Introduction

• Angle Modulation - modulation where the angle of a sine-wave carrier is varied as a function of the intelligence amplitude. Two ways to do it:
  – Phase Modulation (PM) – amount of phase change on angle of carrier is proportional to intelligence amplitude
  – Frequency Modulation (FM) – frequency change on angle of carrier is proportional to intelligence amplitude

• FM developed as alternative to AM in 1931
  – Over 10 years after AM commercial broadcast started
  – Goal was to develop system less susceptible to external noise pickup
Capacitor Microphone FM Generator

- Simplest FM Generator (Transmitter)
- Refer to Fig 5-1 (next slide)
- LC tank and oscillator generate sine-wave output that goes to antenna
- Capacitance on LC Tank is a capacitor microphone (aka condenser mike)
- *Frequency* of impinging sound waves (intelligence) determines the *rate* of output frequency change
- *Amplitude* of impinging sound waves (intelligence) determines the *amount* of output frequency change
Figure 5-1 Capacitor microphone FM generator.
Figure 5-2  FM representation.
Deviation Constant (K)

• Aka Modulation Sensitivity
• The relationship for an FM signal generated signal (e.g., condenser mike) can be expressed as:
  \[ f_{\text{out}} = f_c + Ke_i \]
  Where:
  – \( f_{\text{out}} \): instantaneous output frequency
  – \( f_c \): carrier frequency
  – \( K \): deviation constant (KHz/V)
  – \( e_i \): modulating (intelligence) input
Frequency Deviation ($\delta$)

- Amount of oscillator frequency increase or decrease around the carrier frequency ($f_c$). Computed as:
  \[ \delta = K E_i \]
  Where:
  - $K$: deviation constant
  - $E_i$: magnitude of intelligence

- Ideally, frequency vs time plot is a replica of intelligence, with $\delta$ magnitude (see Fig. 5-2c)

- The intelligence amplitude ($E_i$) determines the \textit{amount} of deviation from carrier frequency ($f_c$)

- The intelligence frequency ($f_i$) determines the \textit{rate} of deviation from carrier frequency ($f_c$)
Modulation Index \( (m_f) \)

- An FM modulated signal can be expressed as:
  \[
  e(t) = E_c \sin (w_c t + m_f \sin w_i t)
  \]
  where:
  - \( E_c \): carrier amplitude
  - \( w_c \): carrier frequency
  - \( w_i \): intelligence angular velocity
  - \( m_f \): modulation index

- The modulation index is defined as:
  \[
  m_f = \frac{\delta}{f_i}
  \]
  Where:
  - \( \delta \): frequency deviation
  - \( f_i \): intelligence frequency
Bessel Functions

• FM formula \( e(t) = E_c \sin (w_c t + m_f \sin w_i t) \) can be solved using Bessel functions:
\[
e(t) = E_c J_0(m_f) \cos w_c t \\
- E_c J_1(m_f) [\cos (w_c - w_i) t - \cos (w_c + w_i) t] \\
+ E_c J_2(m_f) [\cos (w_c - 2w_i) t + \cos (w_c + 2w_i) t] \\
+ E_c J_3(m_f) [\cos (w_c - 3w_i) t + \cos (w_c + 3w_i) t] \\
+ ... 
\]

• That gives us components at frequencies \( f_c, f_c \pm f_i, f_c \pm 2f_i, f_c \pm 3f_i, ... \)

• Spectrum is infinite number of sidebands, but their coefficients \( J_n(m_f) \) diminish quickly (see Table 5-2)
FM Bandwidth

• It can be demonstrated that the required bandwidth to transmit an FM signal with highest significant side-frequency component $J_n$ is:

$$BW = 2nf_i$$

• The bandwidth can also be approximated using the Carlson’s Rule:

$$BW = 2(\delta_{\text{max}} + f_{i(\text{max})})$$

• Carlson’s Rule accounts for ~98% of total power
Deviation Ratio (DR)

- Alternative way to describe the modulation index
- Commonly used in both TV and FM broadcasting
- Ratio of maximum possible frequency deviation to maximum intelligence frequency.
- Computed as:
  \[ DR = \frac{\delta_{\text{max}}}{f_{i(\text{max})}} \]
- FM *wideband* systems have \( DR \geq 1 \)
- FM *narrowband* systems have \( DR < 1 \)
Standard Broadcast FM

• Refer to Fig 5-5 (next slide)
• Uses fixed bandwidth of 200 KHz
  – High fidelity modulating signals up to 15 KHz
  – Superior noise performance (more later)
• Maximum allocated deviation around carrier ($\delta_{\text{max}}$) is $\pm 75$ KHz
• Guard bands of 25 KHz at upper and lower ends
• Carrier required to maintain stability of $\pm 2$ KHz
• Wideband System with Deviation Ratio (DR) of 5
Figure 5-5  Commercial FM bandwidth allocations for two adjacent stations.
Noise Suppression

• Biggest advantage of FM over AM is superior noise characteristic (larger SNR)
• Since in FM system the intelligence is not carried by amplitude (unlike AM), we can remove spikes of external noise by using limiter circuit (see Fig 5-6)
• But spikes of external noise also cause undesired phase shift (thus frequency shift) that cannot be removed.
Figure 5-6  FM, AM noise comparison.
The amount of frequency deviation introduced as error can be computed as:

$$\delta_{error} = \Phi f_i$$

Where:
- $\Phi$: phase shift error (radians)
- $f_i$: intelligence signal frequency

The phase shift error can be computed as:

$$\Phi = \sin^{-1} \frac{1}{\text{SNR}_{in}}$$

Where:
- $\text{SNR}_{in}$ = signal-to-noise ratio measurement at the receiver input (antenna)
It can be demonstrated that maximum phase shift error occurs when \( \text{SNR}_{\text{in}} = 2 \), which corresponds to 30 degrees or 0.52 radians (see Fig 5-7).

Assuming that the internal receiver’s noise is negligible, the resulting output signal-to-noise ratio that goes to the transducer (speaker) can be computed as:

\[
\text{SNR}_{\text{out}} = \frac{\delta_{\text{max}}}{\delta_{\text{error}}}
\]

Notice inherent noise reduction ability of FM: \( \text{SNR}_{\text{out}} \) can be made greater than \( \text{SNR}_{\text{in}} \) by increasing \( m_f \) (that is increase \( \delta \) or decrease \( f_{i(\text{max})} \)).
Figure 5-7  Phase shift ($\phi$) as a result of noise.
Capture Effect

- Inherent ability of FM to reject undesired signals not only applies to noise, but also to reception of undesired stations at same or nearby frequencies.
- Receiver locks on stronger signal and suppress weaker but can fluctuate back and forth when the two are nearly equal (e.g. when riding Car an FM station is abruptly replaced by another one).
- Typical receiver capture ratio is 1 dB.
- Rapid degradation occurs when noise approaches same level as desired signal (FM Threshold).
Figure 5-8  $S/N$ for basic modulation schemes.
Preemphasis

• As seen before, noise suppression ability of FM decreases with higher intelligence signal frequencies
• That is undesired because typically higher intelligence signal frequencies have lower amplitude than low frequencies (e.g. violin vs bass drum)
• Solution: FM stations provide artificial boost to higher frequencies (preemphasis)
• But receivers must correct this effect (deemphasis)
Figure 5-9  Emphasis curves (\( \tau = 75 \ \mu s \)).
Dolby System

• Problem: quality recordings offer very strong high frequencies; standard preemphasis provides same boost to strong and weak high frequencies

• Solution: Dolby System
  – Uses 75 µs time-constant
  – Works like preemphasis, but on a dynamic fashion
  – Amount of emphasis varies depending on loudness level at any instant of emphasis (see Fig 5-11)
  – Weak high frequencies are given a significantly greater boost than stronger ones
  – Receiver requires complex circuitry to reverse curves
Figure 5-11  Dolby dynamic preemphasis.
Figure 5-10  Emphasis circuits.
Varactor Diode Modulator

• Varactor Diode: diode with small internal capacitance that varies with reverse bias voltage
• Used to generate FM directly: amount of deviation on the transmitted signal directly proportional to the amplitude of the intelligence
• Conceptually similar to Capacitor Microphone Generator, but different in that varactor produces enough deviation for practical usage
• See circuit at Fig 5-12
Figure 5-12 Varactor diode modulator.
Voltage Controlled Oscillator (VCO) as Modulator

• Output frequency proportional to input voltage amplitude

• In theory, VCO would be a perfect solution BUT in practice the following dilemma exists:
  – Non crystal-based VCOs that operate at high enough center frequency ($f_c$) with good enough deviation ($\delta_{\text{max}}$) do not have enough linearity and actual carrier frequency drifts around
  – Crystal-based VCO’s offer stable center frequency ($f_c$) but may not operate at a high enough center frequency ($f_c$) and/or may not offer good enough deviation ($\delta_{\text{max}}$)
Phase-Locked-Loop (PLL) Transmitter

- Takes advantage of frequency stability of crystal VCO and wide deviation range of non-crystal VCO
- Amplified audio signal used to frequency-modulate crystal oscillator via a varactor (reference signal)
- Phase Detector used to produce control voltage signal proportional to phase (frequency) difference between reference signal and output signal
- Phase Detector output signal (error) corrects non-crystal VCO center frequency
- See block diagram at Fig. 5-20 & circuit at Fig. 5-21
Figure 5-20 PLL FM transmitter block diagram.
Figure 5-21  PLL FM transmitter schematic.

Except as indicated, decimal values of capacitance are in microfarads (µF); others are in picofarads (pF or µµF); resistance are in ohms.
Stereo FM

• Main motivation was to provide high-fidelity playback
• Two separate 30 Hz to 15 KHz signals: Right & Left
• Broadcast system is compatible with non-stereo receivers
• Uses composite modulating signals (see Fig 5-23)
  – Based on frequency-division multiplexing
  – Two different signals (L + R & L – R) are used to modulate carrier
  – 19 KHz subcarrier
Figure 5-23  Composite modulating signals.
Stereo FM Transmitter

- Refer to Fig 5-24 (next slide)
- Left & Right channels picked up via microphone and individually preemphasized
- Matrix Network generates L + R & L – R signals
- Balanced Modulator used to suppresses carrier and provide double sidebands of L – R signal
- Master Oscillator provides 19 K-Hz pilot carrier for broadcast and for Balance Modulator (after doubling frequency)
Figure 5-24  Stereo FM transmitter.