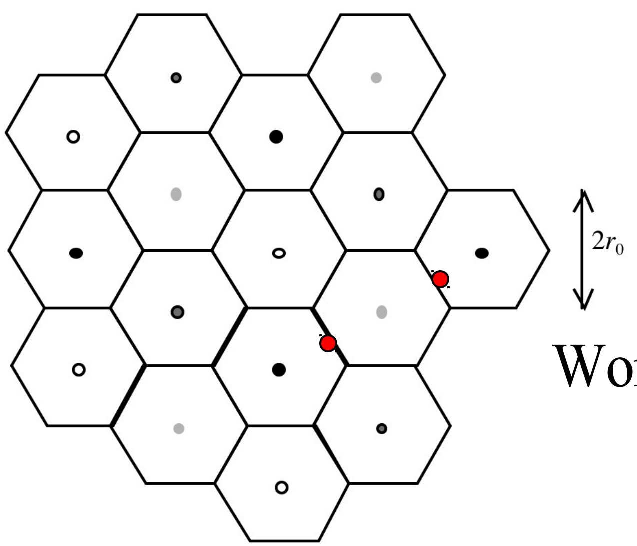
Then we could set $R_s C = \dfrac{1}{10 f_{IF}} = 2e-7$

so that $R_l / R_s = 1000.$

Cellular Radio Concept

Broadcast radio frequencies are regulated so that the same frequency is not used in close proximity, in order to avoid interference, which acts like noise.

The basic idea of early cellular radio was to re-use frequencies in the same manner, where users “hand-off” to new base stations (with new frequency) when they get close



Re-use 4 pattern; suppose propagation loss goes as d^4; what is worst case SIR?

Worst case comes from closest user on same channel

$$SIR = \left(\frac{3r_0}{r_0}\right)^4 = 81$$

Cellular Radio Evolution

1G (1980s) used FM, re-use 7, 30kHz channels

2G (1990s) used digital methods, either TDMA with re-use 4 (GSM system) or CDMA with re-use 1. The latter improved capacity a factor of 10, through use of channel/source coding and antenna sectorization

3G/4G use more sophisticated coding/modulation to get higher rates, and also use more bandwidth

The age of apps has greatly increased rate demand. The only long term way to deal with this is with an overlay network:

Mobile users communicate with an ever more dense network of base station towers

Pedestrians are re-directed to WiFi or Femto-cell stations

Summary

- Early telephone network borrowed many concepts from the telegraph network
  - Same wiring; use of telegraph exchange technology
- Analog communications largely supplanted digital telegraphy because it could convey voice, music, and images
- Digital began its comeback starting in the 1960s
  - Relay problem was original motivation
  - Source and channel coding (Shannon theory) enable greater bandwidth efficiency; possible to implement due to IC development
  - Packet switching and internet protocols promoted growth of data services
  - High speed digital network enables cloud computing to be viable
- Cellular systems borrowed from broadcast concepts
  - Originally niche application, now major gateway to the public network