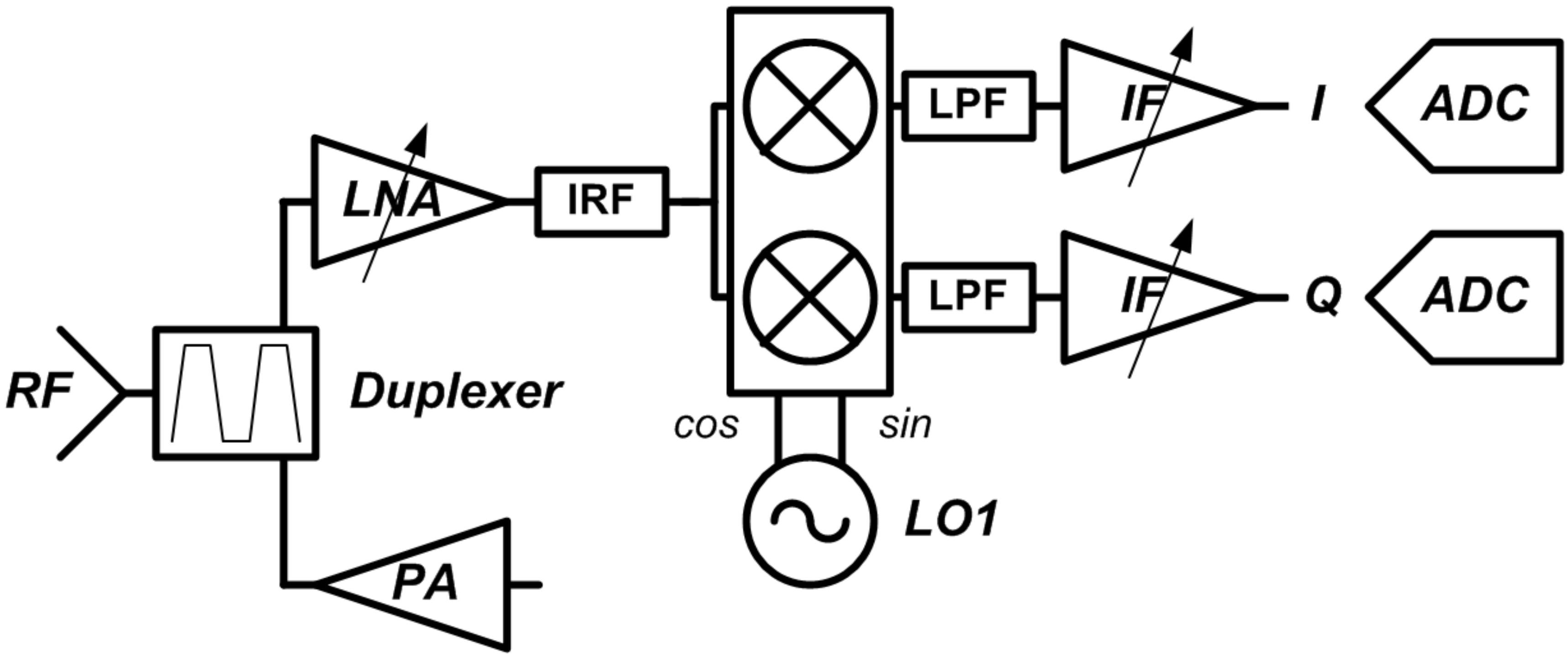
Modern Standards and Distortion

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



LTE-A Frequency Bands

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

Verizon uses Band 2, 4, 13

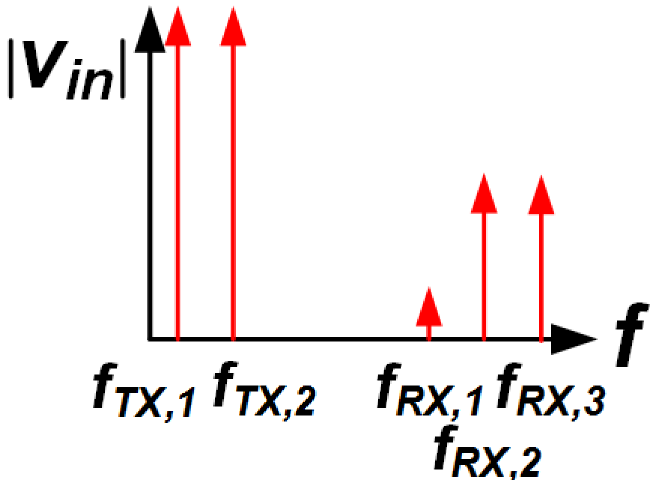
GSM

System	Band	Uplink (MHz)	Downlink (MHz)	Channel number	Equivalent UMTS/LTE band
T-GSM-380	380	380.2–389.8	390.2–399.8	dynamic	
T-GSM-410	410	410.2–419.8	420.2–429.8	dynamic	
GSM-450	450	450.6–457.6	460.6–467.6	259–293	31
GSM-480	480	479.0–486.0	489.0–496.0	306–340	
GSM-710	710	698.2–716.2	728.2–746.2	dynamic	12
GSM-750	750	777.2–792.2	747.2–762.2	438–511	
T-GSM-810	810	806.2–821.2	851.2–866.2	dynamic	27
GSM-850	850	824.2–849.2	869.2–893.8	128–251	5
P-GSM-900	900	890.0–915.0	935.0–960.0	1–124	
E-GSM-900	900	880.0–915.0	925.0–960.0	975–1023, 0-124	8
R-GSM-900	900	876.0–915.0	921.0–960.0	955–1023, 0-124	
T-GSM-900	900	870.4–876.0	915.4–921.0	dynamic^	
DCS-1800	1800	1,710.2–1,784.8	1,805.2–1,879.8	512–885	3
PCS-1900	1900	1,850.2–1,909.8	1,930.2–1,989.8	512–810	2

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

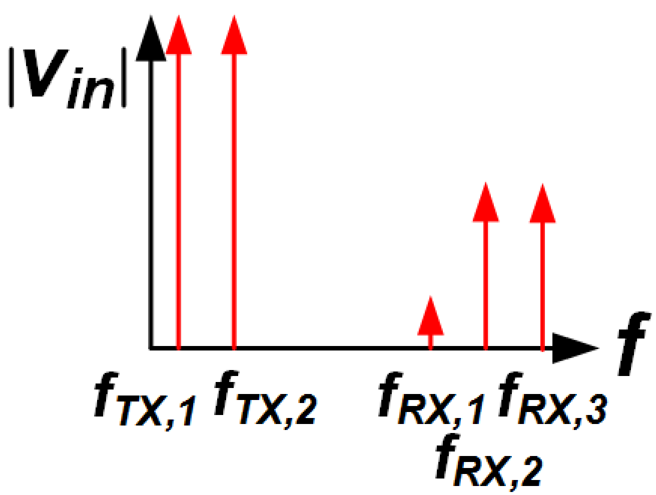


- Signals are represented as “CW” signals. This isn’t really true. We can interpret two ways:

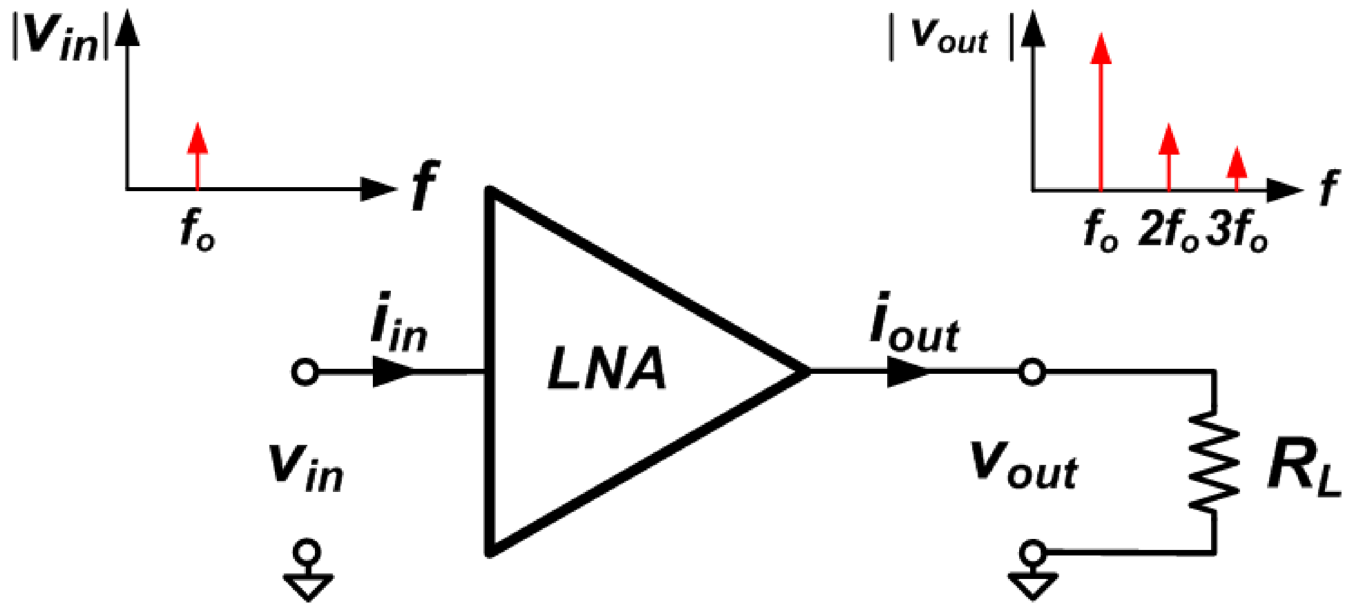
1) Each CW signal is a wideband modulated signal.
2) Each wideband modulated signal is modelled with a multitone (two tones) within 1 BW.

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



$$v_{in} = V_{pk} \cos\left(\omega_o t\right)$$

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

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

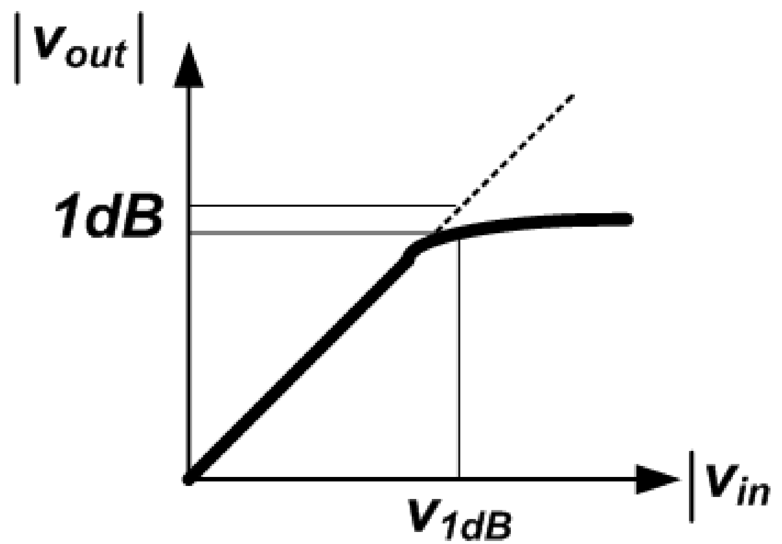
$$HD2 = \frac{\text{Signal at } 2\omega_o}{\text{Signal at } \omega_o} = \frac{1}{2}\left|\frac{g_{m,2}}{g_{m,1}}\right| V_{pk}$$

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

- Total Harmonic Distortion

$$THD = \sqrt{|HD2|^2 + |HD3|^2 + \ldots}$$

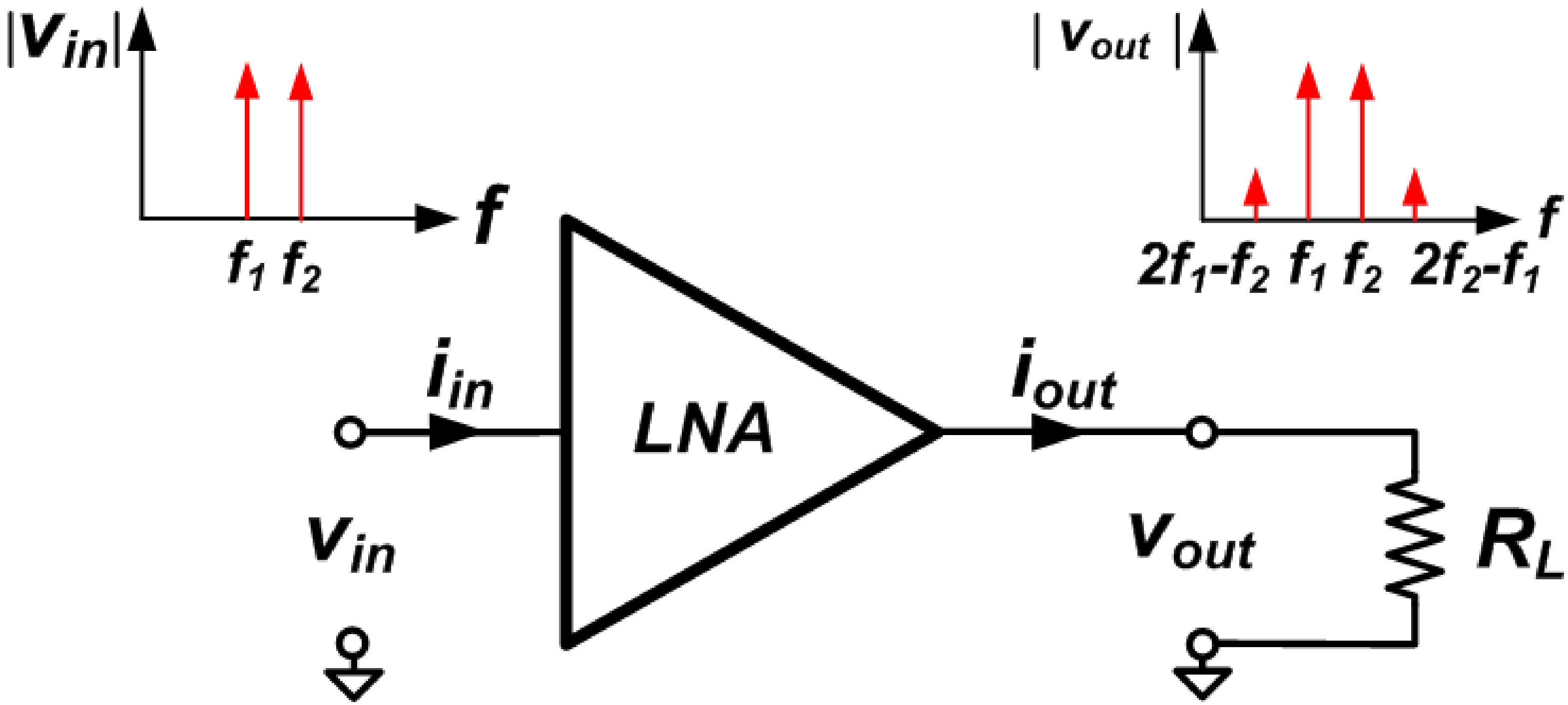
Gain Compression



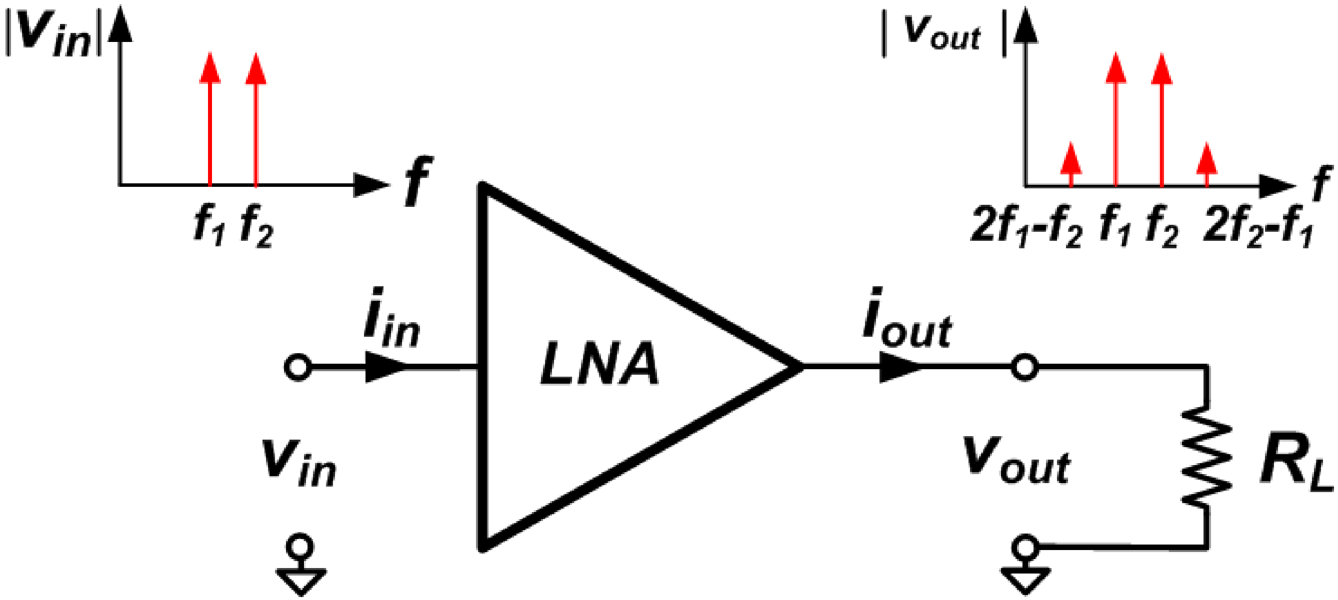
$$20\log_{10}\left(\frac{g_{m,1}V_{pk}+\frac{3}{4}g_{m,3}V_{pk}^{3}}{g_{m,1}V_{pk}}\right)=-1$$

$$V_{1dB}=\sqrt{0.11}\sqrt{\frac{4}{3}\left|\frac{g_{m,1}}{g_{m,3}}\right|}$$

Intermodulation Distortion



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)

$$
\begin{aligned}
i_{out} &= g_{m,1}V_{pk}\left[\cos(\omega_1 t)+\cos(\omega_2 t)\right] \\
&+ g_{m,2}V_{pk}^2\left[\cos(\omega_1 t)+\cos(\omega_2 t)\right]^2 \\
&+ g_{m,3}V_{pk}^3\left[\cos(\omega_1 t)+\cos(\omega_2 t)\right]^3
\end{aligned}
$$

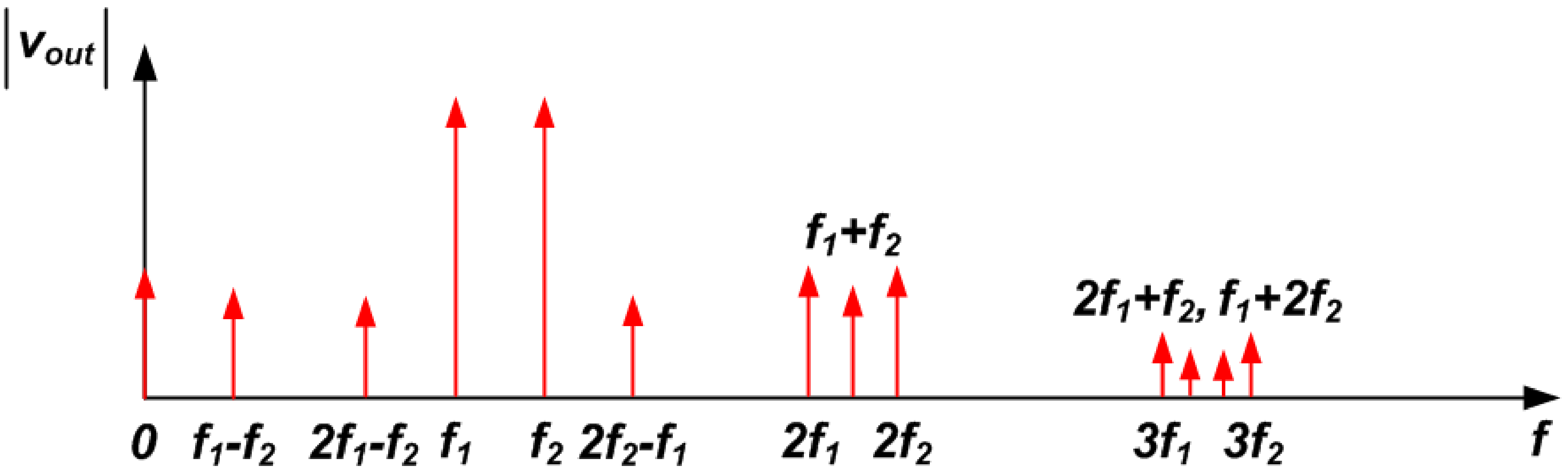
$$
\begin{aligned}
i_{out} &= g_{m,1}V_{pk}\left[\cos(\omega_1 t)+\cos(\omega_2 t)\right] \\
&+ g_{m,2}V_{pk}^2\left[\left(\frac{1+\cos(2\omega_1 t)}{2}\right)+\left(\frac{1+\cos(2\omega_2 t)}{2}\right)\right] \\
&+ g_{m,2}V_{pk}^2\left[\cos\left((\omega_1+\omega_2)t\right)+\cos\left((\omega_1-\omega_2)t\right)\right] \\
&+ g_{m,3}V_{pk}^3\left[\cos(\omega_1 t)+\cos(\omega_2 t)\right]^3
\end{aligned}
$$

Solve for Intermodulation Distortion (II)

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

$$+\frac{1}{4}g_{m,3}V_{pk}^3\left[\cos(3\omega_1 t)+3\cos(\omega_1 t)+\cos(3\omega_2 t)+3\cos(\omega_2 t)\right]$$
$$+\frac{3}{2}g_{m,3}V_{pk}^3\left[\cos(\omega_1 t)+\frac{1}{2}\cos\left((2\omega_1-\omega_2)t\right)+\frac{1}{2}\cos\left((2\omega_1+\omega_2)t\right)\right]$$
$$+\frac{3}{2}g_{m,3}V_{pk}^3\left[\cos(\omega_2 t)+\frac{1}{2}\cos\left((2\omega_2-\omega_1)t\right)+\frac{1}{2}\cos\left((2\omega_2+\omega_1)t\right)\right]$$

Picture of distortion generated from two tones

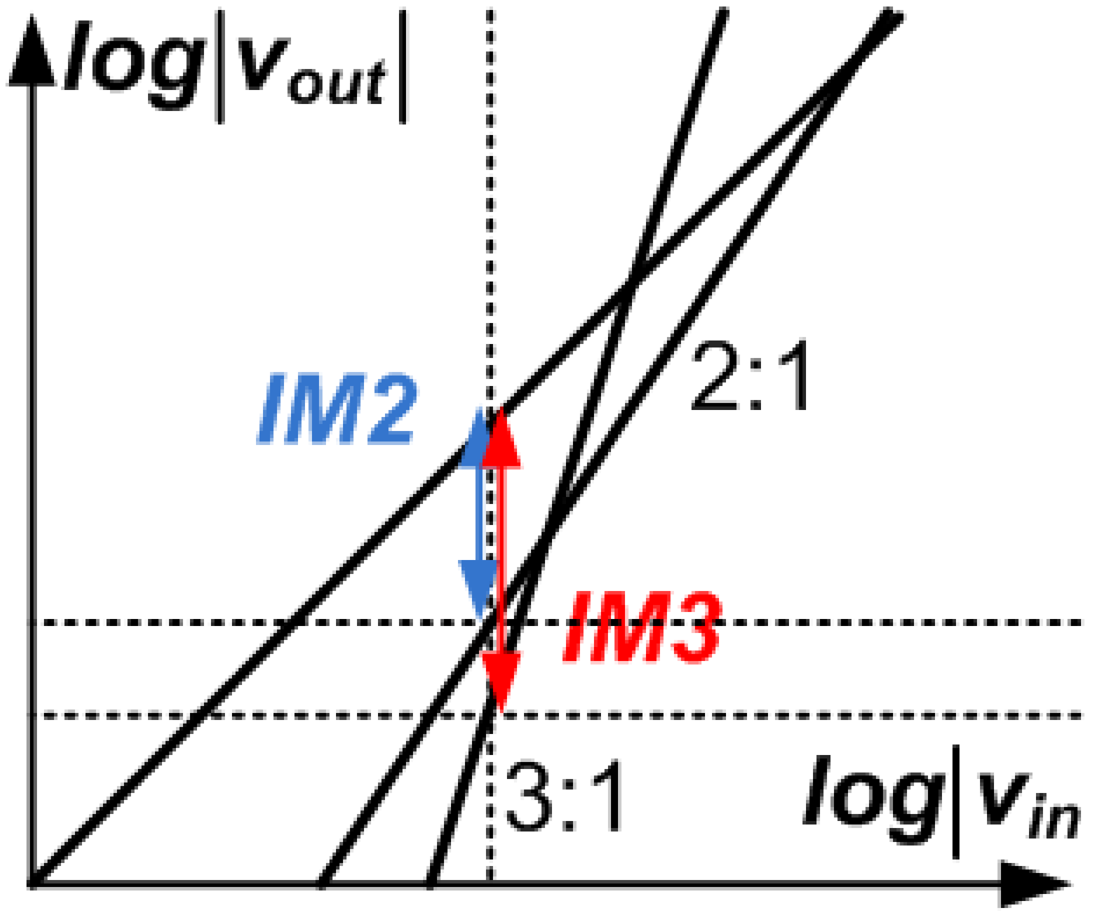


Definition of Intermodulation Distortion

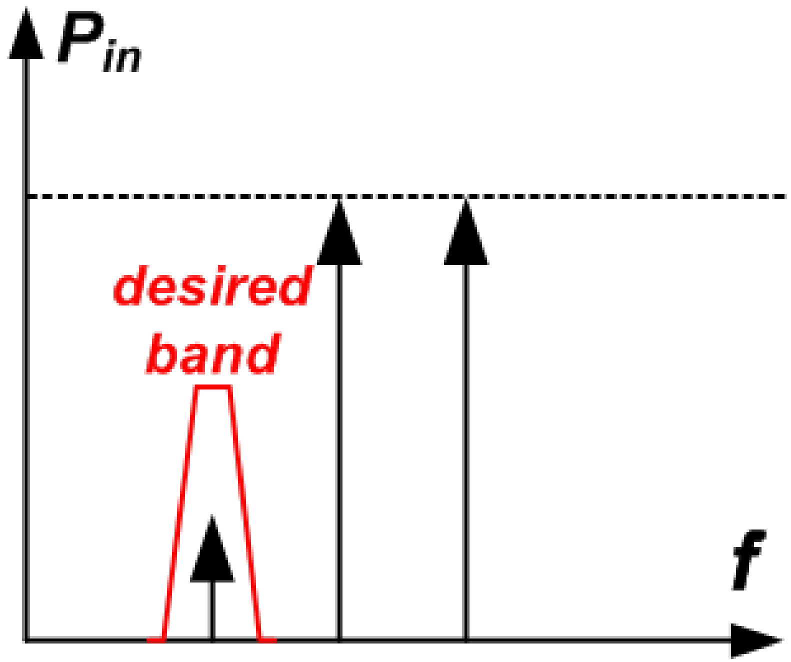
$$IM2 = \frac{\text{Signal at } \omega_1 - \omega_2}{\text{Signal at } \omega_1} = \left|\frac{g_{m,2}}{g_{m,1}}\right| V_{pk}$$

$$IM3 = \frac{\text{Signal at } 2\omega_1 - \omega_2}{\text{Signal at } \omega_1} = \frac{3}{4}\left|\frac{g_{m,3}}{g_{m,1}}\right| V_{pk}^2$$

Graph of IM3 Products



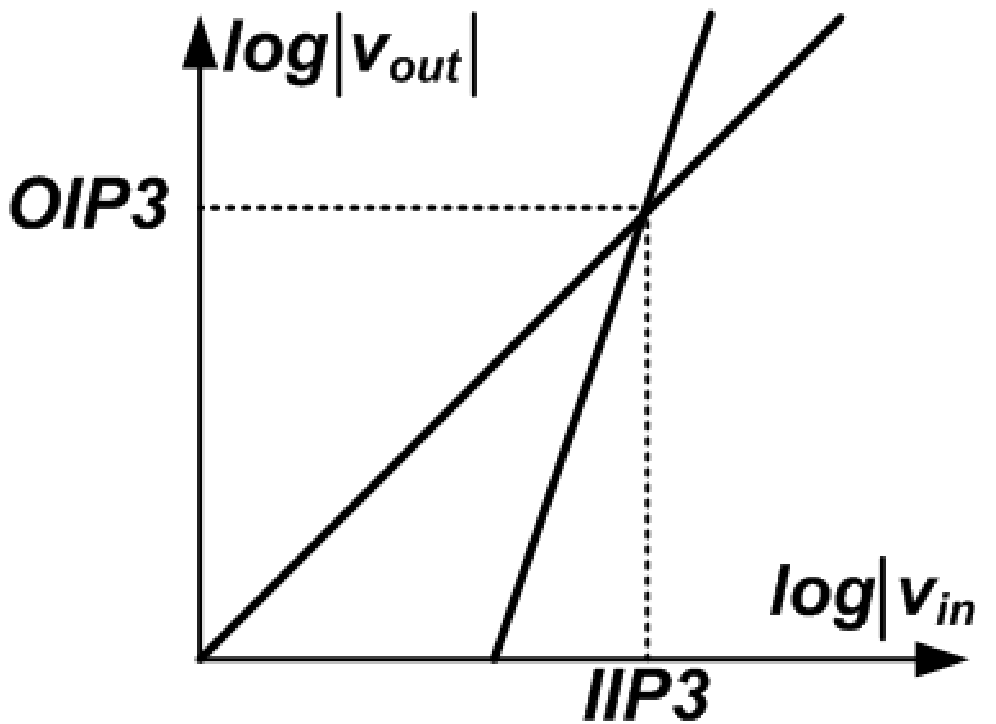
IM3 Issues with FDMA systems



- 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

$$\text{Signal at } 2\omega_1 - \omega_2 = \text{Signal at } \omega_1$$

$$\frac{3}{4}\left|g_{m,3}\right|V_{pk}^3 = \left|g_{m,1}\right|V_{pk}$$

$$IIP3 = \sqrt{\frac{4}{3}\left|\frac{g_{m,1}}{g_{m,3}}\right|}$$

Note the Relationship between IIP3 and P1dB

$$V_{1dB} = \sqrt{0.11}\sqrt{\frac{4}{3}\left|\frac{g_{m,1}}{g_{m,3}}\right|} \qquad IIP3 = \sqrt{\frac{4}{3}\left|\frac{g_{m,1}}{g_{m,3}}\right|}$$

- Factor in front of the 1dB voltage suggests that the 1dB compression occurs <u>9.6 dB </u>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

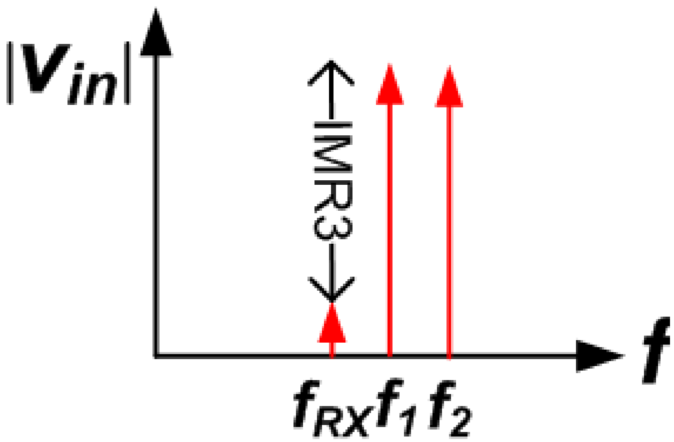
$$IM3 = \frac{\frac{3}{4} g_3 V_J^3}{g_1 V_J} = \frac{4}{3}\frac{g_3}{g_1} V_J^2$$

$$\rightarrow \frac{P_J}{P_{IIP3}} = IM3$$

$$\rightarrow 10\log_{10} P_J - 10\log_{10} P_{IIP3} = \frac{1}{2} 20\log_{10} IM3$$

$$P_J = P_{IIP3} + \frac{IM3}{2}$$

Factor of two because IM3 is based on ratio of voltage



Jammer Rejection

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

Since $IM3 = P_{IM3} - P_J$

$$P_{IIP3} = P_J - \frac{P_{IM3} - P_J}{2} = \frac{3}{2}P_J - \frac{1}{2}P_{IM3}$$

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

$$P_{IM3} = 3P_J - 2P_{IIP3}$$

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

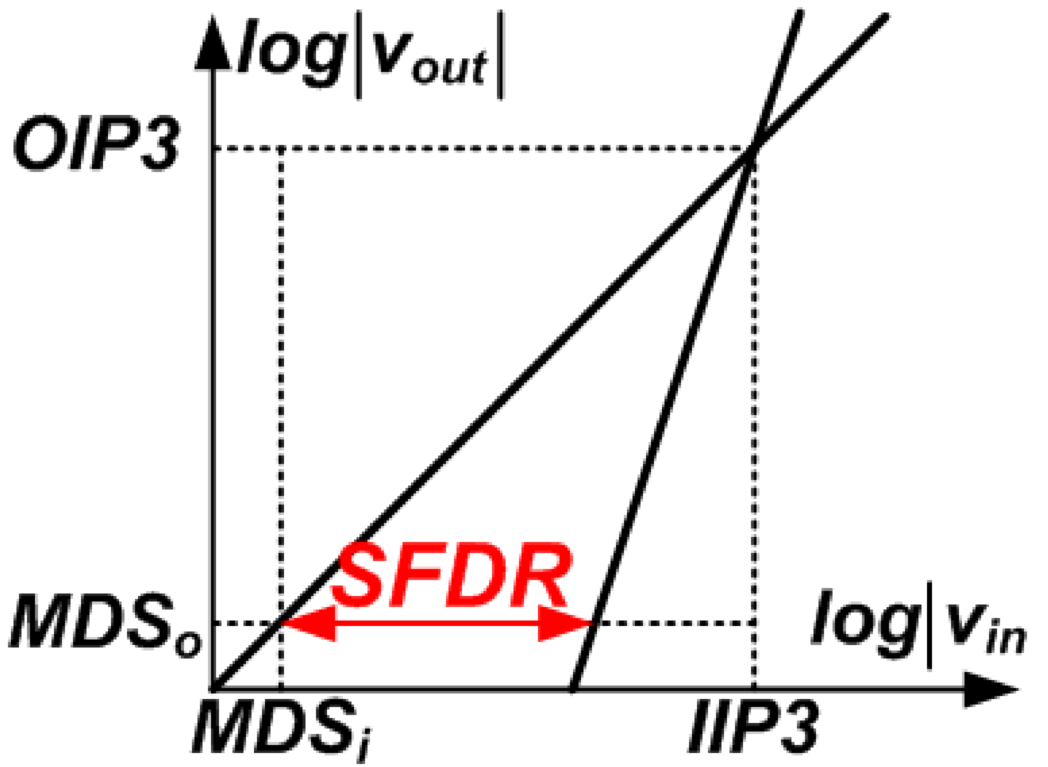
$$P_{sens} = -174dBm + 10\log_{10} 20MHz = -101dBm$$

$$P_{IIP3} = \frac{3}{2}P_J - \frac{1}{2}P_{IM3}$$

$$P_{IIP3} = \frac{3}{2}\left(-40dBm\right) - \frac{1}{2}\left(-111dBm\right) = -4.5dBm$$

- Not too bad for CMOS LNA.

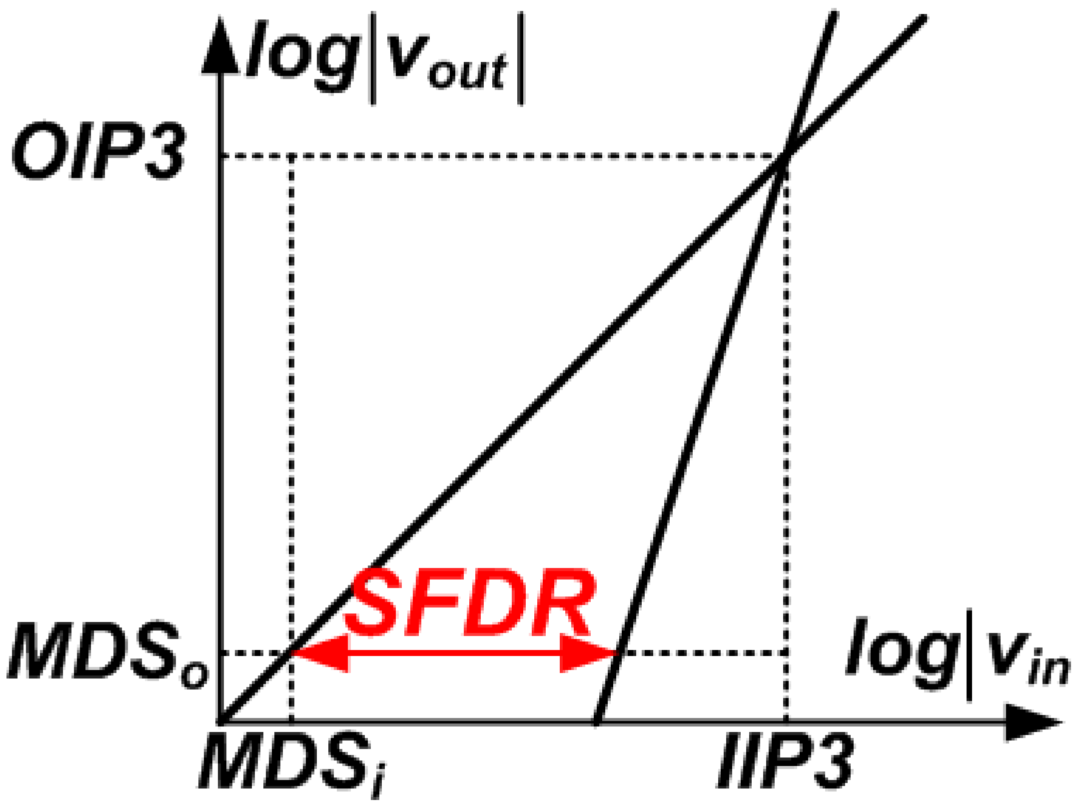
Spur-Free Dynamic Range



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

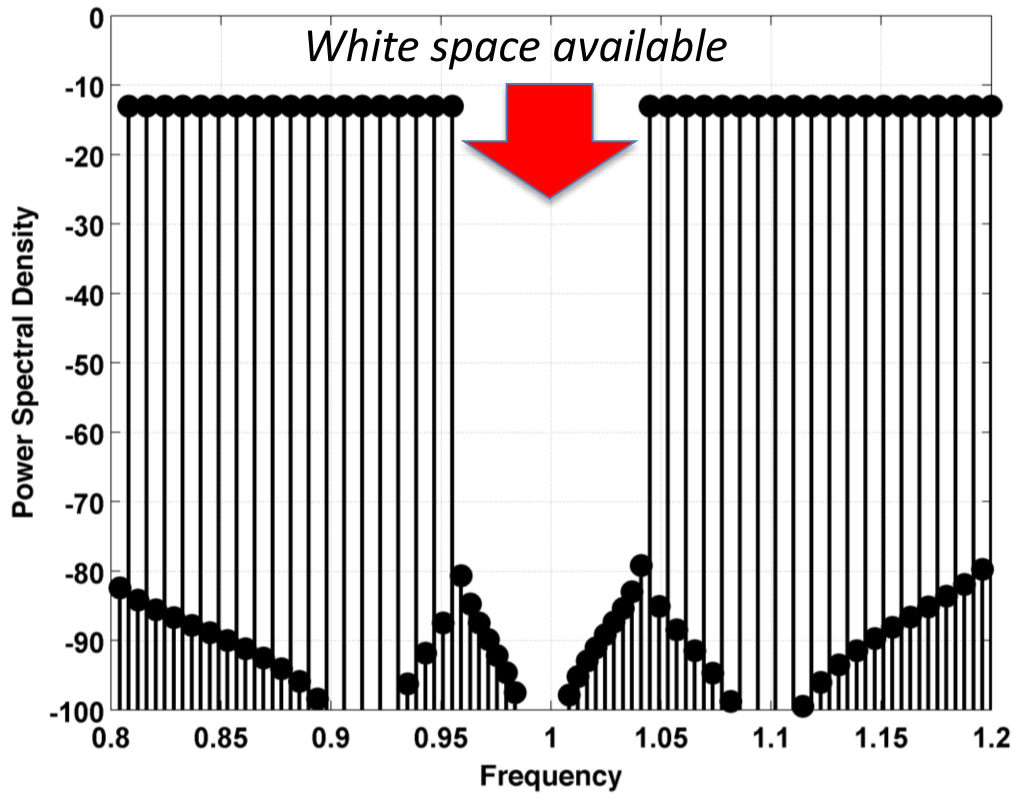
$$SFDR = \left(IIP3 - MDS_i\right) - \frac{1}{3}\left(IIP3 - MDS_i\right)$$

$$SFDR = \frac{2}{3}\left(IIP3 - MDS_i\right)$$

Units are dBc $Hz^{2/3}$

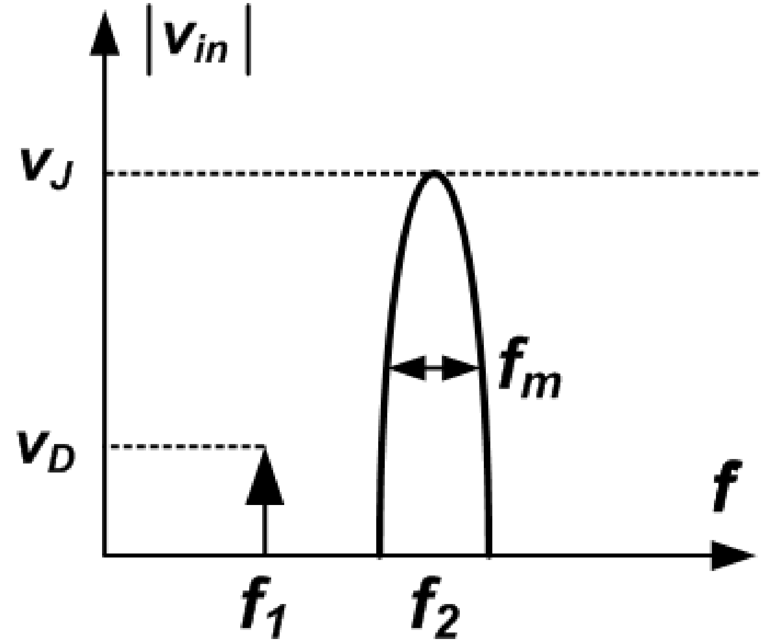
Noise Power Ratio Test

- Are two tones sufficient to interrogate the amplifier linearity?



Cross-Modulation Distortion (XMD)

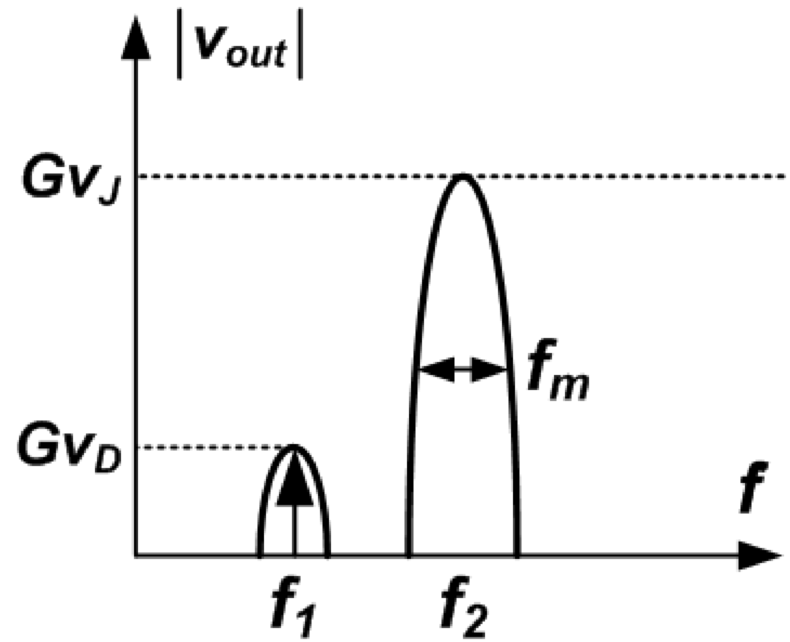
- Occurs with high power transmitters. AM modulated signal copies itself onto neighboring signal.



$$v_{in} = V_D \cos(\omega_1 t) + [1 + m\cos(\omega_m t)] V_J \cos(\omega_2 t)$$

Cross-Modulation Distortion (XMD)

- Modulation of undesired signal becomes impressed on desired signal



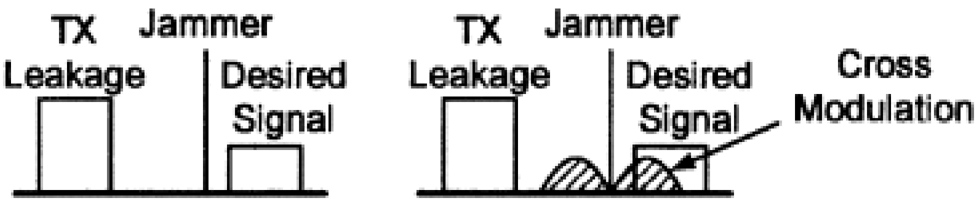
$$v_{out} \approx V_D\left(a_1 + 3a_3V_J^2 m\cos\left(\omega_m t\right)\right)\cos\left(\omega_1 t\right)$$

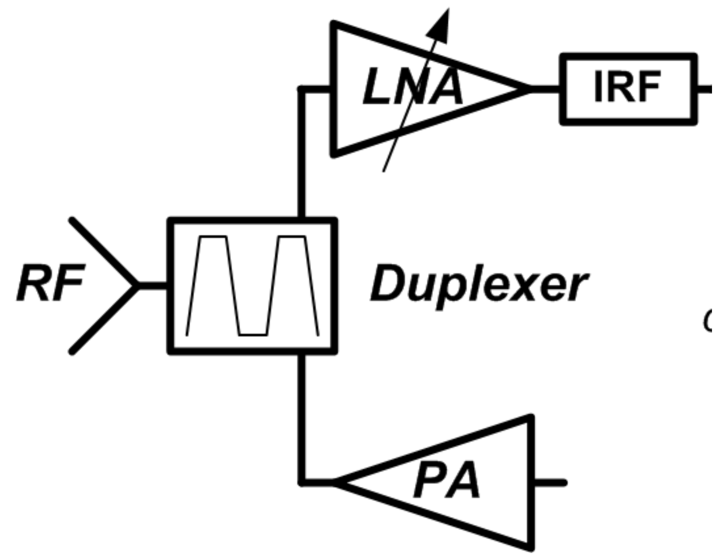
Cross Modulation Distortion

$$XMD = \frac{3|a_3|V_J^2 V_D}{2a_1 V_D} = \frac{3}{2}\frac{|a_3|}{|a_1|}V_J^2$$

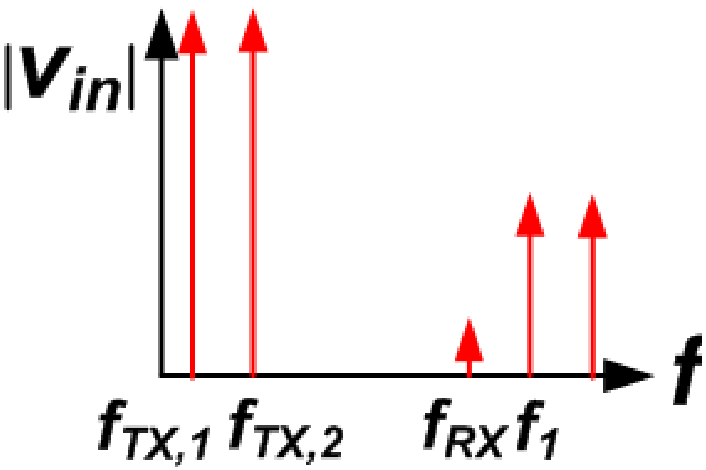
- Similar to intermodulation distortion however CMI results from only one modulated signal

XMD in Full Duplex Systems





Review of Cross Modulation Distortion



$$S_J = g_1 V_J \cos(w_J t)$$

$$S_{XMD} = \frac{3}{2} g_3 V_J V_{TX}^2 \cos((w_J + w_{TX,1} - w_{TX,2})t)$$

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

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

$\omega_{TX,1}$ = 800 MHz
$\omega_{TX,2}$ = 801 MHz

ω_{RX} = 900 MHz
ω_1 = 901 MHz

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

$$XMD = 2(P_{TX,TOTAL} - P_{IIP3}) \rightarrow P_{IIP3} = P_{TX,TOTAL} - \frac{XMD}{2}$$

XMD Requirement

$$P_{IIP3} = P_{TX,TOTAL} - \frac{XMD}{2}$$

Since $XMD = P_{XMD} - P_J$

$$P_{IIP3} = \frac{2P_{TX,TOTAL} + P_J - P_{XMD}}{2}$$

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

XMD Requirement

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

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.

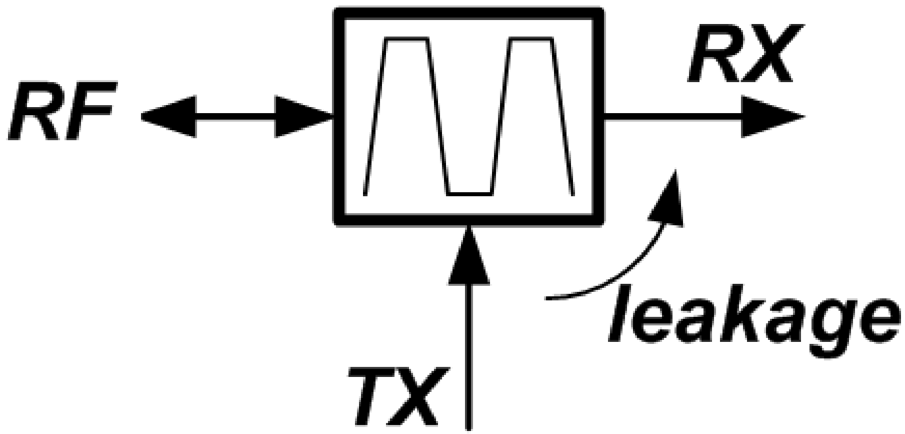
$$P_{sens} = -174dBm + 10\log_{10} 20MHz = -101dBm$$

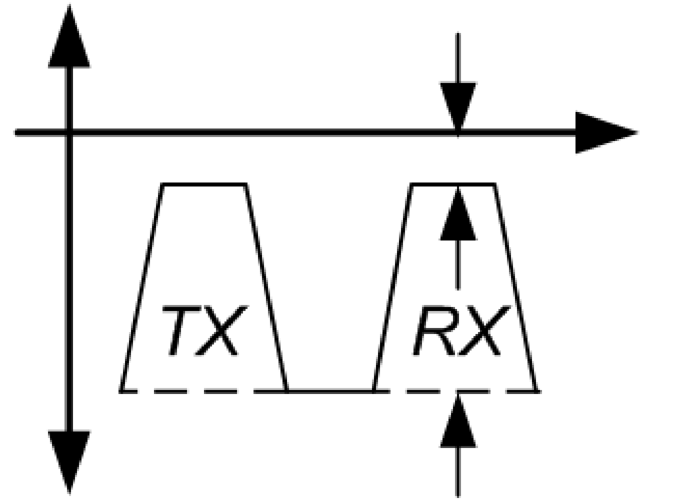
- You can assume NF = 0dB and SNR = 0dB.

$$P_{IIP3} = \frac{\left(P_{CW} + 2P_{TX,TOTAL} - P_{XMD} - 5\right)}{2} = \frac{\left(-40dBm + 2\times 0dBm - \left(-111dBm\right) - 5\right)}{2} = 33dBm$$

- This pretty tough for CMOS LNA.

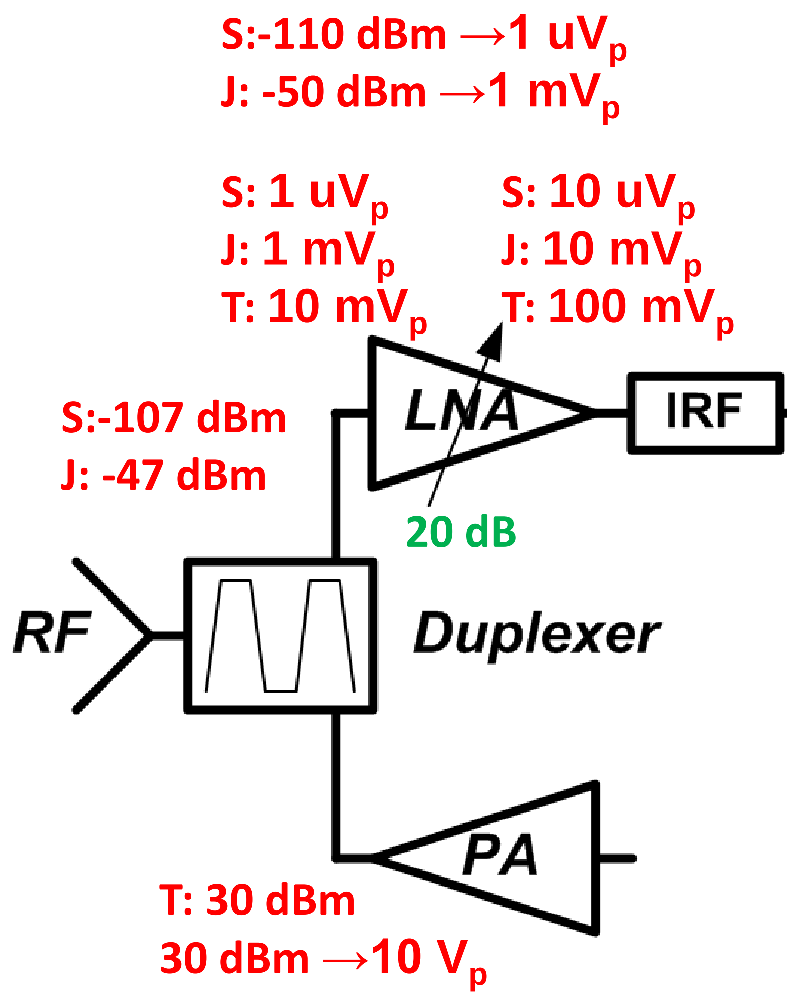
Duplexer





- RF to RX: 3 dB in band
- TX to RF: 3 dB in band
- TX to RX: 60 dB

Receiver Signal Levels

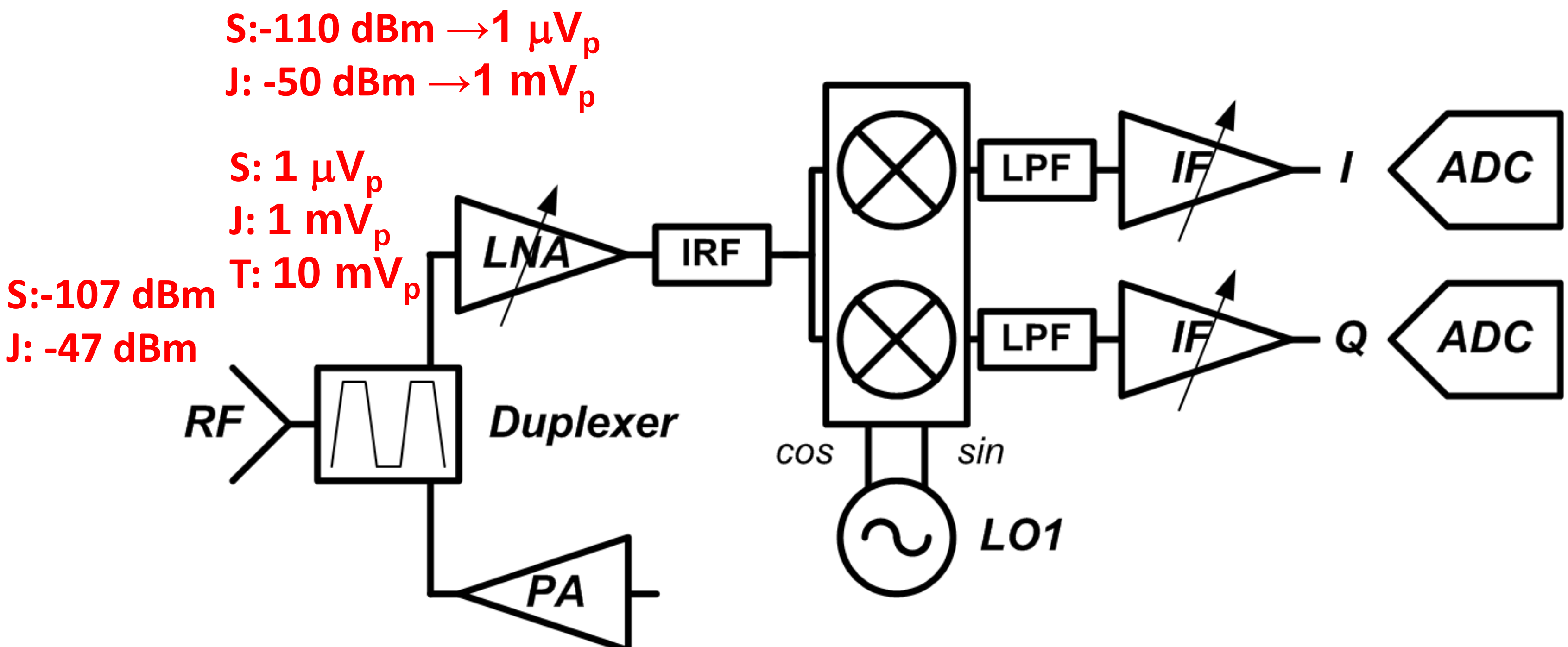


How much linearity is needed?

- Transmit signal is 10 mVp
- Jammer is 1mVp
- Signal is 1uVp
- 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?



Linearity Requirement for IM3

$$P_{IIP3} = P_J - \frac{IM3}{2}$$

$$P_{IIP3} = -50dBm - \frac{\left(-110dBm - \left(-50dBm\right)\right)}{2}$$

$$P_{IIP3} = -20dBm$$

Linearity Requirement for XMD

$$IIP3 = P_{TX,TOTAL} - \frac{XMD}{2}$$

$$XMD = -110dBm - (-50dBm) = -60dB$$

$$IIP3 = -30dBm - \frac{-60dB}{2} = 0dBm$$

- 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