Fundamental Concepts and Performance Measures in RF Transceiver Design

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RFICs in the System Context

Interferrers

Noise

Signal

Antenna

RF Spectrum Environment

Radio Transceiver Link
Topic Outline

- Fundamental Concepts
- Receiver Performance Measures
- Transmitter Performance Measures
Fundamental Concepts in RF Transceiver Design

- Radio Waves and Antennas
- Voltage, Power, and Impedance Levels
- Noise and Limits to Receiver Sensitivity
Radio Waves

Maxwell's Equations (source free):

\[
\begin{align*}
\text{Curl } E &= -\frac{\partial B}{\partial t} \\
\text{Curl } H &= \frac{\partial D}{\partial t} \\
B &= \mu H \\
D &= \varepsilon E
\end{align*}
\]

Plane Wave Solution:

\[
\begin{align*}
E &= E_x(z) \cos\left(\omega_o\left(t - \frac{z}{v_p}\right)\right) \\
H &= H_y(z) \cos\left(\omega_o\left(t - \frac{z}{v_p}\right)\right)
\end{align*}
\]

where \(v_p = \text{velocity of propagation}\)

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 kHz</td>
<td>300 km</td>
</tr>
<tr>
<td>1 MHz</td>
<td>300 m</td>
</tr>
<tr>
<td>1 GHz</td>
<td>0.3 m</td>
</tr>
</tbody>
</table>

Wavelengths

\[
\begin{align*}
\lambda &= \frac{v_p}{f} \\
v_p &= \frac{f}{\sqrt{\mu \varepsilon}} \\
v_p &= c = 2.997 \times 10^8 \text{ m/s in free space}
\end{align*}
\]
Generation and Reception of Radio Waves

No radiation from transmission line (fields cancel)

Voltage Source sets up currents in tx antenna

Currents Launch E and H Fields

Fields induce voltage/current in rx antenna
**RFIC Circuit Designer's View**

$$Z_A'$$

From RFIC Output

$$Z_0$$

mV to Volts

$$P_T$$

Watts

$$Z_L'$$

To RFIC Input

$$Z_A$$


**NOTES:**

Transmit antenna acts as an impedance $$Z_A$$
Receive antenna acts as a voltage source with Thevenin impedance $$Z_A$$

Transmission lines (and PC board traces, bondwires, lead-frames, etc) transform impedances at RF except under special situations.

No impedance transformation if line impedance $$Z_0$$ matches load $$Z$$
$$Z_0=50$$ Ohms is most common

Consider $$Z$$ transformations if length > wavelength/100 (3mm @ 1 GHz)
Typical Antenna Size and Impedance

Resonant Antennas

Dipole

\[ \frac{\lambda}{2} \]

\[ \vec{73+j0} \]

Monopole

\[ \frac{\lambda}{4} \]

\[ \vec{36+j0} \]

Commercial Various Shapes

\[ \vec{50+j0} \]

Non-Resonant Antennas

**50 Ohm Systems**

Vo = $\frac{1}{2} V_s$

Pt = $\frac{V_o^2}{50}$

Vi = $\frac{1}{2} V_{oc}$

Pr = $\frac{V_i^2}{50}$
Representative Voltage and Powers

Transmitted Power and Voltages in 50 Ohm Systems

<table>
<thead>
<tr>
<th>Application</th>
<th>Pout</th>
<th>Vout</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cordless</td>
<td>1mW</td>
<td>0.22</td>
</tr>
<tr>
<td>SS Cordless</td>
<td>0.1W</td>
<td>2.23</td>
</tr>
<tr>
<td>Cellular</td>
<td>0.6W</td>
<td>5.48</td>
</tr>
<tr>
<td>Base</td>
<td>10W</td>
<td>22.4</td>
</tr>
</tbody>
</table>

Simplified Link Equations

\[ P_{\text{density}} = \frac{P_i G_t}{4\pi R^n} \]

\[ P_{\text{rcvd}} = P_{\text{density}} A_{\text{eff}} \]

Received Power and Voltages in 50 Ohm Systems

<table>
<thead>
<tr>
<th>Prvcd</th>
<th>Vrvcvd</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 fW</td>
<td>224 nV</td>
</tr>
<tr>
<td>1 pW</td>
<td>7.07 uV</td>
</tr>
<tr>
<td>1 nW</td>
<td>224 uV</td>
</tr>
<tr>
<td>1 uW</td>
<td>7.07 mV</td>
</tr>
</tbody>
</table>

where \( G_t \) = antenna gain, \( n = 2 \) (free space) to 4, and \( A_{\text{eff}} = \text{effective area of antenna}(A_{\text{eff}} \sim \frac{\lambda^2}{4}) \) for dipole
**Power in dBm and dBW**

\[
P_{dBW} = 10 \log(P)
\]

\[
P_{dBm} = 10 \log\left(\frac{P}{1mW}\right)
\]

### Example Transmitted Powers in dBW and dBm

<table>
<thead>
<tr>
<th>Ptx</th>
<th>P(_{dBW})</th>
<th>P(_{dBm})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mW</td>
<td>-30</td>
<td>0</td>
</tr>
<tr>
<td>100 mW</td>
<td>-10</td>
<td>20</td>
</tr>
<tr>
<td>10 W</td>
<td>10</td>
<td>40</td>
</tr>
</tbody>
</table>

### Example Received Powers in dBm

<table>
<thead>
<tr>
<th>P(_{rcvd})</th>
<th>P(_{dBm})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 fW</td>
<td>-120</td>
</tr>
<tr>
<td>1 pW</td>
<td>-90</td>
</tr>
<tr>
<td>1 nW</td>
<td>-60</td>
</tr>
<tr>
<td>1 uW</td>
<td>-30</td>
</tr>
</tbody>
</table>
**Noise in Communication Systems**

**Sources of Noise:**
- **Antenna Noise** \( P_n = k T_A B \)
- **Circuit Noise** \( i_n^2 = 4 k T B \frac{1}{R} \) or \( i_n^2 = 2 q I_{DC} B \)

where:
- \( k = \) Boltzmann's constant (1.38E-23 J/K)
- \( B = \) Bandwidth in Hz
- \( q = \) Electronic charge (1.602E-19C)
- \( T \) is in Kelvin (typically 290K)

**NOTE:** Best possible sensitivity of receiver is: \( (k T_A B)(F)(S/N_{\text{min}}) \)
where \( B \) is signal bandwidth, \( F \) is noise figure of receiver, and \( S/N_{\text{min}} \) is minimum acceptable \( S/N \) at demod.

**in dBm:** Sensitivity = \(-174 + 10 \log(B) + NF + C/N_{\text{min}} \) (if \( T_A = 290K \))
Receiver Performance

- The Spectrum Environment
- Selectivity and Image Rejection
- Weak Signal Performance
- Strong Signal Performance
- Dynamic Range and Power Consumption
- Example System Design
The RF Spectrum Environment

Spectrum in Suburban Area (80 MHz to 180 MHz)
Reference Level = -30 dBm  Vertical Scale = 10 dB per Division
**Basic Design Requirements**

**Design Requirements:**

- Amplify (weak) desired signal
- Filter out interferers
- Minimize internally generated noise
- Limit bandwidth to maximize S/N and sensitivity
- Demodulate signal
Early Tuned-RF Receiver

British Patent No. 147,147

Problems:

All amplification at RF -> gain & stability problems
Filters must be retuned when changing channels
Limited selectivity
Armstrong's Heterodyne Design

Advantages

- Amplification at two different frequencies
- Easier to get high gain at lower intermediate frequency
- Tuned by changing LO frequency
- Better selectivity (high-quality, fixed-tuned IF filter)

* $f_{RF} + f_{LO}$ and other frequencies also, but filtered out
The Image Problem

\[ f_{RF} = 915 \text{ MHz} \]
\[ f_{\text{Image}} = 893.6 \text{ MHz} \]
\[ f_{\text{IF}} = 10.7 \text{ MHz} \]
\[ f_{\text{LO}} = 904.3 \text{ MHz} \]

Problem: 915 and 893.6 MHz both produce 10.7 MHz when mixed with 904.3 MHz

Solution: Filter out image frequency before mixer (or use "image reject" mixer)

Image Rejection: Amount that image frequency is attenuated
Selectivity

NOTES:

Typical adj chan selectivity = 20 dB, alt chan selectivity = 60 dB
Adjacent channel may not be used in same geographic area
or, "guard bands" may be used at edges of channels
Modern Superhet Design

- Preselct Filter
- Image Filter
- Mixer
- IF Filter
- IF Amps
- ADC / Demod
Weak Signal Performance

Desired Signal $P_s$  Antenna

Noise $P_n=kTB$

Transmission Line $G=-1dB$

Preselect Filter $G=-2dB$

LNA $G=10dB$

Image Filter $G=-3dB$

Power in pW

4
1

S/N=4 (6 dB)

2
1

S/N=2 (3 dB)

20
12
10

S/N=1.67 (2.2 dB)

6.5
6

S/N=1.54 (1.9 dB)

NOTES:

Losses before LNA degrade S/N and sensitivity significantly.
LNA amplifies signal above noise floor (adding some noise).
Later losses produce (ideally) little additional degradation.
Noise Figure

Degradation in S/N and receiver sensitivity is quantified by

"Noise Factor" \( F \) and "Noise Figure" (NF):

\[
F \equiv \frac{S/N @ input}{S/N @ output}
\]

\[
NF \equiv 10 \log(F) \text{ dB}
\]

Applications:

\[
S/N @ output = \frac{S/N @ input}{F} \quad \text{or in dB,} \quad S/N @ output = S/N @ input - NF
\]

\[
\text{Rcvr sensitivity} = \text{Ideal sensitivity} + \text{Rcvr NF}
\]

Typical "Good" values range from 1 to 6 dB for LNA and 1 to 8 dB for receiver as a whole.
Noise Figure Evaluations

Passive Components (tr-line, filter, etc.)

\[
F = \frac{S/N @ \text{input}}{S/N @ \text{output}} = \frac{S_{in}}{S_{out}} \times \frac{N_{out}}{N_{in}} = \frac{S_{in}}{S_{out}} = \frac{1}{\text{Gain}} \quad \rightarrow \quad NF = \text{InsertionLoss(dB)}
\]

Active Components (LNA, active mixer, etc.)

\[
F = \frac{S/N @ \text{input}}{S/N @ \text{output}} = \frac{S_{in}}{S_{out}} \times \frac{N_{out}}{N_{in}} = \frac{1}{\text{Gain}} \times \frac{(\text{Gain})(N_{in}) + N_{out\_excess}}{N_{in}} = 1 + \frac{N_{out\_excess}}{(\text{Gain})N_{in}}
\]

NOTES:
For good LNA, \(N_{out\_excess} < (\text{Gain})(N_{in})\), so \(F < 2\) \((NF < 3\ \text{dB})\)
For mixer, situation is more complex. See lecture on mixers.
Receiver System Noise Figure

\[ F_{rcvr} = F_1 + \frac{F_2-1}{G_1} + \frac{F_3-1}{G_1G_2} + \frac{F_4-1}{G_1G_2G_3} + \frac{F_5-1}{G_1...G_4} + \frac{F_6-1}{G_1...G_5} \]

\[ = 2 + 2 + 0.2 + 3.6 + 0.04 + 0.46 \]

\[ = 8.3 \quad \Rightarrow \quad \text{NF} = 9.2 \text{ dB} \]

NOTE:

Losses ahead of LNA hurt noise figure
LNA gain in this design is low, leading to big hit from mixer
Additional Notes on Noise Figure

- Noise Figure usually assumes $N_{in} = kT_oB$ with $T_o = 290$ K (This is called “Standard Noise Figure”)

- Standard Noise Figure works well for terrestrial links, but is not appropriate for satellite receivers with directional antennas where $T_A \neq 290K$.

- For satellite receivers, use “Operational Noise Figure” $F_{op}$ which assumes $N_{in} = kT_A B$, (where $T_A$ may be 30 to 100 Kelvin).

- $F_{op}$ for receiver can be found from $F$ for receiver from:

$$F_{op} = 1 + (F - 1) \frac{T_o}{T_A}$$

- For satellite receivers, “Noise Temperature” is often used in place of noise figure. (See references)
Strong Signal Performance

Basic Dynamic Range Problem

Weak Signal (-100dBm)

Strong Signal
-20dBm

Blocking Dynamic Range Problem

Weak Desired Signal @ fo

Strong Signal @ f1

Intermod Dynamic Range Problem

Weak Desired Signal @ fo

Strong Signals @ f1 & f2
Basic Dynamic Range Problem

Effects
- Loss of amplitude modulation
- Distortion of phase

Solutions
- Use higher power LNA
- Decrease LNA gain
- Use FM/FSK modulation

NOTE
- Could occur in later stages also
Blocking Problem

Effects
Gain compression in LNA
Desired signal below noise floor at output

Solutions
Use higher power LNA
Decrease LNA gain
Filter out f1 before LNA

NOTE
Could occur in later stages also
Intermod Problem

Effects
LNA generates "intermod products" at \(2f_2-f_1\) & \(2f_1-f_2\). Product at \(2f_1-f_2 = f_0\) overpowers desired signal.

Solutions
Use higher power LNA.
Decrease LNA gain.
Filter out \(f_1, f_2\) before LNA.

NOTE
Could occur in later stages also (especially mixer.)
Expand $v_o$ vs $v_i$ in a Maclaurin series:

$$v_o = A_1 \ v_i + A_2 \ v_i^2 + A_3 \ v_i^3 + ...$$

Small Signal Output  Non-Linear Distortion Terms
Single-Tone Case

Let \( v_i = V \cos(\omega_0 t) \)

Then:

\[
 v_o = A_1 v_i + A_2 v_i^2 + A_3 v_i^3 + ... \\
= A_1 V \cos(\omega_0 t) + \\
\frac{A_2}{2} V^2 [1 + \cos(2\omega_0 t)] + \\
\frac{A_3}{4} V^3 [3 \cos(\omega_0 t) + \cos(3\omega_0 t)] + \\
... \\
\text{Expected small signal output} + \\
\text{Rectification + 2nd harmonic} + \\
\text{Gain compression} + 3rd harm \\
\text{Additional harmonics, etc.}
\]

*Assuming \( A_3 < 0 \)
**1dB Compression Points**

![Diagram showing the relationship between input power, output power, and the 1dB compression point.](image)

**Plot of fundamental frequency output power vs input tone power**

**NOTE**

\[ P_{c_o} \text{ is typically 0.1 to 0.5 of DC power consumption} \]

\[ P_{c_i} = P_{c_o} - \text{Gain (in dB, dBm units)} \]
**Two-Tone Case**

Let \( v_i = V \cos(\omega_1 \ t) + V \cos(\omega_2 \ t) \)

Then:

\[
v_o = A_1 \ v_i + A_2 \ v_i^2 + A_3 \ v_i^3 + \ldots
\]

\[
= A_1 [V \cos(\omega_1 \ t) + V \cos(\omega_2 \ t)] + \\
DC \ offset \ and \ harmonic \ terms + \\
(const)(V^3)[\cos(2\omega_1 - \omega_2) + \cos(2\omega_2 - \omega_1)] + \\
higher \ order \ terms
\]
The Intermod Problem

Can occur in any circuits up to last IF filter. Typically occurs at lower power than blocking problems. Can be mitigated with good preselect filters if interferers are out-of-band. Cannot be filtered if interferers are close to desired signal frequency. Requires higher power LNA, mixer, etc.
Quantifying Intermod Products

For two-tone input:
\[ v_i = V \cos(\omega_1 t) + V \cos(\omega_2 t) \]
\[ v_o = A_1 V \left[ \cos(\omega_1 t) + \cos(\omega_2 t) \right] + (\text{const}) \left( V^3 \right) \left[ \cos(2\omega_1 - \omega_2) + \cos(2\omega_2 - \omega_1) \right] + \text{additional terms} \]

<table>
<thead>
<tr>
<th>Component of Output</th>
<th>Voltage at Output</th>
<th>Power at Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Desired” Signals</td>
<td>[ V_{o1} = A_1 V ]</td>
<td>[ P_{o1} = P_i + \text{const} ]</td>
</tr>
<tr>
<td>Intermods</td>
<td>[ V_{o3} = (\text{const})V^3 ]</td>
<td>[ P_{o3} = 3P_i + \text{const} ]</td>
</tr>
</tbody>
</table>

NOTE: \( P_{o3} \) (power in third-order products) increases 3 times faster than \( P_{o1} \) (power in input signals).
Third Order Intercept Points

Plot P1 and P3 versus Pi at low Pi
Extrapolate to find intercept

Note that
IIP3 = OIP3 - Gain

OIP3 often spec'd since it is higher !!

IIP3 is called the "3rd order Input Intercept Point"
OIP3 is called the "3rd order Output Intercept Point"
Spectrum Analyzer Displays

Low Pi. Intermods at noise floor

Increased Pi. Intermods above noise.

Pi increased by 2 dB. Intermods by 6dB.

High Pi. Higher order products present.
Dynamic Range

At input power $P_{i3}$, 3rd order products fall below noise floor. Difference of this and receiver sensitivity is "Spurious Free Dynamic Range" (SFDR).

1dB compression dynamic range uses compression point ($P_c$) as maximum level and is higher than SFDR.

Total dynamic range (using maximum acceptable input signal) may be significantly higher than both, since compression is acceptable in FM/FSK systems.
Estimating Receiver IIP3 & P_{ci}

\[ \text{IL} = 3 \text{dB} \quad \text{G} = 20 \text{dB} \quad \text{IL} = 3 \text{dB} \quad \text{G} = 15 \text{dB} \quad \text{IL} = 10 \text{dB} \]

- OIP3 = +15 dBm
- P_{co} = 0 dBm
- OIP3 = +15 dBm
- P_{co} = +10 dBm

\[ \text{ADC / Demod} \]

No interferers (ideally) get past final IF filter

<table>
<thead>
<tr>
<th>Component</th>
<th>P_{co}</th>
<th>OIP3</th>
<th>Cumulative Gain (G_c)</th>
<th>P_{ci} = P_{co} - G_c</th>
<th>IIP3 = OIP3 - G_c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preselect Filter</td>
<td>-</td>
<td>-</td>
<td>-3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>LNA</td>
<td>0</td>
<td>15</td>
<td>17</td>
<td>-17</td>
<td>-2</td>
</tr>
<tr>
<td>Image Filter</td>
<td>-</td>
<td>-</td>
<td>14</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mixer</td>
<td>10</td>
<td>15</td>
<td>29</td>
<td>-19</td>
<td>-14</td>
</tr>
</tbody>
</table>

Overall receiver P_{ci} \approx -19 dBm (limited by mixer)

Overall receiver IIP3 \approx -14 dBm (limited by mixer)
Transmitter Performance Issues

- Basic Requirements
- Block Diagrams
- Frequency Stability
- Harmonic and Spurious Emissions
Basic Requirements

Generate RF output at proper frequency.
Amplify to desired power level.
Limit out-of-band / off-channel emissions.
Maximize efficiency to increase "talk time".
Typical Block Diagram

Voice/Data → Modulator → Driver → PA → To RX → Antenna
Frequency Stability

Example Requirements: (900 MHz AMPS cellular service)

Center frequency 824 - 849 MHz
Channel width 30 kHz => Stability = +/- 2.4 ppm over temperature!
Accuracy needed +/- 2 kHz (Less severe for wideband services)

Solutions:

Crystal-controlled frequency synthesis
Temperature controlled/compensated crystal reference
Power Amplifier Basics

\[ P_{dc} = V_{dc} I_{dc} \]

\[ P_o = P_i G \leq P_{co} < P_{dc} \]

Basic Efficiency = \( \frac{P_o}{P_{dc}} \)

To Maximize Talk-Time:

- Run \( P_o \) close to output compression point \( P_{co} \)
- Design PA for high efficiency
- Limit \( P_o \) to that needed for communication (power control)
Harmonic / Spurious Emissions

Minimize/filter synthesizer and modulator spurious outputs

Filter PA output to attenuate harmonics and out-of-band noise

Harmonics and spurious are often spec'ed in terms of "dBc" (dB relative to carrier)
Spectral Regrowth and ACPR

PA running close to compression point spreads spectrum

Adjacent Channel Power Ratio (ACPR) gives ratio of power in adjacent and desired channels

Solutions:
Back off Po in PA relative to compression point.
Design modulation to minimize spectral regrowth.
Do not use adjacent channels in same cell.
For More Information ...


- Various data sheets and application notes on RFICs available on the web.