Modern Standards and Distortion
Transmit/Receive Schemes

• Time Division Duplex (TDD)
  – Example: GSM
  – TX/RX in the same/separate bands. Antenna is switched between TX and RX on millisecond scales.

• Frequency Division Duplex (FDD)
  – Example: CDMA/LTE
  – TX and RX are simultaneously operating at separate bands. Require a duplexer to isolate the bands.
Basic FDD System

RF → Duplexer → LNA → IRF → LO1 → cos, sin

IF → LPF → ADC

IF → LPF → ADC

Q → ADC

I → ADC
# LTE-A Frequency Bands

<table>
<thead>
<tr>
<th>Operating Band</th>
<th>Uplink (UL) operating band BS receive/UE transmit</th>
<th>Downlink (DL) operating band BS transmit /UE receive</th>
<th>Duplex Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1920 MHz – 1980 MHz</td>
<td>2110 MHz – 2170 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>2</td>
<td>1850 MHz – 1910 MHz</td>
<td>1930 MHz – 1990 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>3</td>
<td>1710 MHz – 1785 MHz</td>
<td>1805 MHz – 1880 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>4</td>
<td>1710 MHz – 1755 MHz</td>
<td>2110 MHz – 2155 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>5</td>
<td>824 MHz – 849 MHz</td>
<td>869 MHz – 894 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>6</td>
<td>830 MHz– 840 MHz</td>
<td>865 MHz – 875 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>7</td>
<td>2500 MHz – 2570 MHz</td>
<td>2620 MHz – 2690 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>8</td>
<td>880 MHz – 915 MHz</td>
<td>925 MHz – 960 MHz</td>
<td>FDD</td>
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<tr>
<td>9</td>
<td>1749.9 MHz – 1784.9 MHz</td>
<td>1844.9 MHz – 1879.9 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>10</td>
<td>1710 MHz – 1770 MHz</td>
<td>2110 MHz – 2170 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>11</td>
<td>1427.9 MHz – 1447.9 MHz</td>
<td>1475.9 MHz – 1495.9 MHz</td>
<td>FDD</td>
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<tr>
<td>12</td>
<td>698 MHz – 716 MHz</td>
<td>728 MHz – 746 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>13</td>
<td>777 MHz – 787 MHz</td>
<td>746 MHz – 756 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>14</td>
<td>788 MHz – 798 MHz</td>
<td>758 MHz – 768 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>15</td>
<td>Reserved</td>
<td>Reserved</td>
<td>-</td>
</tr>
<tr>
<td>16</td>
<td>Reserved</td>
<td>Reserved</td>
<td>-</td>
</tr>
</tbody>
</table>

Verizon uses Band 2, 4, 13
## GSM

<table>
<thead>
<tr>
<th>System</th>
<th>Band</th>
<th>Uplink (MHz)</th>
<th>Downlink (MHz)</th>
<th>Channel number</th>
<th>Equivalent UMTS/LTE band</th>
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</thead>
<tbody>
<tr>
<td>T-GSM-380</td>
<td>380</td>
<td>380.2–389.8</td>
<td>390.2–399.8</td>
<td>dynamic</td>
<td></td>
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<tr>
<td>T-GSM-410</td>
<td>410</td>
<td>410.2–419.8</td>
<td>420.2–429.8</td>
<td>dynamic</td>
<td></td>
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<tr>
<td>GSM-450</td>
<td>450</td>
<td>450.6–457.6</td>
<td>460.6–467.6</td>
<td>259–293</td>
<td>31</td>
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<tr>
<td>GSM-480</td>
<td>480</td>
<td>479.0–486.0</td>
<td>489.0–496.0</td>
<td>306–340</td>
<td></td>
</tr>
<tr>
<td>GSM-710</td>
<td>710</td>
<td>698.2–716.2</td>
<td>728.2–746.2</td>
<td>dynamic</td>
<td>12</td>
</tr>
<tr>
<td>GSM-750</td>
<td>750</td>
<td>777.2–792.2</td>
<td>747.2–762.2</td>
<td>438–511</td>
<td></td>
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<tr>
<td>T-GSM-810</td>
<td>810</td>
<td>806.2–821.2</td>
<td>851.2–866.2</td>
<td>dynamic</td>
<td>27</td>
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<tr>
<td>GSM-850</td>
<td>850</td>
<td>824.2–849.2</td>
<td>869.2–893.8</td>
<td>128–251</td>
<td>5</td>
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<tr>
<td>P-GSM-900</td>
<td>900</td>
<td>890.0–915.0</td>
<td>935.0–960.0</td>
<td>1–124</td>
<td></td>
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<tr>
<td>E-GSM-900</td>
<td>900</td>
<td>880.0–915.0</td>
<td>925.0–960.0</td>
<td>975–1023, 0-124</td>
<td>8</td>
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<tr>
<td>R-GSM-900</td>
<td>900</td>
<td>876.0–915.0</td>
<td>921.0–960.0</td>
<td>955–1023, 0-124</td>
<td></td>
</tr>
<tr>
<td>T-GSM-900</td>
<td>900</td>
<td>870.4–876.0</td>
<td>915.4–921.0</td>
<td>dynamic^</td>
<td></td>
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<tr>
<td>DCS-1800</td>
<td>1800</td>
<td>1,710.2–1,784.8</td>
<td>1,805.2–1,879.8</td>
<td>512–885</td>
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<td>PCS-1900</td>
<td>1900</td>
<td>1,850.2–1,909.8</td>
<td>1,930.2–1,989.8</td>
<td>512–810</td>
<td>2</td>
</tr>
</tbody>
</table>

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Implications

• GSM 33 dBm transmit power (TDD) 30 dB path loss so 1m away the power is 0 dBm at 800 MHz. This means that you have a 0 dBm blocker

• LTE with TDD/FDD still uses 24 dBm max power. LTE 2.7 GHz and higher path loss is higher. In TD LTE systems, -15 dBm.

• Duplex offset . 40/50 , 80/100 MHz. center to center
Distortion in Cellular Systems

- Signals are represented as “CW” signals. This isn’t really true. We can interpret two ways:
  1) Each CW signal is a wideband modulated signal.
  2) Each wideband modulated signal is modelled with a multitone (two tones) within 1 BW.
In-band (IB) and Out-of-band (OOB) Distortion

- TX blockers are typically considered to be around 0 dBm (for GSM) or 10 dBm (for 3GPP/4G)
- RX blockers are typically around -40 dBm
Effect of Device Nonlinearity: Harmonic Distortion

\[ v_{in} = V_{pk} \cos(\omega_o t) \]

\[ i_{out} = \sum_{k=1}^{3} g_{m,k} \left( V_{pk} \cos(\omega_o t) \right)^k \]

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Solving for Basic Harmonic Distortion

\[ i_{out} = \frac{g_{m,2}}{2} V_{pk}^2 + \left( g_{m,1} V_{pk} + \frac{3g_{m,3}}{4} V_{pk}^3 \right) \cos(\omega_o t) \]

\[ + \frac{g_{m,2}}{2} V_{pk}^2 \cos(2\omega_o t) + \frac{g_{m,3}}{4} V_{pk}^3 \cos(3\omega_o t) \]

• Features??
Defining Harmonic Distortion

\[ HD2 = \frac{\text{Signal at } 2\omega_o}{\text{Signal at } \omega_o} = \frac{1}{2} \left| \frac{g_{m,2}}{g_{m,1}} \right| V_{pk} \]

\[ HD3 = \frac{\text{Signal at } 3\omega_o}{\text{Signal at } \omega_o} = \frac{1}{4} \left| \frac{g_{m,3}}{g_{m,1}} \right| V_{pk}^2 \]

• Total Harmonic Distortion

\[ THD = \sqrt{|HD2|^2 + |HD3|^2 + \ldots} \]
Gain Compression

\[ 20 \log_{10} \left( \frac{g_{m,1} V_{pk} + \frac{3}{4} g_{m,3} V_{pk}^3}{g_{m,1} V_{pk}} \right) = -1 \]

\[ V_{1dB} = \sqrt{0.11} \left[ \frac{4}{3} \left| \frac{g_{m,1}}{g_{m,3}} \right| \right] \]
Intermodulation Distortion

\[ |V_{in}| \rightarrow f \quad f_1, f_2 \quad \rightarrow |V_{out}| \]

\[ i_{in} \rightarrow LNA \rightarrow i_{out} \]

\[ V_{in} \quad \downarrow \quad V_{out} \quad R_L \]
Effect of Device Nonlinearity: Intermodulation Distortion

\[ v_{in} = V_{pk} \left[ \cos(\omega_1 t) + \cos(\omega_2 t) \right] \]

\[ i_{out} = \sum_{k=1}^{3} g_{m,k} V_{pk}^k \left[ \cos(\omega_1 t) + \cos(\omega_2 t) \right]^k \]
Solve for Intermodulation Distortion (I)

\[ i_{out} = g_{m,1} V_{pk} \left[ \cos(\omega_1 t) + \cos(\omega_2 t) \right] \]
\[ + g_{m,2} V_{pk}^2 \left[ \cos(\omega_1 t) + \cos(\omega_2 t) \right]^2 \]
\[ + g_{m,3} V_{pk}^3 \left[ \cos(\omega_1 t) + \cos(\omega_2 t) \right]^3 \]
Solve for Intermodulation Distortion (II)

\[ i_{out} = g_{m,1} V_{pk} \left[ \cos(\omega_1 t) + \cos(\omega_2 t) \right] \]

\[ + g_{m,2} V_{pk}^2 \left[ \cos(\omega_1 t) + \cos(\omega_2 t) \right]^2 \]

\[ + g_{m,3} V_{pk}^3 \left[ \cos(\omega_1 t) + \cos(\omega_2 t) \right]^3 \]

\[ + \frac{1}{4} g_{m,3} V_{pk}^3 \left[ \cos(3\omega_1 t) + 3\cos(\omega_1 t) + \cos(3\omega_2 t) + 3\cos(\omega_2 t) \right] \]

\[ + \frac{3}{2} g_{m,3} V_{pk}^3 \left[ \cos(\omega_1 t) + \frac{1}{2}\cos((2\omega_1 - \omega_2) t) + \frac{1}{2}\cos((2\omega_1 + \omega_2) t) \right] \]

\[ + \frac{3}{2} g_{m,3} V_{pk}^3 \left[ \cos(\omega_2 t) + \frac{1}{2}\cos((2\omega_2 - \omega_1) t) + \frac{1}{2}\cos((2\omega_2 + \omega_1) t) \right] \]
Picture of distortion generated from two tones
Definition of Intermodulation Distortion

\[ IM\,2 = \frac{\text{Signal at } \omega_1 - \omega_2}{\text{Signal at } \omega_1} = \left| \frac{g_{m,2}}{g_{m,1}} \right| V_{p_k} \]

\[ IM\,3 = \frac{\text{Signal at } 2\omega_1 - \omega_2}{\text{Signal at } \omega_1} = \frac{3}{4} \left| \frac{g_{m,3}}{g_{m,1}} \right| V_{p_k}^2 \]
Graph of IM3 Products
IM3 Issues with FDMA systems

- IM3 tone generated by 2 jammers in adjacent channels will fall into desired signal channel.
- Typically, we desire to keep the IM3 tone at least 20 dB below the desired signal.
Input-Intercept/Output-Intercept Points

- 3rd-order Input-intercept Point (IIP3)
- 3rd-order Output-intercept Point (OIP3)
Definition of the Input Intercept Point

\[
\text{Signal at } 2w_1 - w_2 = \text{Signal at } w_1
\]

\[
\frac{3}{4} |g_{m,3}| V_{pk}^3 = |g_{m,1}| V_{pk}
\]

\[
IIP_3 = \sqrt{\frac{4}{3}} \left| \frac{g_{m,1}}{g_{m,3}} \right|
\]
Note the Relationship between IIP3 and P1dB

\[ V_{1dB} = \sqrt{0.11} \sqrt{\frac{4}{3} \left| \frac{g_{m,1}}{g_{m,3}} \right|} \quad IIP3 = \sqrt{\frac{4}{3} \left| \frac{g_{m,1}}{g_{m,3}} \right|} \]

• Factor in front of the 1dB voltage suggests that the 1dB compression occurs \(9.6\,\text{dB}\) below IIP3.

• A cruder rule of thumb is that IIP3 is 10 dB higher than P1dB.
Jammer Linearity Requirement

- Non-linearity in gain
  \[ v_o = g_1 v_i + g_2 v_i^2 + g_3 v_i^3 \]
  \[ IIP3 = \sqrt{\frac{4}{3} \frac{g_1}{g_3}} \]

- In terms of power
  \[ IM3 = \frac{3}{4} \frac{g_3 V_j^3}{g_1 V_j} = \frac{4}{3} \frac{g_3 V_j^2}{g_1} \]
  \[ \rightarrow \frac{P_J}{P_{IIP3}} = IM3 \]
  \[ \rightarrow 10 \log_{10} P_J - 10 \log_{10} P_{IIP3} = \frac{1}{2} \cdot 20 \log_{10} IM3 \]
  \[ P_J = P_{IIP3} + \frac{IM3}{2} \]

Factor of two because IM3 is based on ratio of voltage

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Jammer Rejection

\[ P_{\text{IIP3}} = P_J \frac{IM3}{2} \quad \text{or} \quad IM3 = 2(P_J - P_{\text{IIP3}}) \]

Since \[ IM3 = P_{\text{IM3}} \cdot P_J \]

\[ P_{\text{IIP3}} = P_J \frac{P_{\text{IM3}}}{2} \cdot \frac{P_J}{2} = \frac{3}{2} P_J \cdot \frac{1}{2} P_{\text{IM3}} \]

• Typically we want to find the distortion at a desired band

\[ P_{\text{IM3}} = 3P_J \cdot 2P_{\text{IIP3}} \]

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Example

- We assumed that IB blockers are -40 dBm.
- What IIP3 is required to keep distortion 10 dB below noise floor?
Example Cont.

• We assumed that IB blockers are -40 dBm.
• For sensitivity, assume 10 MHz channel for 4G.

\[
P_{en} = 174\, dBm + 10\log_{10} 20\, MHz = 161\, dBm
\]

• You can assume NF = 0 dB and SNR = 0 dB.

\[
P_{IIP3} = \frac{3}{2} P_I \left( \frac{1}{2} P_{IM3} \right)
\]

\[
P_{III} = \frac{3}{2} \left( 40\, dBm \right) \frac{1}{2} \left( 111\, dBm \right) = -4.5\, dBm
\]

• Not too bad for CMOS LNA.
Spur-Free Dynamic Range
Minimum Detectable Signal

\[ MDS_i = FkT \Delta f \]
\[ MDS_o = FGkT \Delta f \]
Solve for the SFDR

- Minimum detectable signal is the weakest signal that can be resolved in a given bandwidth

\[
SFDR = \left( IIP3 - MDS_i \right) - \frac{1}{3} \left( IIP3 - MDS_i \right)
\]

\[
SFDR = \frac{2}{3} \left( IIP3 - MDS_i \right) \quad \text{Units are dBC Hz}^{2/3}
\]
Noise Power Ratio Test

• Are two tones sufficient to interrogate the amplifier linearity?
Cross-Modulation Distortion (XMD)

- Occurs with high power transmitters. AM modulated signal copies itself onto neighboring signal.

\[ v_{in} = V_D \cos(\omega_1 t) + \left[ 1 + m \cos(\omega_m t) \right] V_J \cos(\omega_2 t) \]
Cross-Modulation Distortion (XMD)

- Modulation of undesired signal becomes impressed on desired signal

\[ v_{out} = V_D \left( a_1 + 3a_3 V_J^2 m \cos \left( \frac{m}{m} t \right) \right) \cos \left( \frac{1}{1} t \right) \]
Cross Modulation Distortion

\[ XMD = \frac{3|a_3|V_J^2V_D}{2a_1V_D} = \frac{3|a_3|}{2|a_1|} V_J^2 \]

• Similar to intermodulation distortion however CMI results from only one modulated signal
XMD in Full Duplex Systems

[Diagram showing TX leakage, jammer, and desired signal on the left, and a Duplexer with LNA, IRF, and PA on the right.]
Review of Cross Modulation Distortion

\[ S_J = g_1 V_J \cos(jt) \]

\[ S_{XMD} = \frac{3}{2} g_3 V_J V_{TX}^2 \cos\left( j + \frac{\omega_{TX,1} + \omega_{TX,2}}{2}\right) t \]

\[ XMD = \frac{S_{XMD}}{S_J} = \frac{3}{2} \frac{g_3 V_J V_{TX}^2}{g_1 V_J} = \frac{3g_3 V_{TX}^2}{2g_1} \]

\[ \omega_{XMD} = \omega_J + \omega_{TX,1} - \omega_{TX,2} \]

\[ \omega_{TX,1} = 800 \text{ MHz} \]
\[ \omega_{TX,2} = 801 \text{ MHz} \]
\[ \omega_{RX} = 900 \text{ MHz} \]
\[ \omega_1 = 901 \text{ MHz} \]

\[ XMD = 2 \left( 10 \log_{10} \left( \frac{V_{TX}^2}{R_s} \right) \right) - 10 \log_{10} \left( \frac{V_{IP3}^2}{2R_s} \right) \]

\[ XMD = 2 \left( P_{TX,TOTAL} - P_{IP3} \right) \rightarrow P_{IP3} = P_{TX,TOTAL} \left( \frac{XMD}{2} \right) \]
XMD Requirement

\[ P_{III} = P_{TX,TOTAL} \frac{XMD}{2} \]

Since \[ XMD = P_{XMD} P_J \]

\[ P_{III} = \frac{2P_{TX,TOTAL} + P_J}{2} \]

• This equation was based on CW signals for the TX and blockers. Therefore this equation is “approximate”.

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XMD Requirement

\[ P_{IIP3} = \left( \frac{P_{CW} + 2P_{TX,TOTAL}}{2} \frac{P_{XMD} 5}{P_{XMD}} \right) \]

Larson and Aparin, TMTT 2005

• Factor of 5 is added to account for the modulated nature of the TX, CW.
• Other factors are derived based on narrowband/wideband modulation.
Example

• We assumed that IB blockers are -40 dBm and OOB blockers are 0 dBm.
• What XMD is required to keep distortion 10 dB below noise floor?
Example Cont.

• We assumed that IB blockers are -40 dBm and OOB blockers are 0 dBm.

• For sensitivity, assume 10 MHz channel for 4G.

\[
P_{sens} = 174\text{dBm} + 10\log_{10} 20\text{MHz} = 101\text{dBm}
\]

• You can assume NF = 0dB and SNR = 0dB.

\[
P_{\text{IIp3}} = \frac{\left( P_{CW} + 2P_{TX\text{ TOTAL}} - P_{XMD} \right)^5}{2} \left( 40\text{dBm} + 2\times0\text{dBm} - \frac{111\text{dBm}}{5} \right) = 33\text{dBm}
\]

This pretty tough for CMOS LNA.
Duplexer

- RF to RX: 3 dB in band
- TX to RF: 3 dB in band
- TX to RX: 60 dB
Receiver Signal Levels

S: -110 dBm → 1 uV_p
J: -50 dBm → 1 mV_p

S: 10 uV_p
J: 10 mV_p
T: 100 mV_p

S: -107 dBm
J: -47 dBm

20 dB

RF

Duplexer

LNA

IRF

PA

T: 30 dBm
30 dBm → 10 V_p

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How much linearity is needed?

• Transmit signal is 10 mVp
• Jammer is 1mVp
• Signal is 1μVp
• Amplifier
  – Power Gain: 20 dB
  – Noise Figure: 2dB
  – IIP3 ??
Linearity Requirement Exercise (I)

• What IIP3 (power) is required to keep the IM3 product at the minimum detectable signal for the example receiver described below?

S: -110 dBm → 1 μV_p
J: -50 dBm → 1 mV_p

S: 1 μV_p
J: 1 mV_p
T: 10 mV_p

S: -107 dBm
J: -47 dBm
Linearity Requirement for IM3

\[ P_{IIIP3} = P_J \frac{IM3}{2} \]

\[ P_{IIIP3} = 50dBm \left( \frac{110dBm - (50dBm)}{2} \right) \]

\[ P_{IIIP3} = 20dBm \]
Linearity Requirement for XMD

\[
IIP3 = P_{TX,TOTAL} \left( \frac{XMD}{2} \right)
\]

\[
XMD = 110\text{dBm} \left( \frac{50\text{dBm}}{2} \right) = 60\text{dB}
\]

\[
IIP3 = 30\text{dBm} \left( \frac{60\text{dB}}{2} \right) = 0\text{dBm}
\]

- Cross modulation distortion imposes a tougher linearity requirement on the receiver than the two-tone intermodulation.
Summary of Metrics

• One-dB Compression – One tone
• Intermodulation Distortion – Two tone
• Intercept Point – Two Tone
• Spur-Free Dynamic Range – Two tone
• Carrier-to-Interference Ratio – Multi-tone
• Cross-Modulation Index – Modulated one/two tone