Communication system performance revisited

Slide from before:
Performance Concerns
- DC offset
- Image rejection
- Quadrature requirements
- Noise and noise figure
- Phase noise and Jitter
- Distortion
  - Compression
  - Deserialization
  - Cross modulation
  - Intermodulation
  - IP2, IP3
  - Harmonic distortion (THD, SFDR, ...)
- Bit error rate
- Data rate (bandwidth)

System level concerns
- Data rate (voice, text, image, video, ...)
- Cost (CMOS, SiGe, ...)
- Mobility (fixed, indoor, outdoor, ground vehicle, airborne, ...)
- Battery life (power consumption)
- Weight (discrete, multi-chip, single chip, ...)
- Multi-standard support (hardware sharing)
- Security (baseband DSP)
- Quality of service (protocol, transceiver)

Mobility vs. Bit Rate
Where is UWB?
Where is Military?

Cost vs. Bit Rate

Motorola 3G Smart Phone Architecture
Transceiver performance

- Transceiver Overview
- Transmitter Performance Spec.
- Transmitter Architecture
- Receiver Performance Spec.
- Receiver Architecture
- Receiver Link Budget

Transmitter Performance Spec.

- Output Power
- Spurious Emission
- Adjacent Channel Power Ratio; ACPR
- Frequency Stability
- Data rate
- Bandwidth efficiency
- Noise immunity
Increasing Information

- Information in a source
  - Mathematical Models of Sources
  - Information Measures
- Compressing information
  - Huffman encoding
  - Lempel-Ziv-Welch Algorithm
  - Optimal Compression?
- Quantization of analog data
  - Scalar Quantization
  - Vector Quantization
  - Model Based Coding
    - \(\mu\)-law encoding
    - Delta Modulation
    - Linear Predictor Coding (LPC)

Increasing Noise Immunity

- Error correction coding
- Block coding
- Channel coding
- Adaptive feedback coding
- Diversity
  - Space time diversity

Increasing bandwidth Efficiency

- Modulation of digital data into analog waveforms
  - Impact of Modulation on Bandwidth efficiency

Output Power

\[ P_L = -10 \log \left( \frac{P_t}{P_r} \right) - 10 \log \left( \frac{G_t}{G_r} \right) \left( \frac{1}{400} \right) \left( \frac{1}{L} \right) \]

<table>
<thead>
<tr>
<th>f (GHz)</th>
<th>D (m)</th>
<th>Top Loss (dB)</th>
<th>10</th>
<th>20</th>
<th>30</th>
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<td>10</td>
<td>60.23</td>
<td>20</td>
<td>70.23</td>
<td>80</td>
</tr>
</tbody>
</table>

Spurious Emission

Adjacent Channel Power Ratio

- Definition depends on specification

\[ ACPR = \frac{P_{\text{adj}}}{P_{\text{main}}} \]
Adjacent channel reject

Transmit Specifications
• Transmit spectrum mask

Transmitter Architecture
• RF/BB Interface
• Direct Conversion Transmitter
• Two-step Conversion Transmitter
• Offset PLL Transmitter

BPSK Transmitter
\[
s_{BPSK}(t) = \begin{cases} \frac{2E}{T_s} \cos(2\pi f_c t + \theta) & \text{bit 1} \\ \frac{2E}{T_s} \cos(2\pi f_c t + \theta) & \text{bit 0} \end{cases}
\]

QPSK transmitter
• Direct-conversion transmitter

Pros: less spurious synthesized
Cons: more LO pulling

• Direct-conversion transmitter with offset LO

Pros: less LO pulling
Cons: more spurious synthesized

• Two-Step Transmitters

Pros: less LO pulling
superior IQ matching
Cons: required high-Q bandpass filter

• Two-step transmitter

• Offset PLL transmitter

Pros: less LO pulling
Cons: more spurious synthesized

Transmitter Performance Check
1. Sensitivity and Dynamic Range
2. Unwanted Emission
Receiver Performance Spec.
• Sensitivity
• Selectivity
• Spurious Response Rejection
• Intermodulation Rejection
• Receiver Self-quieting
• Dynamic Range

Receiver Specifications

Sensitivity

Sensitivity Example

Calculate Receiver Noise Figure
• Stage Thermal Noise
• Image Noise
• LO Wideband Phase Noise

$$F_{\text{snr}} = 1 + \frac{F_1 - 1}{1 + G_1} + \frac{F_2 - 1}{G_2} + \frac{F_3 - 1}{G_2 G_3} + L$$
Selectivity

- IF filter rejection at the adjacent channel
- LO spurious in IF bandwidth
- Phase noise of LO

![Selectivity Diagram]

Spurious Response

\[ IF = n \cdot RF + m \cdot LO \]
\[ IF = m \cdot \frac{LO}{RF} + n \]
\[ y = \frac{IF}{RF}, x = \frac{LO}{RF} \]
\[ y = m \cdot x + n \]
\[ |m| + |n| = \text{order of spurious response} \]

![Spurious Response Diagram]
• Nonlinearity and Spurious response

Receiver Self-quieting

\[ f_{RF} = f_{LO1} + f_{IF1} = n \cdot f_{LO2} \]

Dynamic Range

\[ DR_{1dB} = P_{1dB, in} - P_{in, min} \]
\[ DR_0 = P_{0dB, in} - P_{in, min} \]
\[ = \frac{2P_{IP3}}{3} \]
\[ = \frac{2(P_{IP3, in} - P_{in, min})}{3} - SNR_{min} \]

Super-heterodyne Receiver

– easy to design
– problem of image
– problem of half IF

Receiver Architectures

• Heterodyne Receiver
• Direct Conversion Receiver
• Low-IF Receiver
• Image Reject Receiver
Heterodyne Receiver

- IF receiver

\[ a(t) = \cos(\omega_r t + m(t) + \phi) \]

\[ b(t) = a(t) \cdot \cos(\omega_{lo} t + \theta) \]

\[ = \cos(\omega_r t + m(t) + \phi) \cdot \cos(\omega_{lo} t + \theta) \]

\[ - \frac{1}{2} \cos((\omega_r + \omega_{lo}) t + m(t) + \phi + \theta) \]

\[ + \frac{1}{2} \cos((\omega_r - \omega_{lo}) t + m(t) + \phi - \theta) \]

if \( \omega_r = \omega_{rf} = \omega_{lo} + \omega_{sp} \Rightarrow OK \)

if \( \omega_r = \omega_{iw} = \omega_{lo} - \omega_{sp} \Rightarrow ? \)

Problem of Image Signal

- One solution: Image Rejection Filter
- Image rejection ratio:

\[ H_{ir}(\omega_r) = \frac{1}{\frac{H_{ir}(\omega_{iw})}{\omega_{rf}} - \frac{1}{\omega_{sp}}} \]

Need \( \omega_{rf} \) and \( \omega_{lo} \) to be far away

Problem of Half IF

- Second order harmonic

\( |(\omega_r + \omega_{lo}) - 2\omega_r| = \omega_{sp} \)

\[ \frac{\omega_r + \omega_{lo} - \omega_{sp}}{2} = \frac{\omega_r - \omega_{lo} - \omega_{sp}}{2} \]

How to Select IF?

- Spurious Response
- Image Rejection v.s. Channel Selection
- Filter Availability
Filter Availability

- Example 1
  - $f_{RF} = 1800\text{MHz}$
  - $f_{IF} = 10\text{MHz}$
  - Is this filter available?
  
  \[
  \frac{f_{RF}}{f_{IF}} = \frac{1800}{10} = 180
  \]
  \[
  Q = \frac{f_{RF}}{BW} = \frac{1800}{20} = 90
  \]

Image Rejection v.s. Channel Selection

\[
Q_{RF} = \frac{f_{RF}}{BW}
\]

IF Selection

- Usually $f_{RF}/f_{IF} < 10$
- Example 2 (Multistage IF)
  - $f_{RF} = 900\text{MHz}$
  - $f_{IF1} = 250\text{MHz}$
  - $f_{IF2} = 50\text{MHz}$
  - $f_{IF3} = 10\text{MHz}$

Summary of Heterodyne Receiver

- Down converts RF to IF thus introduces image problem; avoid image signal by image reject filter
- As frequency / bandwidth increases, multi-stage IF is necessary
- Not suitable for integration due to off-chip filters
- Sensitive to external parasitic signal
- Expensive and high power consumption

Direct Conversion Receivers

- Easy to single chip
- Channel Selection
- DC offsets
- I/Q Mismatch
- Even-Order Distortion
- Flick Noise: choose a suitable code
- LO Leakage
Direct Conversion Receiver

- Zero-IF Receiver

\[ A \cos(\omega t) \]

Channel Selection

- Different placement of three block

Comparison and trade-offs

- Assume normalized input full range of +- 1V for the ADC
- Input signal (signal after mixer) amplitude can range from ~<1 mV to just under 1V
- \( f_{RF} = 1.8 \text{GHz}, f_{IF} = 100 \text{MHz}, f_{ch} = 200 \text{KHz} \)
- Input signal is wideband but the desired signal component is narrow band (IF)
- DSP in digital domain is omnipotent

Comparison and trade-offs

- BPF
  - Good Q (>25), excellent dynamic range
  - Blocks unwanted channels
- AGC amplifier
  - Only need to maintain in-channel linearity
  - Example gains: 1, 4, 16, 64, 250, 1000
  - Ensures \( V_{inBPF} \) to full range
- ADC
  - 6 bit is sufficient, this gives at least:
    - 16 quantization levels for \( 1/4 \) full range
    - Can do sub-sampling, \( \rightarrow \) low speed ADC: ADC speed >400KSPS

Comparison and trade-offs

- AGC amplifier
  - Need excellent dynamic range and wide band linearity
  - Example gains: 1, 4, 16, 250, 1000
  - Ensures \( V_{inBPF} \) to full range
- BPF
  - Good Q (>25), but no need for high dynamic range
  - Blocks unwanted channels
- ADC
  - 6 bit is sufficient, this gives at least:
    - 16 quantization levels for \( 1/4 \) full range
    - But need high-speed ADC: ADC speed >200MSPS
- BPF
  - Implement in DSP domain
- **BPF**
  - Good Q (>25), excellent dynamic range
  - Blocks unwanted channels
  - But ADC input ranges from sub mV to 1V
- **ADC**
  - High resolution is required
  - At least 16 bits to ensure 16 quantization levels for 1/4 mV weak signals
  - Narrow band allows sub-sampling, => low speed ADC: ADC speed >400KSPS
  - Currently 16 bit 1-5MSPS ADCs available
- **No AGC amplifier used**

**Mirror Signal**
- Upper sideband and lower sideband are identical

![Mirror Signal Diagram](image1)

**Mirror Signal**
- Upper sideband and lower sideband are not identical

![Mirror Signal Diagram](image2)

**Mirror Signal Suppression**
- Quadrature Down Conversion

![Mirror Signal Suppression Diagram](image3)

**Quadrature Conversion**

\[
a(t) = \cos(\omega_{LO} t + \theta)
\]
\[
u_i(t) = a(t) \cdot \cos(\omega_{LO} t + \theta)
\]
\[
u_q(t) = a(t) \cdot \sin(\omega_{LO} t + \theta)
\]
\[
u_r(t) = \frac{1}{2} \cos(m(t) + \phi - \theta)
\]
\[
u_q(t) = \frac{1}{2} \sin(m(t) + \phi - \theta)
\]
\[
\frac{v_r(t)}{v_q(t)} = \tan(-m(t) + \theta - \phi)
\]
\[
m(t) = -\tan^{-1}\left(\frac{v_q(t)}{v_r(t)}\right) + \theta - \phi
\]
Quadrature Down Conversion

**DC Offset (Self-mixing)**

\[ x_{\text{offset,DC}}(t) = A_{\text{mixer}}(\omega) \cdot a_{\text{loc}}(t) \cdot a_{\text{loc}}(t) \]
\[ = A_{\text{mixer}}(\omega) \cdot A_{\text{LO}} \cos(\omega t + \theta) \cdot A_{\text{LO}} \cos(\omega t + \theta) \]
\[ = 2 \cdot A_{\text{mixer}}(\omega) \cdot A_{\text{LO}}^2 \left( 1 + \cos(2(\omega t + \theta)) \right) \]

\[ x_{\text{offset,DC}}(t) = A_{\text{mixer}} \cdot A_{\text{LO}} \cdot \cos(\omega t + \theta) \cdot \cos(\omega t + \theta) \]
\[ = 2 \cdot A_{\text{mixer}} \cdot A_{\text{LO}}^2 \left( 1 + \cos(2(\omega t + \theta)) \right) \]

**DC Offset Cancellation**

- Capacitive Coupling
  - Requires a large capacitor
- Negative Feedback
  - Nonlinear
- TDMA Offset Cancellation
  - Requires a large capacitor

**I/Q Mismatch**

**Phase & Gain Error**

\[ x_{\text{IBB}}(t) = \frac{1 + E}{2} \cos(\omega t + \theta/2) \]
\[ x_{\text{QBB}}(t) = \frac{1 - E}{2} \sin(\omega t - \theta/2) \]

\[ x_{\text{IBB}}(t) = \frac{1 + E}{2} \cos(m(t) + \phi/2) \]
\[ x_{\text{QBB}}(t) = \frac{1 - E}{2} \sin(m(t) - \phi/2) \]

**Gain error**

\[ a(t) = A \cos(\omega t + m(t) + \phi) \]
Even-Order Distortion

\[ x_{\text{even}}(t) = \frac{1}{2}(1 + \epsilon) \cos \theta \frac{1}{2}(1 - \epsilon) \sin \theta \]

\[ x_{\text{odd}}(t) = -\frac{1}{2}(1 + \epsilon) \sin \theta \frac{1}{2}(1 - \epsilon) \cos \theta \]

Summary of Direct Conversion Receiver
- No need for imager reject filter
- Suitable for monolithic integration with baseband
- DC offsets due to crosstalk of input ports of mixer
- Even order IM direct feed through to baseband
- Quadrature down conversion suppresses mirror
- I/Q mismatch due to mismatches in parasitics
- Low power consumption attributed to less hardware

Low-IF Receivers
- Possible way to implant digital IF
- Low-IF cause image reject problem

Low-IF Down Conversion

Mirror Signal Suppression (1)
Image Reject Receiver

- Hartley Architecture

Graphical interpretation in spectral domain

IQ error effect

- Ideal IQ: image completely rejected
- If signal and image not single tone, 90° shift is not exact
- Local oscillator’s sine and cosine not matched in magnitude and phase
- 90° phase shifter may have both gain and phase error
- All lead to incomplete image rejection
90 degree phase shift

\[ \sin(\omega t) \xrightarrow{\text{90 degree phase shift}} -\cos(\omega t) \]

\[ \sin(\omega t) \xrightarrow{\text{90 degree phase shift}} -\cos(\omega t) \]

\[ +j/2 \quad \text{RF} \quad -j/2 \quad \omega \]

\[ 0 \quad \text{RF} \quad +j \quad 0 \quad \omega \]

\[ \times \]

\[ 0 \quad -j/2 \quad 0 \quad -1/2 \quad \omega \]

\[ \frac{1}{RC} = \omega_{RF} \]

Gain Mismatch Due to RC errors:

\[ \frac{\Delta A}{A} = \frac{1}{\sqrt{1 + (R + \Delta R)^2 (C + \Delta C)^2} \omega^2} \times \frac{1}{\sqrt{1 + R^2 C^2} \omega^2} \]

\[ \frac{\Delta A}{A} = \frac{\Delta R + \Delta C}{R^2 + \Delta R + \Delta C^2} \frac{1}{\sqrt{2}} \]

Image Reject Receiver

• Hartley Architecture

Image Reject Receiver

• Weaver Architecture

\[ x(t) = A_{RF} \cos(\omega_{RF} t + \theta_1) + A_{in} \cos(\omega_{in} t + \theta_2) \]

\[ x_R(t) = \frac{A_{RF}}{2} \sin(\omega_{LO1} - \omega_{RF} t - \theta_1) + \frac{A_{in}}{2} \sin(\omega_{LO1} - \omega_{in} t - \theta_2) \]

\[ x_L(t) = -\frac{A_{RF}}{2} \sin(\omega_{LO2} - \omega_{RF} t + \theta_1) + \frac{A_{in}}{2} \sin(\omega_{LO2} - \omega_{in} t + \theta_2) \]

\[ x_B(t) = \frac{A_{RF}}{2} \cos(\omega_{LO1} - \omega_{RF} t - \theta_1) + \frac{A_{in}}{2} \cos(\omega_{LO1} - \omega_{in} t - \theta_2) \]

\[ x_D(t) = \frac{A_{RF}}{2} \cos(\omega_{LO2} - \omega_{RF} t + \theta_1) + \frac{A_{in}}{2} \cos(\omega_{LO2} - \omega_{in} t + \theta_2) \]
\[
x_c(t) = x_j(t) \sin \omega_{\text{jLo}} t \\
= -\frac{A_{\text{tr}}}{4} \cos \left[ \omega_{\text{rf}} - \omega_{\text{jLo}} - \omega_{\text{jLo}} \right] t + \theta \] 
\]
\[
x_c(t) = x_j(t) \cos \omega_{\text{jLo}} t \\
= \frac{A_{\text{tr}}}{4} \cos \left[ \omega_{\text{rf}} - \omega_{\text{jLo}} - \omega_{\text{jLo}} \right] t + \theta \] 
\]
\[
x_{\text{input}}(t) = x_j(t) - x_c(t) = \frac{A_{\text{tr}}}{2} \cos \left[ \omega_{\text{rf}} - \omega_{\text{jLo}} - \omega_{\text{jLo}} \right] t + \theta \] 

**Weaver Architecture**

**Quadrature Weaver Architecture**

**Receiver Link Budget Analysis**

- Noise Figure Calculation
- IP3 Calculation
- Image Rejection Calculation
- Frequency Planning

**Noise Figure Calculation**

\[
SNR_{\text{max}} = \frac{E_s}{N_0} \Rightarrow SNR_{\text{max}} (dB) = \frac{E_s}{N_0} (dB) + 10 \log \left( \frac{R_{\text{ref}}}{BW} \right)
\]

\[
SNR = \frac{E_s}{N_0} \Rightarrow SNR_{\text{max}} (dB) = \frac{E_s}{N_0} (dB) + 10 \log \left( \frac{R_{\text{ref}}}{BW} \right)
\]

**Table: Receiver Link Budget Analysis**

<table>
<thead>
<tr>
<th>Standard</th>
<th>Bandwidth (MHz)</th>
<th>Sensitivity (dBm)</th>
<th>Noise Floor (dBm)</th>
<th>NF (dB)</th>
<th>SNR (dB)</th>
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</thead>
<tbody>
<tr>
<td>DECT</td>
<td>1.706-15.95</td>
<td>63.30</td>
<td>-60.00</td>
<td>29.30</td>
<td>56.00</td>
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<tr>
<td>GSM</td>
<td>2.086-3.08</td>
<td>59.00</td>
<td>-105.00</td>
<td>17.70</td>
<td>37.70</td>
</tr>
<tr>
<td>WLAN</td>
<td>2.085-5.56</td>
<td>35.01</td>
<td>-60.70</td>
<td>9.70</td>
<td>15.10</td>
</tr>
</tbody>
</table>
**IP3 Calculation**

\[
DR_d' = \frac{2(\text{IP}_{3} - P_d)}{3} - SNR_{\text{min}}
\]

\[
\text{IP}_{3} = \frac{3}{2} \left( DR_d' + SNR_{\text{min}} \right) + P_d
\]

\[
P_{\text{out}} = \text{IP}_{3} - 10
\]

<table>
<thead>
<tr>
<th>Standard</th>
<th>DR</th>
<th>SFDR</th>
<th>IP3</th>
<th>Pmax</th>
<th>Bandwidth</th>
<th>10log(BW)</th>
<th>Sensitivity(dBm)</th>
</tr>
</thead>
<tbody>
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<td>Bluetooth</td>
<td>50.00</td>
<td>36.57</td>
<td>-10.00</td>
<td>-20.00</td>
<td>1.00E+06</td>
<td>60.00</td>
<td>-70.00</td>
</tr>
<tr>
<td>GSM</td>
<td>87.00</td>
<td>61.67</td>
<td>-5.00</td>
<td>-15.00</td>
<td>2.00E+05</td>
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<tr>
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<td>6.00</td>
<td>-4.00</td>
<td>2.00E+06</td>
<td>63.01</td>
<td>-80.00</td>
</tr>
</tbody>
</table>

**Image Rejection Calculation**

\[
\text{IRR}_{\text{required}} = \text{P}_{\text{image}} - \text{P}_{\text{desired}} + SNR_{\text{min}}
\]