RF System Design

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Outline

- Circuits for Wireless
- Wireless Communications
  - duplex, access, and cellular communication systems
  - standards
- Receivers:
  - heterodyne
  - homodyne
  - image reject
- Transmitters
  - modulation
  - up-conversion
- Transceivers
  - frequency synthesis
  - examples
RF IC design

- Market Requirements
- Communication Theory
- Microwave techniques
- Modulation
- Discretes
- Standards
- Architectures
- IC design RF, mixed-mode, digital

TRANSCEIVER
Receiver
Freq. Synth.
Transmitter

Circuits for Wireless
Circuits for Wireless - Overview

- Noise limits the smallest signal
  - noise figure
  - cascade of stages
- Distortion limits the largest signal
  - large (interfering) signals:
    - compression, blocking, and desensitization
    - inter-modulation
    - cascade of stages
- Dynamic Range

Noise Figure

- Max. thermal noise power from linear passive network e.g. antenna: \( N_{\text{max}} = kT \cdot BW \)
- Noise Factor: \( F = \frac{(S / N)_{\text{in}}}{(S / N)_{\text{out}}} = 1 + \frac{N_{\text{added eq@input}}}{N_{\text{in}}} \)
- Noise Figure: \( NF = 10 \log_{10} (F) \geq 0 \text{dB} \)

<table>
<thead>
<tr>
<th>NF [dB]</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1.25</td>
</tr>
<tr>
<td>2</td>
<td>1.6</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

\((S/N)_{\text{out}} = 1/2 (S/N)_{\text{in}}\)
Cascade of Stages: Friis Equation

Avail. Power Gain: \( A_{p1} \)
Noise factor: \( F_1 \)

\[
F = 1 + (F_1 - 1) + \frac{(F_2 - 1)}{A_{p1}} + \frac{(F_3 - 1)}{A_{p1} A_{p2}}
\]

later blocks contribute less to the noise figure if they are preceded with gain

Noise of lossy passive circuit

- Lossy passive circuit (e.g. filter): \( F = \text{Loss} \)
- E.g. Band-select filter & LNA:

\[
F = F_{\text{filt}} + \frac{(F_{\text{LNA}} - 1)}{A_P}
\]

\[
F = L + \frac{(F_{\text{LNA}} - 1)}{1/L} = L \cdot F_{\text{LNA}}
\]

Loss adds immediately to noise figure!
**Sensitivity**

- sensitivity = minimal signal level that receiver can detect for a given (S/N) at the output:

\[
F = \frac{(S/N)_{\text{in}}}{(S/N)_{\text{out}}} = \frac{P_{\text{signal in}}}{P_{\text{noise in}}} \cdot \frac{1}{(S/N)_{\text{out}}}
\]

\[
P_{\text{signal in}} = F \cdot (S/N)_{\text{out}} \cdot P_{\text{noise in}}
= F \cdot (S/N)_{\text{out}} \cdot kT \cdot \text{BW}
\]

- E.g. GSM (BW=200kHz, (S/N)_{out} > 9dB):

\[
P_{\text{signal in}} = NF + (S/N)_{\text{out}} - 174 \text{dBm} / \text{Hz} + 10 \log_{10}(\text{BW})
= 6 + 10 - 174 + 53 = -105 \text{dBm}
\]

for a receiver with a noise figure of 6dB

---

**Distortion:**

- Circuits have non-linearities
  - hard: e.g. supply clipping
  - weak: \( y_{\text{out}} = G_1 \cdot x_{\text{in}} + G_2 \cdot x_{\text{in}}^2 + G_3 \cdot x_{\text{in}}^3 + \cdots \)
    \[ G_1 \gg G_2 \text{ & } G_1 \gg G_3 \]
- Effects:
  - Gain compression
  - Blocking & Desensitization
  - Inter-modulation: IP2 & IP3
- Cascade of stages
Gain Compression

Inter-modulation: 2nd order
Inter-modulation: 3rd order

\[ 2\omega_1 - \omega_2 \quad 2\omega_2 - \omega_1 \]

\[ P_{\text{out}} \, [\text{dBm}] \]

\[ P_{\text{in}} \, [\text{dBm}] \]

IIP\(_3\) for a cascade of stages

\[ \frac{1}{A_{\text{IIP}\,3}^2} \leq \frac{1}{A_{\text{IIP}\,3}^2} + \frac{G_{A1}^2}{A_{\text{IIP}\,3}^2} + \frac{G_{B1}^2 \cdot G_{C1}^2}{A_{\text{IIP}\,3}^2} \]

- worst-case approximation for narrow band systems!
- voltage/current levels and gains
- effect of non-linearities more important at later stages!
Spurious Free Dynamic Range

\[
\text{dynamic range} = \frac{\text{max. input level}}{\text{min. input level}}
\]

• under certain conditions:
  - min. level such that \((S/N)_{\text{out}}\) is sufficient
  - max. level such that:
    - effects of non-linearities are \(\leq\) noise
    - i.e. IM3 products \(\leq\) noise
• other applications use different conditions

Spurious Free Dynamic Range

\[
P_{\text{out}} [\text{dBm}]
\]

\[
P_{\text{in}} [\text{dBm}]
\]
Wireless Communications - Overview

• ‘ether’ is one medium shared by all
• 1\textsuperscript{st} problem: Duplexing
  - how to arrange for a two way communication link
• 2\textsuperscript{nd} problem: Multiple Access
  - how to arrange for multiple users
**Duplexing - Overview**

- Establish two way communications:
  - Time division duplex:
    - same rcv and xmt frequency channel
    - alternating in time between rcv & xmt
  - Frequency division duplex:
    - different frequency channel for rcv and xmt
    - full duplex possible

**Time Division Duplex (TDD)**

- peer to peer communications
- antenna switch
**TDD design issues**

+ mobile units can communicate
+ Switch low loss (<1dB)
+ XMT cannot desensitize RCV
- nearby XMT can overload RCV
+ channel leakage from P/A reduction by proper timing
  • packet based communication:
    - Synchronization & Buffering needed
    - digital implementation

**Frequency Division Duplex (FDD)**

- base station <> mobile unit
- no peer to peer communication
- duplex filter
**FDD design issues**

- duplexer loss (2~3dB)
  - adds directly to noise figure
  - reduces XMT efficiency
- duplexer isolation < ~50dB
  - still desensitization of RCV by XMT possible
+ less sensitive to nearby XMT
- direct XMT antenna connection
  - LO transients or P/A switch results in channel leakage
+ analog implementation

**Multiple Access - Overview**

- **Frequency Division Multiple Access (FDMA)**
  - divide band in channels & allocate different channel for each user
- **Time Division Multiple Access (TDMA)**
  - same channel for different users but each user accesses in a different time-slot
- **Code Division Multiple Access (CDMA)**
  - all users use same channel at same time but have a different code
- **Carrier Sense Multiple Access (CSMA)**
  - all users use same channel at different (random) times
**Frequency Division Multiple Access (FDMA)**

- each user is assigned a channel
- FDD & FDMA ➔ xmt & rcv channel
  + implementation can be done analog
  - you need high quality filters (loss...)

**Time Division Multiple Access (TDMA)**

- each user is assigned a slot
  - synchronization & data buffering ➔ digital
  + add coding, correction, compression ➔ capacity ↑
  + FDD & TDMA:
    - time RCV & XMT non-simultaneous ➔ advantages of TDD
Code Division Multiple Access (CDMA)

- each user has different code
  ~ speaks different language
- Direct Sequence Spread Spectrum
  - code used to encode data
- Frequency Hopping Spread Spectrum
  - code used to select frequency sequence

Carrier sense multiple access (CSMA)

- sense medium before transmit
  - if free, transmit information
  - if collision, back-off and re-send information
- system implications similar to TDMA
- BUT,
  + no synchronization necessary
  - no guaranteed bandwidth

  ➡ used for data communications
e.g. wireless LAN
Cellular Communications System

- large number of users
- cellular system
  - stations far enough ➔ frequency reuse
  - far ~ transmitted power
- Co-channel interference
  - ~ distance 2 co-channel cells/cell radius
  - power independent
  - 7 reuse: ratio = 4.6 (18dB)
- Base-station & mobile unit
  - forward/up link: base ➔ mobile
  - reverse/down link: mobile ➔ base
  - hand-off: switch base stations

Channel characteristics

- Path-loss:
  - propagation characteristics
- Multi-path fading:
  - direct & reflected signals interfere at rcv
- Delay Spread:
  - direct & delayed signals interfere

  ➔ fast & large variations in signal strength in moving receiver

  ➔ “frequency blocking” in stationary receiver
Standards - Some Examples

• Advanced Mobile Phone Service (AMPS)
• North American Digital Standard (NADS) IS-54
• IS-95 DS CDMA - Qualcomm CDMA
• Global System for Mobile Communications (GSM)
• Digital Enhanced Cordless Telephone (DECT)
• IEEE 802.11
• HiperLAN
• ..........

GSM

• Global System for Mobile Communications
• FDD:
  - RCV: 935-960 MHz
  - XMT: 890-915 MHz
• FDMA & TDMA:
  - 200 kHz Channels
  - frame = 8 slots: 4 rcv & 4 xmt
  - RCV & XMT slot offset by 3 time slots
  - data rate ~ 270kbits/sec
• GMSK modulation
  - constant envelope - BT=0.3
GSM Type approval (summary)

• Receiver
  - BER ~10^{-3} or S/N @ demodulator > 9dB
  - signal range: -102dBm to -15dBm
  for signal of -99dBm:
    - blocking: in band: -43 up to -23dBm
    out of band: 0dBm
  - inter-modulation: -49dBm @800kHz & @1600kHz
  for signal of -82dBm:
    - co-channel test: 9dB smaller interferer in same channel
    - adjacent channel (@200kHz): 9dB larger
    - alternate channel (@400kHz): 41dB larger

• Transmitter
  - close-in: modulation spectrum (spectral mask)
  - wide-band: noise spectrum e.g.
    • noise@3MHz < -115dBc/Hz
    • noise@6MHz < -130dBc/Hz
    • noise@25MHz < -130/-136dBc/Hz
  - average phase error < 5 deg.RMS
  - output power
    • up to 2-3 Watt: 33-35dBm
    • power control: 28dB
  - carrier leakage < 40dBc
Radio Receiver Problem (e.g. GSM)

- small signal: down to -102dBm
- narrow band signal: 200kHz on ~900MHz
- very hostile environment ➔ interference
  - e.g. blocking signals ~100dB larger than signal !!
Filter as RCV

- e.g. GSM  
  fo=900MHz  
  BW=200kHz
- Quality factor: ~4500  
  - high Q ➔ high loss ➔ high NF
- High rejection & sharp filter
- Tunable filter  
  - center frequency accuracy

No Filter Technology available

Heterodyne Receiver

- down-convert signal to lower fixed intermediate frequency (IF) for filtering  
  ➔ Q lower  
  ➔ fixed frequency
- Mixer  
  - $z_{out} = K \cdot x_{in} \cdot y_{in}$
  - frequency translation:
    - $x_{in} \oplus \omega_1$ & $y_{in} \oplus \omega_2$ ➔ $z_{out} \oplus |\omega_2 +/ - \omega_1|
  - conversion gain:  
    - CVG = $z_{out} / x_{in} = K \cdot y_{in}$
Heterodyne Receiver: IMAGES 

- $f_0 + f_{IF}$ & $f_0 - f_{IF}$ mix with $f_0$ to same $f_{IF}$
- potential interference
- add IMAGE REJECT FILTER before mixer

Heterodyne: choice of IF

- high IF  + more relaxed image filter
  + smaller IF filter
  - higher Q  ➔ higher loss
- multiple IFs: distribute channel filtering
- filter-amplify-filter-amplify
- gain at different frequencies: no oscillation risk
Mixer Spurious Responses

- image frequency
- feed-through to IF: (LO $\rightarrow$ IF and RF $\rightarrow$ IF)
- mixer: never only second but also higher order
  - e.g. spurious response table for double balanced mixer

<table>
<thead>
<tr>
<th>$f_{RF}$</th>
<th>6 $f_{LO}$</th>
<th>5 $f_{LO}$</th>
<th>4 $f_{LO}$</th>
<th>3 $f_{LO}$</th>
<th>2 $f_{LO}$</th>
<th>$f_{LO}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 $f_{RF}$</td>
<td>-100</td>
<td>-92</td>
<td>-97</td>
<td>-95</td>
<td>-100</td>
<td>-100</td>
</tr>
<tr>
<td>5 $f_{RF}$</td>
<td>-90</td>
<td>-84</td>
<td>-86</td>
<td>-72</td>
<td>-92</td>
<td>-70</td>
</tr>
<tr>
<td>4 $f_{RF}$</td>
<td>-90</td>
<td>-84</td>
<td>-97</td>
<td>-86</td>
<td>-97</td>
<td>-90</td>
</tr>
<tr>
<td>3 $f_{RF}$</td>
<td>-75</td>
<td>-63</td>
<td>-66</td>
<td>-72</td>
<td>-72</td>
<td>-58</td>
</tr>
<tr>
<td>2 $f_{RF}$</td>
<td>-70</td>
<td>-72</td>
<td>-72</td>
<td>-70</td>
<td>-82</td>
<td>-62</td>
</tr>
<tr>
<td>1 $f_{RF}$</td>
<td>-60</td>
<td>0</td>
<td>-35</td>
<td>-15</td>
<td>-37</td>
<td>-37</td>
</tr>
</tbody>
</table>

- frequency planning

Frequency Planning: spurious responses

- e.g. low side injection difference mixer
  - $f_{IF} = f_{LO} - f_{RF}$
  - e.g. GSM RCV
    - RF in: 925-960MHz
    - IF: 71MHz
    - LO: 996-1031MHz
- find all spur frequencies $f_s$
  - $|n f_s +/- m f_{LO}| = f_{IF}$
  - n: 0, 1, 2 ...; m: 0, 1, 2, ....
Spurious Responses

Channel frequency [MHz]

Spur Frequency [MHz] (LO order, RF order)

(2*996)-(2*960.5)=71

Desired Image

Spurious Responses (zoom)

Channel frequency [MHz]
Level Diagram

Band-limited signal: Complex envelope

\[ r(t) = a(t) \cdot \cos(\omega \cdot t + \phi(t)) \]
\[ r(t) = I(t) \cdot \cos(\omega \cdot t) - Q(t) \cdot \sin(\omega \cdot t) \]

\[ a(t) = \sqrt{I(t)^2 + Q(t)^2} \]
\[ \phi(t) = \tan^{-1}\left(\frac{Q(t)}{I(t)}\right) \]
Homodyne Receiver

- $f_{LO} = f_{RF} \rightarrow f_{IF} = 0$
- image = signal
- quadrature down-converter
- lowpass filter does channel selection

Homodyne design issues (1)

- Lowpass filters for channel selection
  - can be integrated on IC
  - high dynamic range required
    - preceded by limited gain or filtering
  - a lot of (programmable) gain at DC
    - parasitic feedback can cause stability problems
  - DC offset
  - 1/f noise
Homodyne design issues (2)

- Time-varying DC offsets
  - self-mixing
    - LO leakage
    - RF leakage
- LO emission
- I/Q mismatches

Homodyne design issues (3)

- Even order distortion
  - IM2@LNA -> LF signal -> mixer RF/IF feed-through
  - IM2@Mixer -> LF signal & DC
  - differential circuits
  - but P/A single-ended -> antenna SE -> LNA SE
  - single-ended to differential conversion at RF ....
Why not for IF

- Passive IF filters: high DR
- DC offset out of band: ac coupling
- IM2 out of band: ac coupling
- @IF 1/f noise low
- DC offset out of band
- $f_{LO} = f_{RF} +/\mathbf{- f}_{IF}$ : emission filtered
- Modern IF: zero-IF back-end to go into DSP

Image Reject Receiver: Hartley

- no IMR filter
- image rejection depends on
  - quadrature accuracy
  - gain matching
- 90 degrees shift in signal path
Image Reject Receiver: Weaver

- use 2\textsuperscript{nd} quadrature mixing stage instead of 90\textdegree{} shift
- additional secondary image

Transmitters
Transmitters - Overview

• Basic functions:
  - modulation:
    • encode the information on a waveform’s amplitude, phase or frequency
  - up-conversion:
    • move signal to desired RF carrier frequency
  - power amplification
    • amplify signal to deliver wanted power to antenna for emission

Direct VCO modulation

• only constant envelope modulation
• VCO in open loop during XMT
  - frequency drift
  - pushing/pulling
  - close-in VCO noise
  - switch time XMT/RCV includes lock time
• compact
**Quadrature Modulator**

- Any modulation format
  - see complex envelope
- But unwanted sideband when
  - non perfect quadrature
  - gain mismatches

\[
a(t) \cos(\omega_0 t) + a(t) \cos(\omega_0 t + \phi(t))
\]

\[
\sin(\omega_0 t)
\]

**Quadrature modulator: Side-band rejection**

\[
(1 + \Delta/2) \cos(\omega_{LO} t + \Delta\phi/2)
\]

\[
\cos(\omega_{IF} t) + \cos((\omega_{LO} + \omega_{IF}) t) + \gamma \cos((\omega_{LO} - \omega_{IF}) t)
\]

\[
(1 - \Delta/2) \sin(\omega_{LO} t - \Delta\phi/2)
\]

\[
\omega_{LO} \quad \omega_{IF} \quad \omega_{LO} \quad \omega_{LO} + \omega_{IF} \quad \omega_{LO} - \omega_{IF}
\]

\[
\text{Phase Error [dB]} \\
\text{Phase Error [deg]}
\]
**Multi-step Up-conversion**

- good image reject filter necessary
- potential for other spurs
- extra filter to reject broadband noise

\[
a(t) \cos(\omega_F t) + \phi(t) \sin(\omega_F t)
\]

**Direct Up-conversion**

- no IF and no spurs: relaxed filtering
- extra filter to reject broadband noise
- potential RF VCO re-modulation by P/A out
  - VCO shielding
- quadrature RF signal required

\[
a(t) \cos(\omega_R t) + \phi(t) \sin(\omega_R t)
\]
Indirect VCO modulation

- only constant envelope modulation
- loop filter BW > signal BW
- low broadband noise!
- Tx-VCO: high power & low noise (e.g. $P_{\text{out}}$ 10dBm typ. in GSM)
- potential for spurs

Power amplifier & output filters

- TDD: P/A - switch - antenna
  - ~1dB loss in switch
- FDD: P/A - duplexer - antenna
  - ~2-3dB loss in switch
  - 30-50% of P/A power dissipated in duplexer
- average efficiency P/A << 50%
  - depends strongly on modulation format
- $P_{\text{out}}/P_{\text{DC}} << 25%$
Frequency Synthesizer

• 3\textsuperscript{rd} subsystem in transceiver

- RCV:
  - phase noise level in side bands
  - discrete spurs

- XMT:
  - RMS phase error = integrated phase noise
  - wideband noise
  - discrete spurs
Transceiver Design

• **Meet the standard !!!!**
• Architecture selection and system design
  - Bill of materials
  - Frequency planning:
    • # VCOs & spurious responses
  - Power consumption:
    • Transmitter (P/A) talk time
    • Receiver standby time
  - Partitioning
    • Hardware/Software
    • Analog/Digital
• Time to market & Price & Package

GSM Transceiver Example

• Lucent Technologies W2020 [10]
Recent Transceiver Architectures

- Some Trends:
  - integration & cost reduction
  - dual band
  - multi standard
- Some Techniques
  - Zero-IF
  - Low-IF
  - Double Low-IF
  - Wide-band-IF
  - IF sampling
  - Δ−Σ decimation filter as channel select
  - Software Radio
  - ……..

Acknowledgments

- I would like to thank the following colleagues for stimulating discussions:
  - Kirk Ashby, Mihai Banu, Paul Davis, Jack Glas, Venu Gopinathan