Chapter 7: Analog Communication Systems

- Receiver block diagram design
- Image frequency bands that may cause spurious responses (more filter requirements)
- Signal Multiplexing
  - Frequency division (FDM) and
  - Time division (TDM)
- Phase-Lock Loops (PLL)
Multiplexing

• Combining multiple signals into a wider bandwidth system for transmission
  – Typically multiplex in time or frequency
    • TDM time division multiplexing
    • FDM frequency division multiplexing
  – For time multiplexing, “PAM sampling”, bandwidth based on PAM pulse periods
  – For frequency multiplexing, bandwidth is the sum of all the multiplexed elements plus their guard bands
Multiplexing Methods

- Frequency division multiplexing (FDM)
- Time division multiplexing (TDM)
- Quadrature-carrier multiplexing or quadrature amplitude modulation (QAM) – complex signals
- Code division multiplexing (see Chap. 15)
- Spatial multiplexing
  - Antenna direction
  - Signal polarization

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Time-Division Multiplexing (TDM)

- Interleaved signals in times that occupy assigned time slots
  - 6 time slots shown; therefore, 6-TDM
Frequency-Division Multiplexing (FDM)

- Signal frequency bands stacked together, but transmitted as one wider bandwidth signal
  - 6 frequency bands shown
  - Similar to 6 adjacent radio stations using one transmitter
FDM transmitter

Figure 7.2-1

Stacked Frequency Bands

Guard Bands: allow for individual frequency band filter transition bands

- Transmitter
- Receiver
FDM receiver

Guard Bands: allow for receiver filter transition bands

Cross Talk: unwanted energy from adjacent FDM channels

Post-De-FDM Baseband Bandwidths:

- Signal Passband + both guard bands
FDM MATLAB Example

- FDM Example
  - FM Modulate the chirp, gong and train
  - FDM of the three FM signals

![Sequential FFTs of the TDM-FM Modulated Waveform](image-url)
FDMA satellite repeater system

Figure 7.2-3

Nominal 36 MHz BW Links
- 1200 Voice Channels or
- 400 channels of 64 kbps or
- 16 channels of 1.544 Mbps each or
- One 50 Mbps data stream
Quadrature-Carrier Multiplexing

Figure 7.2-6

\[ s_c(t) = A \cdot [x_1(t) \cdot \cos(2\pi f_c t) \pm x_2(t) \cdot \sin(2\pi f_c t)] \]

A special case of FDM
“Orthogonal” Signals at the same frequency
Quadrature Carrier Math

\[ x_c(t) = A \cdot x_1(t) \cdot \cos(2\pi f_c \cdot t) \pm A \cdot x_2(t) \cdot \sin(2\pi f_c \cdot t) \]

\[ y_I(t) = [A \cdot x_1(t) \cdot \cos(2\pi f_c \cdot t) \pm A \cdot x_2(t) \cdot \sin(2\pi f_c \cdot t)] \cdot \cos(2\pi f_c \cdot t + \theta) \]

\[ y_Q(t) = [A \cdot x_1(t) \cdot \cos(2\pi f_c \cdot t) \pm A \cdot x_2(t) \cdot \sin(2\pi f_c \cdot t)] \cdot \sin(2\pi f_c \cdot t + \theta) \]

\[ y_{ILPF}(t) = \left[ \frac{A}{2} \cdot x_1(t) \cdot \cos(\theta) \pm \frac{A}{2} \cdot x_2(t) \cdot \sin(\theta) \right] = \frac{A}{2} \cdot x_1(t) \bigg|_{\theta=0} \]

\[ y_{QLPF}(t) = \left[ \frac{A}{2} \cdot x_1(t) \cdot \sin(\theta) \pm \frac{A}{2} \cdot x_2(t) \cdot \cos(\theta) \right] = \pm \frac{A}{2} \cdot x_2(t) \bigg|_{\theta=0} \]

Two signals multiplexed on the same frequency.

What happens if the receiver carrier is not perfectly synchronized or, for example, 90 deg off?
Quadrature FDM Channels

• Each of the frequency bands or channels may have signal that are in quadrature.
  – Doubling the channel capacity
  – Phase synchronization of the receiver with the received waveform is required!

  – A precursor to Orthogonal Frequency Division Multiplexing (OFDM)
    • Part of the theory behind modern cell phone and WiFi signal formats.
Time-Division Multiplexing (TDM)

- Interleaved signals in times that occupy assigned time slots
  - 6 time slots shown; therefore, 6-TDM
TDM – Insert more signals!

Analog signal and corresponding PAM signal: Figure 6.2-1

Signal #1

Signal #2
TDM system

(a) block diagram (b) waveforms

Figure 7.2-7

PAM inputs multiplexed in time

PAM outputs for reconstruction
TDM synchronization markers

Figure 7.2-9

One time slot used for a marker/synchronization
TDM Continuous Transmitter

(a) TDM transmitter with baseband filtering  (b) baseband waveform

Figure 7.2-10
TDM MATLAB Example

• Time Multiplex Time-sampled Waveforms
  – Chirp, Gong, Train
  – One “sawtooth” extra channel
  – Note: This did not start with true “PAM”; therefore, a BPF should not be used before demultiplexing.
Cross talk in TDM

\[ A_{ct} = A \cdot \exp(-2\pi B T_g) \]

\[ k_{ct} = 10 \cdot \log_{10} \left( \frac{A_{ct}}{A} \right) \approx -54.5 \cdot B \cdot T_g \text{ (in dB)} \]

\[ \text{B = 3dB Bandwidth} \]

Figure 7.2-12

Sufficient time must be available for the receiver to transition from one PAM level to the next. Otherwise adjacent signals effect each other – defined as cross talk.
TDM/PPM with guard time

- Time-division-multiplexing multiple pulse-position-modulated signals.
  - Pulse center +/- $t_0$

\[ t_0 \quad \tau \quad t_0 \quad T_g \quad \tau \quad \frac{\tau}{2} \quad t_0 \quad T_g \]

\[ \frac{T_s}{M} \quad \text{time} \]
TDM/PPM with guard time

4th ed. Figure 7.2-13 is wrong: Fix - Tg is between the signal pulses

5th ed. Figure 7.2-13 is wrong: t₀ is on opposite side of pulses

Forward and backward maximum locations, t₀

\[
\frac{T_s}{M} \geq \frac{\tau}{2} + t_0 + T_g + t_0 + \frac{\tau}{2}
\]

\[
t_0 \leq \frac{1}{2} \left( \frac{T_s}{M} - \tau - T_g \right)
\]
Comparing TDM and FDM

• TDM based on time slots
  – Overlap in frequency domain
  – Bandwidth of total signal defines cross talk
  – Well supported by digital circuitry, multiple mux rates
  – Synchronization concerns
  – Time based receiver; therefore, less dependent upon filter performance or ripple

• FDM based on frequency slots
  – Overlap in time domain
  – Guard bands and filtering determine cross talk
  – Simple frequency assignments
TDM, FDM, TDD and FDD

• TDM: Time division multiplex
• FDM: Frequency division multiples

For Two-way Communications
• TDD: Time division duplex
  – One side talks and then the other side talks
  – Note that only one transmission can happen at a time on the signal frequency being used
• FDD: Frequency division duplex
  – Two different frequencies are used so both sides can talk simultaneously
Frequency Synthesis

- All wireless designs require defined reference frequencies for transmitting and receiving waveforms.
- Local Oscillators are used to provide the reference frequencies
  - Fixed tuned LOs may use RC, SAW or crystals
  - Synthesized LOs typically use frequency and/or phase-lock loops
  - Carrier/Phase Synchronous LOs are required for synchronous signal demodulation

\[ f_{\text{out}} = N \cdot \frac{f_{\text{ref}}}{R} \]
The Phase Locked Loop

- If the phases of two analog or digital signals that are approximately the same in frequency are compared, it can be determined which one leads or lags.

- A difference signal can be generated and a feedback loop can cause one signal to lock onto the other …
Analog Phase Comparator

Phase comparators (a) analog Figure 7.3-1

\[ x_c(t) = A_c \cos \theta_c(t) \]
\[ y(t) = \frac{1}{2} A_c A_v \sin \epsilon(t) \]
\[ v(t) = A_v \cos \theta_c(t) \]
\[ \theta_v(t) = \theta_c(t) - \epsilon(t) + 90^\circ \]

\[ e_{\text{phase}}(t) = A_c \cdot \cos[\theta_c(t)] \cdot A_v \cdot \cos[\theta_v(t)] = A_c \cdot A_v \cdot \cos[\theta_c(t)] \cdot \cos[\theta_c(t) - \epsilon(t) + \frac{\pi}{2}] \]
\[ e_{\text{phase}}(t) = \frac{A_c \cdot A_v}{2} \cdot \cos[-\epsilon(t) + \frac{\pi}{2}] = \frac{A_c \cdot A_v}{2} \cdot \sin[\epsilon(t)] \approx \frac{A_c \cdot A_v}{2} \cdot \epsilon(t) \]

- Performance depends on the small angle approximation
- A “linear” capture range (linearize sine about zero)
Digital Phase Comparator

Phase comparators (b) digital Figure 7.3-1

- The operation tracks leading and lagging edge comparisons of two digital, 50% duty cycle, square-wave inputs
  - Typically, bipolar current pulses are output that represent which signal leads and how much time mismatch there is.
Phase Lock Loop Model

Phase-lock loop

Figure 7.3-2

\[ x_c(t) = 2 \cos \theta_c(t) \]
\[ y(t) = K_a \sin \epsilon(t) \]
\[ v(t) = \cos \theta_v(t) \]

- Phase Comparator
- Loop Filter
- Loop Gain
- VCO

A linearized system model in phase is used
Phase Lock Loop Math (1)

\[ \theta_c(t) = 2\pi f_c \cdot t + \varphi(t) \]

\[ x_c(t) = 2 \cos \theta_c(t) \]

\[ v(t) = \cos \theta_v(t) \]

\[ \theta_v(t) = 2\pi (f_c - \Delta f) \cdot t + \varphi_v(t) + \frac{\pi}{2} \]

\[ \varphi_v(t) = 2\pi K_v \int_0^t y(\lambda) \cdot d\lambda \]

\[ \varepsilon(t) = \theta_c(t) - \theta_v(t) + \frac{\pi}{2} = 2\pi \Delta f \cdot t + \varphi(t) - \varphi_v(t) \]

Phase Equivalents in Boxes

Phase-lock loop: Figure 7.3-2
Phase Lock Loop Math (2)

Phase-lock loop Figure 7.3-2

Steady State Operation Derivation

A non-linear differential equation

\[
\frac{d\varepsilon(t)}{dt} + 2\pi \cdot K \cdot \sin(\varepsilon(t)) = 2\pi \cdot \Delta f + \frac{d\phi(t)}{dt}
\]

\[
K = K_v \cdot K_a
\]
Phase Lock Loop Math (3)

- For a stable input frequency reference
  \[
  \frac{d\varphi(t)}{dt} = 0
  \]
  \[
  \frac{1}{2\pi \cdot K} \cdot \frac{d\varepsilon(t)}{dt} + \sin(\varepsilon(t)) = \frac{\Delta f}{K}
  \]

- At steady state
  \[
  \frac{d\varepsilon(t)}{dt} = 0
  \]
  \[
  \sin(\varepsilon(t)) = \frac{\Delta f}{K}
  \]
  \[
  \varepsilon_{ss} = \arcsin \left( \frac{\Delta f}{K} \right)
  \]
  \[
  1 \geq \left| \frac{\Delta f}{K} \right|
  \]

- Resulting in
  \[
  y_{ss} = K_a \cdot \sin(\varepsilon_{ss}) = K_a \cdot \frac{\Delta f}{K} = \frac{\Delta f}{K_v}
  \]
  \[
  v_{ss}(t) = \cos \left( 2\pi f_c t + (\varphi_0 - \varepsilon_{ss}) + \frac{\pi}{2} \right)
  \]
Phase Lock Loop Math (4)

• Other steady state inferences: The transient response
\[
\frac{d\varepsilon(t)}{dt} + 2\pi \cdot K \cdot \sin(\varepsilon(t)) = 0
\]

• with the transient error solution of
\[
\varepsilon(t) = \varepsilon(t_0) \cdot \exp[-2\pi \cdot K \cdot (t - t_0)]
\]

• From before, we can define a frequency “capture” range for “locking-the-loop” as
\[
1 \geq \frac{|\Delta f|}{K} \quad K \geq |\Delta f| \quad f_v - K < f < f_v + K
\]
Linearized PLL Models

- Using a loop model that defines the phases offsets of the sine or cosine waveforms

\[ x_c(t) = 2 \cos [\omega_c t + \phi(t)] \]

\[ v(t) = \cos [\omega_c t + \phi_v(t) + 90^\circ] \]

Linearized PLL models
(a) time domain
(b) phase domain
Figure 7.3-8
PLL Phase Models

Linearized PLL models
(b) phase domain
(c) Laplace domain

Figure 7.3-8

\[
Y(s) = \frac{K_a \cdot H(s)}{1 + K_a \cdot H(s) \cdot \frac{K_v}{s}} \cdot \Phi_c(s)
\]

\[
\frac{Y(s)}{\Phi_c(s)} = \frac{s \cdot K_a \cdot H(s)}{s + K_a \cdot K_v \cdot H(s)}
\]
PLL Model Frequency Response

• Frequency Response for \( H(s) = K_H \)
  \[
  \frac{Y(s)}{\Phi_c(s)} = \frac{s \cdot K_a \cdot K_H}{s + K_a \cdot K_v \cdot K_H}
  \]

• Frequency Response for \( H(s) = \frac{p_H}{s + p_H} \)
  \[
  \frac{Y(s)}{\Phi_c(s)} = \frac{s \cdot K_a \cdot p_H}{s^2 + p_H \cdot s + K_a \cdot K_v \cdot p_H}
  \]
PLL Model Steady State Error

• Error
\[ \varepsilon(s) = \Phi_c(s) - \frac{K_v}{s} \cdot Y(s) = \left[ 1 - \frac{K_v}{s} \cdot \frac{s \cdot K_a \cdot H(s)}{s + K_a \cdot K_v \cdot H(s)} \right] \cdot \Phi_c(s) \]

\[ \varepsilon(s) = \frac{s}{s + K_a \cdot K_v \cdot H(s)} \cdot \Phi_c(s) \]

\[ \varepsilon_{ss} = \lim_{s \to 0} \left\{ s \cdot \frac{s}{s + K_a \cdot K_v \cdot H(s)} \cdot \Phi_c(s) \right\} \]

• For \( H(s) = K_H \)
\[ \varepsilon_{ss} = \lim_{s \to 0} \left\{ \frac{s^2}{K_a \cdot K_v \cdot K_H} \cdot \Phi_c(0) \right\} = 0 \]

• For \( H(s) = \frac{p_H}{s + p_H} \)
\[ \varepsilon_{ss} = \lim_{s \to 0} \left\{ \frac{s^2 \cdot (s + p_H)}{s^2 + p_H \cdot s + K_a \cdot K_v \cdot p_H} \cdot \Phi_c(0) \right\} = 0 \]
PLL Integrated Circuits

- Analog Devices: ADF4001 200 MHz Clock Generator PLL

Applications of PLL

- Frequency Synthesis
  - With tuning steps for radios
- Synchronous Signal Regeneration
  - FM Pilot, TV color burst, etc.
  - Coherent AM and DSB demodulator/detector
- Clock generation for digital electronics
- FM demodulator/detector

… and much more
Frequency Synthesis

- Synthesizing higher frequencies with known step sizes

$$f_{\text{out}} = N \cdot \frac{f_{\text{ref}}}{R}$$

- Divide $f_{\text{ref}}$ to provide a reference (or smaller) step size $\frac{f_{\text{ref}}}{R} = f_{\text{step}}$

- Divide $f_{\text{out}}$ for input at the phase comparator $\frac{f_{\text{out}}}{N} = \frac{f_{\text{ref}}}{R}$

- Resulting in $f_{\text{out}} = \left(\frac{N}{R}\right) \cdot f_{\text{ref}}$
ADF4360-7: Integrated Synthesizer and VCO

FEATURES
- Output frequency range: 350 MHz to 1800 MHz
- 3.0 V to 3.6 V power supply
- 1.8 V logic compatibility
- Integer-N synthesizer
- 3-wire serial interface
- Analog and digital lock detect

APPLICATIONS
- Wireless handsets (DECT, GSM, PCS, DCS, WCDMA)
- Wireless LANs
- CATV equipment

http://www.analog.com/en/prod/0,,770_850_ADF4360%252D7%2C00.html
PLL References

• Analog Devices Technical Articles
    – Phase Locked Loops for High-Frequency Receivers and Transmitters – Part 1
      • http://www.analog.com/library/analogDialogue/cd/vol33n1.pdf#page=11
    – Phase-Locked Loops for High-Frequency Receivers and Transmitters - Part 2
      • http://www.analog.com/library/analogDialogue/cd/vol33n1.pdf#page=15
    – Phase Locked Loops for High-Frequency Receivers and Transmitters – Part 3
      • http://www.analog.com/library/analogDialogue/cd/vol33n1.pdf#page=20
Synchronous Detection
Frequency Synthesis

• The PLL provides a way to “adapt” to the incoming frequency and lock to the phase

• This is required for a “synchronous receiver” for any of the modulation forms previously described!
Providing a Synchronous LO

PLL pilot filter with two phase discriminators: Figure 7.3-3

For systems where a carrier can be isolated, such as AM, FM Stereo, NTSC-TV, etc.
Costas PLL system for synchronous detection: Figure 7.3-4

\[ y_{ss} = \sin(2 \cdot \varepsilon_{ss}) \cdot \int_{t-T}^{t} [x(t)]^2 \cdot dt = \sin(2 \cdot \varepsilon_{ss}) \cdot \frac{1}{T} \cdot S_{xx} \]

For systems where a carrier is not isolated, such as DSB.
**FM Demodulation with a PLL**

**PLL Phase**

\[ Y(s) = \frac{1}{K_v} \cdot \frac{j \cdot f \cdot K \cdot H(f)}{j \cdot f + K \cdot H(f)} \cdot \Phi_c(f) \]

**FM Phase**

\[ \Phi_c(f) = \frac{2\pi \cdot \Delta_f \cdot X(f)}{j \cdot 2\pi \cdot f} \]

\[ Y(s) = \frac{1}{K_v} \cdot \frac{j \cdot f \cdot K \cdot H(f)}{j \cdot f + K \cdot H(f)} \cdot \frac{\Delta_f \cdot X(f)}{j \cdot f} \]

\[ Y(s) = \frac{\Delta_f}{K_v} \cdot \left[ \frac{K \cdot H(f)}{j \cdot f + K \cdot H(f)} \right] \cdot X(f) \]

Let \( H(s) = K_H \)

\[ Y(s) = \frac{\Delta_f}{K_v} \cdot \left[ \frac{K \cdot K_H}{j \cdot f + K \cdot K_H} \right] \cdot X(f) \]

LPF of Message