Modulation Techniques for Mobile Radio

- Amplitude Modulation
- Angle Modulation
- Digital Modulation—an Overview
- Pulse Shaping Techniques
- Linear Modulation Techniques
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Frequency Modulation vs. Amplitude Modulation

- FM signals have all their information in phase or frequency of the carrier
- AM signals have all their information in the amplitude of the carrier
- Frequency modulation has better noise immunity when compared to amplitude modulation
- AM signals are able to occupy less bandwidth as compared to FM signals
- Frequency modulation exhibits a so-called capture effect characteristic
Amplitude Modulation

- AM signal can be represented as (see Fig. 1)
  \[ s_{AM}(t) = A_c[1 + m(t)]\cos(2\pi f_c t) \]

- For a sinusoidal modulating signal \( m(t) = \frac{A_m}{A_c}\cos(2\pi f_m t) \)
  the modulation index is given by
  \[ k = \frac{A_m}{A_c} \]

- The spectrum of an AM signal can be show to be (see Fig. 2)
  \[ S_{AM}(f) = \frac{1}{2} A_c[\delta(f - f_c) + M(f - f_c) + \delta(f + f_c) + M(f + f_c)] \]
Amplitude Modulation

Figure
(a) A sinusoidal modulating signal.
(b) Corresponding AM signal with modulation index 0.5.
Amplitude Modulation

Figure
(a) Spectrum of a message signal.
(b) Spectrum of the corresponding AM signal.
Angle Modulation

- The two most important classes of angle modulation being frequency modulation and phase modulation
- Frequency modulation (FM) can be represented as

\[
S_{FM}(t) = A_c \cos[2\pi f_c t + \theta(t)] = A_c \cos \left[ 2\pi f_c t + 2\pi k_f \int_{-\infty}^{t} m(\eta) d\eta \right]
\]

\(A_c\): amplitude of the carrier
\(f_c\): carrier frequency
\(k_f\): frequency deviation constant

- Phase modulation (PM) can be represented as

\[
S_{PM}(t) = A_c \cos[2\pi f_c t + k_\theta m(t)] \quad k_\theta: \text{phase deviation constant}
\]
FM modulation Methods

- Direct method (see Fig. 3)
  - The carrier frequency is directly varied in accordance with the input modulating signal

- Indirect method (see Fig. 4)
  - A narrowband FM signal is generated using a balanced modulator and frequency multiplication is used to increase both the frequency deviation and the carrier frequency to the required level, can be expressed as

\[
S_{FM}(t) \approx A_c \cos 2\pi f_c t - A_c \theta(t) \sin 2\pi f_c t
\]
Figure 3
A simple reactance modulator in which the capacitance of a varactor diode is changed to vary the frequency of a simple oscillator. This circuit serves as a VCO.
FM Modulation Methods

Figure 4
Indirect method for generating a wideband FM signal. A narrowband FM signal is generated using a balanced modulator and then frequency multiplied to generate a wideband FM signal.
FM Detection Technique

- Slope Detector (see Fig. 5)
- Zero-crossing Detector (see Fig. 6)
- PLL for FM Detection (see Fig. 7)
- Quadrature Detection (see Fig. 8)
FM Detection Technique

- Slope Detector

\[ v_{in}(t) = A_c \cos[2\pi f_c t + \theta(t)] = A_c \cos \left[ 2\pi f_c t + 2\pi k_f \int_{-\infty}^{t} m(\eta') d\eta \right] \]

\[ v_1(t) = V_1 \cos[2\pi f_c t + \theta(t)] = V_1 \cos \left[ 2\pi f_c t + 2\pi k_f \int_{-\infty}^{t} m(\eta') d\eta \right] \]

\[ v_2(t) = -V_1 \left[ 2\pi f_c t + \frac{d\theta}{dt} \right] \sin(2\pi f_c t + \theta(t)) \]

\[ v_{out}(t) = V_1 \left[ 2\pi f_c + \frac{d}{dt} \theta(t) \right] = V_1 2\pi f_c + V_1 2\pi k_f m(t) \]

Figure 5
Block diagram of a slope detector type FM demodulator.
FM Detection Technique

- Zero-crossing Detector

![Block diagram of a zero-crossing detector and associated waveforms](image-url)
FM Detection Technique

• PLL for FM Detection

\[ S_{FM(t)} \]
input FM signal

\[ m(t) \]
demodulated output signal

Phase Detector

Loop Amplifier and Low Pass Filter

Voltage Controlled Oscillator (VCO)

Figure 7
Block diagram of a PLL used as a frequency demodulator.
FM Detection Technique

- Quadrature detection

\[ v_\phi(t) = \rho A_c \cos[2\pi f_c t + 2\pi k_f \int m(\eta) d\eta + \phi(f_i(t))] \]

\[ v_0(t) = \rho^2 A_c^2 2\pi K_f m(t) = Cm(t) \]

Figure 8
Block diagram of a quadrature detector.

Characteristics of the phase-shift network with constant gain and linear phase.
Digital Modulation—an Overview

- Factors that influence the choice of digital modulation
  - power efficiency \( \eta_p \)
  - bandwidth efficiency \( \eta_B \)

\[
\eta_B = \frac{R}{B} \quad \text{bps} / \text{Hz}
\]
Digital Modulation—an Overview

- Bandwidth and power spectral density of digital signals
  - the power spectral density of a random signal $w(t)$ is defined as [1]
    \[ p_w(f) = \lim_{T \to \infty} \left( \frac{|W_T(f)|^2}{T} \right) \]
  - the PSD of the bandpass signal is given by
    \[ P_s(f) = \frac{1}{4} \left[ P_g(f - f_c) + P_g(-f - f_c) \right] \]
    Where $P_g(f)$ is the PSD of $g(t)$, and $g(t)$ is the complex baseband envelop $s(t) = \text{Re}\{g(t)\exp(j2\pi f_c t)\}$
Pulse Shaping Techniques

- Nyquist criterion for ISI cancellation
- Raised cosine rolloff filter (see Fig. 9-10)

\[
H_{RC}(f) = \begin{cases} 
\frac{1}{2} \left[ 1 + \cos \left( \frac{\pi (2T_s |f| - 1 + \alpha)}{2\alpha} \right) \right] & 0 \leq |f| \leq (1 - \alpha)/2T_s \\
0 & (1 - \alpha)/2T_s < |f| \leq (1 + \alpha)/2T_s \\
|f| > (1 + \alpha)/2T_s
\end{cases}
\]

\[
h_{RC}(t) = \left( \frac{\sin(\pi t/T_s)}{\pi t} \right) \left( \frac{\cos(\pi \alpha t/T_s)}{1 - (4\alpha t/(2T_s))^2} \right)
\]
Raised Cosine Rolloff Filter

Figure 9
Magnitude transfer function of a raised cosine filter.
Raised Cosine Rolloff Filter

Figure 10
Impulse response of a raised cosine rolloff filter.
Linear Modulation Techniques

- Digital modulation techniques are classified as linear and nonlinear.
- The amplitude of transmitted signal, \( s(t) \), varies linearly with the modulating digital signal, \( m(t) \).

\[
s(t) = Re[Am(t)exp(j2\pi f_c t)] \\
= A[m_R(t)\cos(2\pi f_c t) - m_I(t)\sin(2\pi f_c t)]
\]

\[
\begin{align*}
A & : \text{the amplitude} \\
f_c & : \text{the carrier frequency} \\
m(t) & = m_R(t) + jm_I(t) : \text{the modulated signal}
\end{align*}
\]
Binary Phase Shift Keying (BPSK)

- The information of the transmitted signal is modulated into the phase of the carrier signal.

\[
S_{BPSK}(t) = \sqrt{\frac{2E_b}{T_b}} \cos(2\pi f_c t + \theta_c)
\]

\[
S_{BPSK}(t) = \sqrt{\frac{2E_b}{T_b}} \cos(2\pi f_c t + \pi + \theta_c)
= -\sqrt{\frac{2E_b}{T_b}} \cos(2\pi f_c t + \theta_c)
\]

\[
P_{BPSK} = \frac{E_b}{2} \left[ \left( \frac{\sin\pi(f - f_c)T_b}{\pi(f - f_c)T_b} \right)^2 + \left( \frac{\sin\pi(-f - f_c)T_b}{\pi(-f - f_c)T_b} \right)^2 \right]
\]

Figure 11: Power Spectral Density (PSD) of a BPSK signal.
Coherent BPSK Receiver with carrier recovery circuits

- The received BPSK signal

\[ S_{BPSK}(t) = m(t) \sqrt{\frac{2E_b}{T_b}} \cos(2\pi f_c t + \theta_c + \theta_{ch}) \]

\[ = m(t) \sqrt{\frac{2E_b}{T_b}} \cos(2\pi f_c t + \theta) \]

- The bit error rate in an AWGN channel

\[ P_{e,BPSK} = Q\left(\frac{\sqrt{2E_b}}{\sqrt{N_0}}\right) \]

Figure 12
BPSK receiver with carrier recovery circuits.
Differential Phase Shift Keying (DPSK)

- A noncoherent form of PSK
- The input binary sequence is differentially encoded firstly.
- An example

\[
\begin{align*}
\{m_k\} &\quad 1 \ 0 \ 0 \ 1 \ 0 \ 1 \ 1 \ 0 \\
\{d_{k-1}\} &\quad 1 \ 1 \ 0 \ 1 \ 1 \ 0 \ 0 \ 0 \\
\{d_k\} &\quad 1 \ 1 \ 0 \ 1 \ 1 \ 0 \ 0 \ 0 \ 1 \\

\end{align*}
\]

\[
d_k = m_k \oplus d_{k-1}
\]

- The bit error rate in an AWGN channel

\[
P_{e,DPSK} = \frac{1}{2} \exp \left( \frac{E_b}{N_0} \right)
\]
Quadrature Phase Shift Keying (QPSK)

- 2 bits are transmitted on a signal modulation symbol.
- Therefore, QPSK has twice the bandwidth efficiency of BPSK.

\[
S_{QPSK}(t) = \sqrt{\frac{2E_s}{T_s}} \cos(2\pi f_c t + (i-1)\frac{\pi}{2}) \quad 0 \leq t \leq T_s \quad i=1,2,3,4.
\]

Figure 15
(a) QPSK constellation where the carrier phases are 0, π/2, π, 3π/2.
(b) QPSK constellation where the carrier phases are π/4, 3π/4, 5π/4, 7π/4.
Spectrum and Bandwidth of QPSK Signals

- The null-to-null RF bandwidth is equal to the bit rate $R_b$.
- The BW is half of a BPSK signal.
- The bit error rate in an AWGN channel

$$P_{e,BPSK} = Q\left(\sqrt{\frac{2E_b}{N_0}}\right)$$
QPSK Signal Transmission Technique

- The bit stream $m(t)$ is split into two bit streams $m_I(t)$ and $m_Q(t)$ (in-phase and quadrature stream).
- The two binary streams are separately modulated by two carriers, which are in quadrature.

![Block diagram of a QPSK transmitter.](image-url)

Figure 17
Block diagram of a QPSK transmitter.
Coherent QPSK Signal Detection Technique

- The frontend bandpass filter remove the out-of-band noise and adjacent channel interference.
- The filtered output is split into two parts, and each part is coherently demodulated using in-phase and quadrature carriers.

Figure 18
Block diagram of a QPSK receiver.
Offset QPSK

- OQPSK signaling is similar to QPSK, except for the time alignment of the even and odd bit streams.
- Thus, OQPSK can eliminate 180° phase transition, and prevent the signal envelope to go to zero.

![Diagram of Offset QPSK waveforms](image)

Figure 19
The time offset waveforms that are applied to the in-phase and quadrature arms of an OQPSK modulator. Notice that a half-symbol offset is used.
\(\pi/4\) QPSK

- \(\pi/4\) QPSK is a quadrature phase shift keying technique.
- It offers a compromises between OQPSK and QPSK.
- The maximum phase change of \(\pi/4\) QPSK is limited to \(\pm 135^\circ\).
- An extremely attractive feature of \(\pi/4\) QPSK is that it can be noncoherently detected.
- Further, it has been found that in the presence of multipath spread and fading, \(\pi/4\) QPSK performs better than OQPSK [2].
Constellation diagram of $\pi/4$ QPSK signal and Carrier Phase Shifts corresponding to input bit pairs

Information bits | Phase shift $\phi_k$
--- | ---
1 1 | $\pi/4$
0 1 | $3\pi/4$
0 0 | $-3\pi/4$
1 0 | $-\pi/4$

Figure 20
Constellation diagram of a $\pi/4$ QPSK signal: (a) possible states for $\theta_k$ when $\theta_{k-1} = n\pi/4$; (b) possible states when $\theta_{k-1} = n\pi/2$; (c) all possible states.
Generic $\pi/4$ QPSK Transmitter

Figure 21
Generic $\pi/4$ QPSK transmitter.
π/4 QPSK Detection Techniques

- Baseband differential detector (see Fig. 22)
- IF differential detection (see Fig. 23)
- FM discriminator (see Fig. 24)
$\pi/4$ QPSK Baseband differential detector [3]

Figure 22
Block diagram of a baseband differential detector [From [Feh91] © IEEE].
\[ \pi/4 \text{ QPSK IF differential detection} \]

**Figure 23**
Block diagram of an IF differential detector for \( \pi/4 \text{ QPSK} \).
π/4 QPSK FM discriminator

Figure 24
FM discriminator detector for π/4 DQPSK demodulation.
The constant envelope family of modulations has following advantage [4]:

- Power efficient Class C amplifiers can be used without introducing degradation in the spectrum occupancy of the transmitted signal.

- Low out-of-band radiation of the order of -60 dB to -70 dB can be achieved.

- Limiter-discriminator detection can be used, which simplified receiver design and provides high immunity against random FM noise and signal fluctuations due to Rayleigh fading.
Binary Frequency Shift Keying (BFSK)

- The information of the transmitted signal is modulated into the frequency of the carrier signal.
- In general, an FSK signal may be represented as

\[ S_{FSK}(t) = v_H(t) = \sqrt{\frac{2E_b}{T_b}} \cos(2\pi f_c + 2\pi \Delta f) t \]

\[ S_{FSK}(t) = v_L(t) = \sqrt{\frac{2E_b}{T_b}} \cos(2\pi f_c - 2\pi \Delta f) t \]
Detection of Binary FSK

Coherent

Noncoherent

Figure 25
Coherent detection of FSK signals.

Figure 26
Block diagram of noncoherent FSK receiver.
Minimum Shift Keying (MSK)

- Minimum shift keying (MSK) is a special type of continuous phase-frequency shift keying (CPFSK).
- MSK is sometimes referred to as fast FSK, as the frequency spacing used is only half as much as that used in conventional noncoherent FSK [5].
- An MSK signal also can be thought of as a special form of OQPSK where the baseband rectangular pulses are replaced with half-sinusoidal pulses [6].

\[ S_{MSK}(t) = m_I(t)\cos\left(\frac{\pi t}{2T_b}\right)\cos(2\pi f_c t) + m_Q(t)\sin\left(\frac{\pi t}{2T_b}\right)\sin(2\pi f_c t) \]
From this figure, the MSK spectrum has lower sidelobes than QPSK and OQPSK.
Block diagram of an MSK transmitter

\[ S_{MSK}(t) = m_I(t)\cos\left(\frac{\pi t}{2T_b}\right)\cos(2\pi f_c t) + m_Q(t)\sin\left(\frac{\pi t}{2T_b}\right)\sin(2\pi f_c t) \]
Figure 29
Block diagram of an MSK receiver.
Gaussian Minimum Shift Keying (GMSK)

- GMSK is a simple binary modulation scheme which may be viewed as a derivative of MSK.
- In GMSK, the sidelobe levels of the spectrum are further reduced by passing the modulating NRZ data waveform through a premodulation Gaussian pulse-shaping filter [7].
- In practice, GMSK is most attractive for its excellent power efficiency (due to the constant envelope).
The impulse response of the GMSK premodulation filter

\[ h_G(t) = \frac{\sqrt{\pi}}{\alpha} \exp\left(-\frac{\pi^2}{\alpha^2} t^2\right), \quad \alpha = \frac{\sqrt{2\ln 2}}{B} \]

**Figure 30**
Block diagram of a GMSK transmitter using direct FM generation.
Block Diagram of a GMSK receiver

Figure 31
Block diagram of a GMSK receiver.
Power Spectrum density of a GMSK signal [7]

Figure 32
Combined Linear/Constant Envelope Modulation Techniques

- Digital baseband data may be sent by varying both the envelope and phase (frequency) of an RF carrier.
- This can offer two degrees of freedom, thus such modulation techniques are called M-ary modulation.
- In M-ary signaling scheme, two or more bits are grouped together to form symbols.
- Depending on whether the amplitude, phase, or frequency of the carrier is varied, the modulation scheme is called M-ary ASK, M-ary PSK, or M-ary FSK.
- M-ary modulation schemes achieve better bandwidth efficiency at the expense of power efficiency.
M-ary Phase Shift Keying (MPSK)

\[ S_i(t) = \sqrt{\frac{2E_s}{T_s}} \cos \left[ (i-1) \frac{2\pi}{M} \right] \cos(2\pi f_c t) + \sqrt{\frac{2E_s}{T_s}} \sin \left[ (i-1) \frac{2\pi}{M} \right] \sin(2\pi f_c t) \]

where \( E_s = (\log_2 M) E_b \) and \( T_s = (\log_2 M) T_b \)

**Figure 33**
Constellation diagram of an M-ary PSK system (M=8).
M-ary PSK power spectral density

Figure 34
M-ary PSK power spectral density, for \( M = 8, 16 \), (PSD for both rectangular and raised cosine filtered pulses are shown for fixed \( R_b \)).
M-ary Quadrature Amplitude Modulation (QAM)

\[ S_i(t) = \sqrt{\frac{2E_{\text{min}}}{T_s}} a_i \cos \left( (i-1) \frac{2\pi}{M} \right) \cos(2\pi f_c t) + \sqrt{\frac{2E_{\text{min}}}{T_s}} b_i \sin \left( (i-1) \frac{2\pi}{M} \right) \sin(2\pi f_c t) \]

where \( E_{\text{min}} \) is the energy of the signal with the lowest amplitude, and \( a_i \) and \( b_i \) are a pair of independent integers.

Figure 35
Constellation diagram of an M-ary QAM (M=16) signal set.
M-ary Frequency Shift Keying (MFSK)

\[ S_i(t) = \sqrt{\frac{2E_s}{T_s}} \cos \left( \frac{\pi}{T_s} (n_c + i) t \right) \quad 0 \leq t \leq T_s \quad i = 1, 2, \ldots, M \]

where \( f_c = n_c / 2T_s \) for some fixed integer \( n_c \), and the signal frequencies are separated by \( 1/2T_s \) Hertz.

- The orthogonality characteristic of MFSK has led researches to explore Orthogonal Frequency Division Multiplexing (OFDM)
Spread Spectrum Modulation Techniques

- Pseudo-noise (PN) Sequences

Figure 36
Block diagram of a generalized feedback shift register with \( m \) stages.
Direct Sequence Spread Spectrum (DS-SS)

\[ S_{ss}(t) = \sqrt{\frac{2E_s}{T_s}} m(t) p(t) \cos(2\pi f_c t + \theta) \]

- \( m(t) \) is the data sequence,
- \( p(t) \) is the PN spreading sequence,
- \( f_c \) is the carrier frequency,
- \( \theta \) is the carrier phase angle at \( t=0 \)
Interference Suppress in the Spread Spectrum

Figure 38
Spectra of desired received signal with interference: (a) wideband filter output and (b) correlator output after despreading.
Figure 39
Block diagram of frequency hopping (FH) system with single channel modulation.
Performance of Digital Modulation in Slow, Flat Fading Channels

Figure 40
Bit error rate performance of binary modulation schemes in a Rayleigh, flat fading channel as compared to a typical performance curve in AWGN.
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