TELECOM Paris

INSTITUT POLYTECHNIQUE DE PARIS

Duplexer, Antenna & PA for RF Front End

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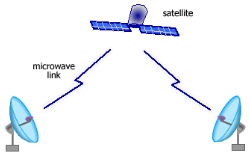
Wireless communication systems

Satellite communications



Cellular networks

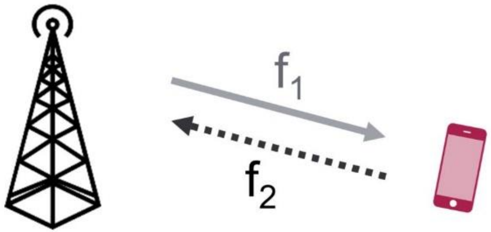
Internet of Things

Autonomous cars

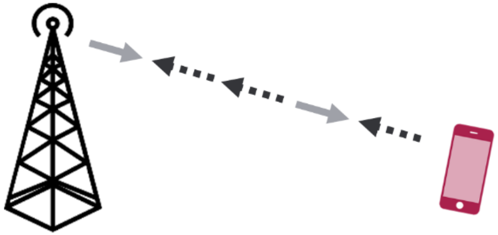
Wireless communication technology evolves fast →MANY hardware design challenges to overcome!

Wireless communication systems

- In FDD (Frequency Division Duplex) mode, different frequencies are used for transmitting and receiving.
- In TDD (Time Division Duplex) mode, the same frequency band is used but users can transmit only in specific time intervals.



FDD



TDD

Wireless communication systems

Band No.	Band Definition	Uplink Frequency Range	Downlink Frequency Range	FDD/TDD System
1	Mid-Band	1920-1980 MHz	2110-2170 MHz	FDD
2	Mid-Band	1850-1910 MHz	1930-1990 MHz	FDD
3	Mid-Band	1710-1785 MHz	1805-1880 MHz	FDD
4	Mid-Band	1710-1755 MHz	2110-2155 MHz	FDD
5	Low-Band	824-849 MHz	869-894 MHz	FDD
6	Low-Band	830-840 MHz	875-885 MHz	FDD
7	High-Band	2500-2570 MHz	2620-2690 MHz	FDD
8	Low-Band	880-915 MHz	925-960 MHz	FDD
9	Mid-Band	1749.9-1784.9 MHz	1844.9-1879.9 MHz	FDD
10	Mid-Band	1710-1770 MHz	2110-2170 MHz	FDD
11	Mid-Band	1427.9-1452.9 MHz	1475.9-1500.9 MHz	FDD
33	Mid-Band	1900-1920 MHz		TDD
34	Mid-Band	2010-2025 MHz		TDD
35	Mid-Band	1850-1910 MHz		TDD
36	Mid-Band	1930-1990 MHz		TDD
37	Mid-Band	1910-1930 MHz		TDD

FDD channels

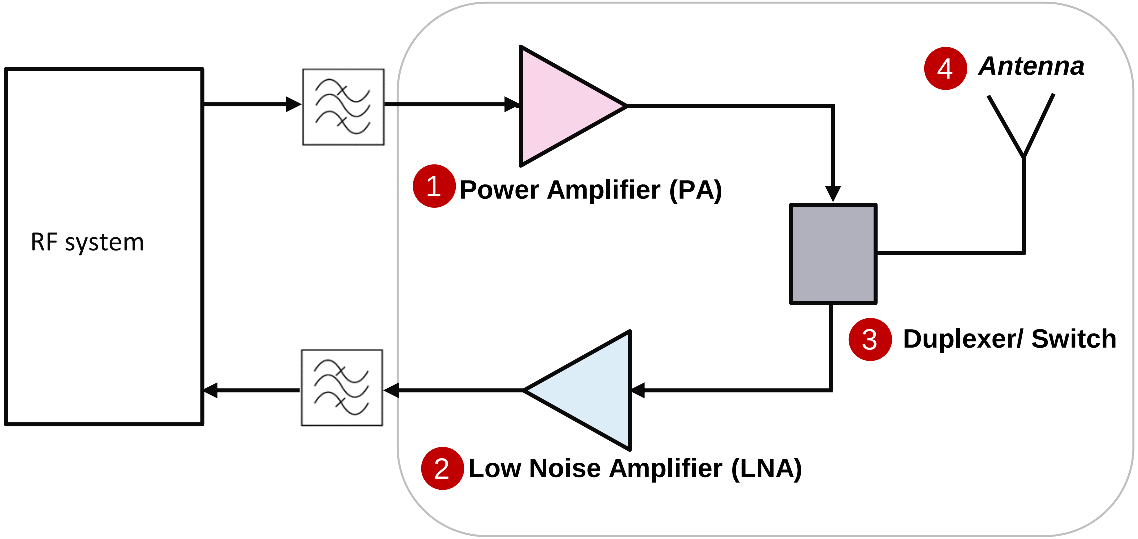
TDD channels

Example of specifications for spectrum usage
(FDD and TDD systems)

3rd Generation Partnership Project (3GPP) refers to a number of standards for mobile communications (e.g. GSM, LTE, 5G etc)

Source: https://www.3gpp.org/

RF Front End



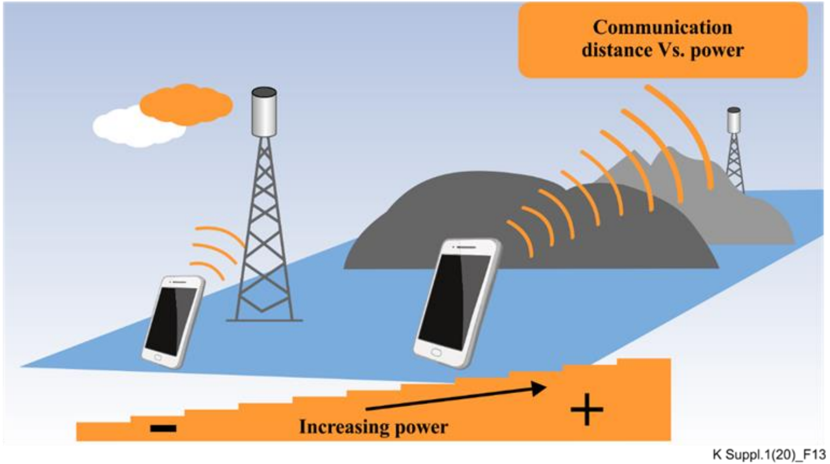
Block diagram of a simplified RF front end

Our focus today: (1) power amplifier, (2) low noise amplifier, (3) switch/duplexer and (4) antenna.

Outline

- Power Amplifier (PA)
- Low Noise Amplifier (LNA)
- Antennas
- Duplexer/ Switch

Introduction to Power Amplifiers

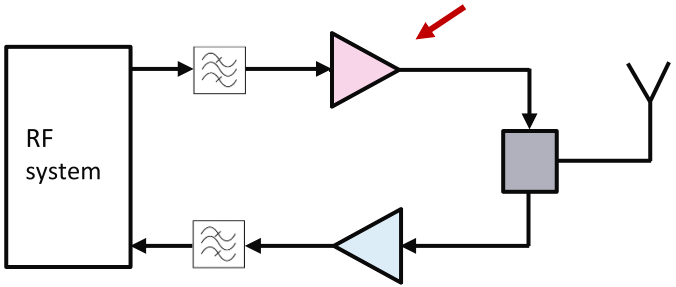


The main function of a power amplifier is to amplify its input signal.

Source: https://emfguide.itu.int

Introduction to Power Amplifiers

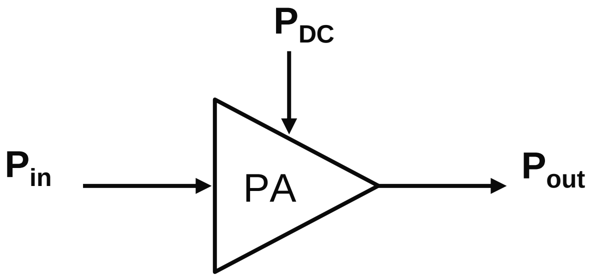
- **Power amplifiers** (PAs) are used in the final stage of radar and radio transmitters to increase the radiated power level.
- Their output power level can vary from a few mW to MW. In the case of mobile communications systems (e.g. voice and data), the PA output can be in the order of 100-500 mW, in the case of radar systems it can be in the order of 1-100 W.



Key performance parameters are the gain, efficiency (thermal effects), linearity..

Power Amplifier - Gain

The gain of a power amplifier is defined as the ratio between its output power to its input power.



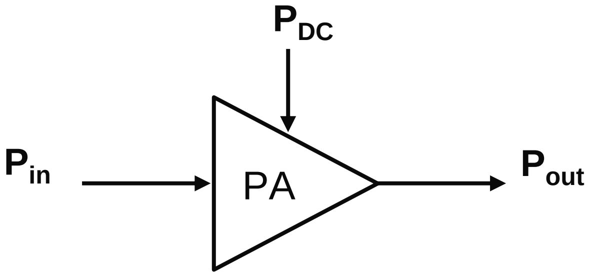
Gain (G) $G = \frac{P_{out}}{P_{in}}$

Gain in dB $G_{dB} = 10 \log_{10} \left(\frac{P_{out}}{P_{in}} \right)$

Power Amplifier - Efficiency

- The power amplifier dominates the power consumption of radio transmitters & impacts heavily the battery life time of the devices.

- Drain efficiency (DE) and Power Added Efficiency (PAE) are two important metrics for the efficiency of a power amplifier. PAE is the most popular metric. The drain efficiency does not take into account the gain of the power amplifier.



Drain efficiency (DE)

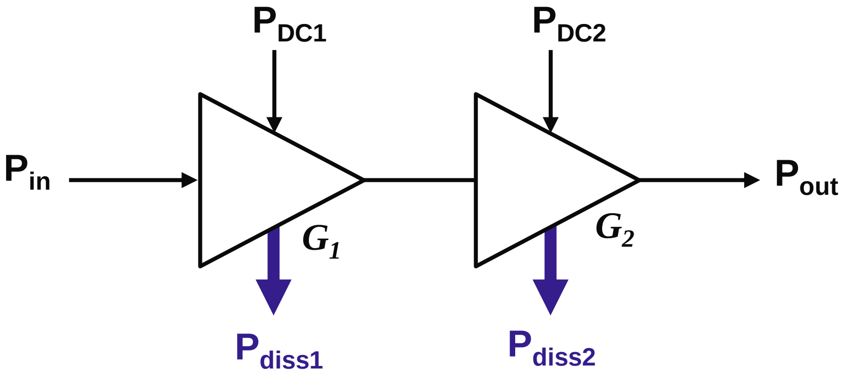
$$\eta_{\mathrm{DE}} = \frac{P_{out}}{P_{DC}}$$

Power Added Efficiency (PAE)

$$\eta_{\mathrm{PAE}} = \frac{P_{out} - Pin}{P_{DC}}$$

$$\eta_{\mathrm{PAE}} = \left(1 - \frac{1}{G}\right)\frac{P_{out}}{P_{DC}} \rightarrow \eta_{\mathrm{PAE}} = \left(1 - \frac{1}{G}\right)\eta_{\mathrm{DE}}$$

Power Amplifiers in cascade topology



Cascaded 2-stage matched PA

Overall gain

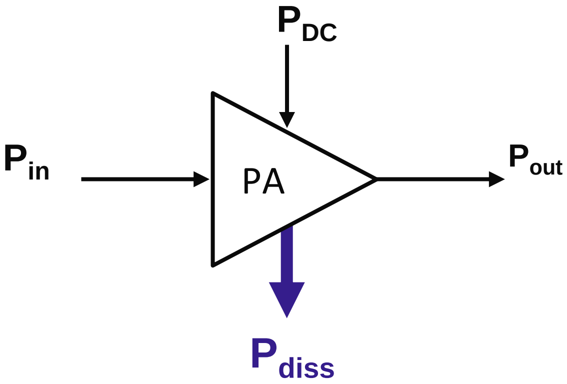
$$G_T = G_1 G_2$$

$$G_{T(dB)} = G_{1(dB)} + G_{2(dB)}$$

Overall efficiency

$$\eta = \frac{\eta_2}{1 + \frac{P_{DC1}}{P_{DC2}}} = \frac{\eta_2}{1 + \frac{\eta_2}{\eta_1 G_2}}$$

Power Amplifier – Thermal Behavior



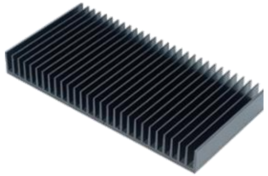
$$P_{diss} + P_{out} = P_{in} + P_{DC}$$

$$P_{diss} = (P_{in} - P_{out}) + P_{DC}$$

$$P_{diss} = P_{DC}(1 - \eta_{\mathrm{PAE}})$$

Thermal behaviour depends on P_{DC} and PAE

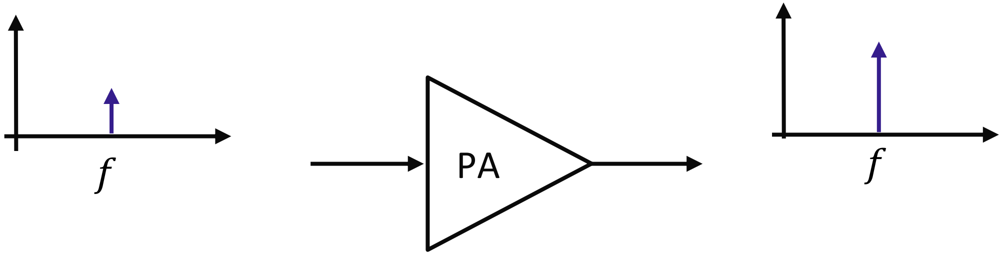
Power amplifiers get warm during their operation and the generated heat should be dissipated to avoid damaging the power amplifier → heatsinks typically used



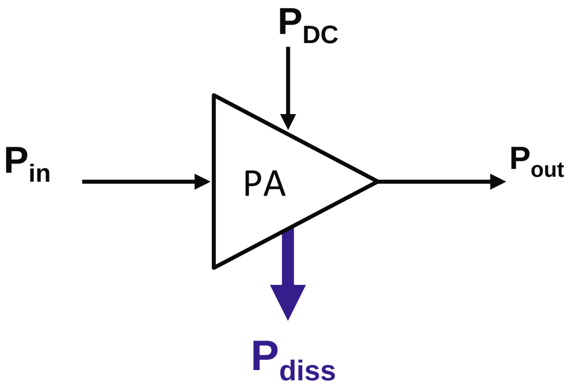
Power Amplifier Linearity

In a typical transceiver system, the most important source of nonlinear distortion is the power amplifier. Many metrics and different signal excitations (single-tone excitation, modulated signals etc) are used for the characterization of the non linear behavior of the power amplifiers.

Ideal behavior of a linear power amplifier

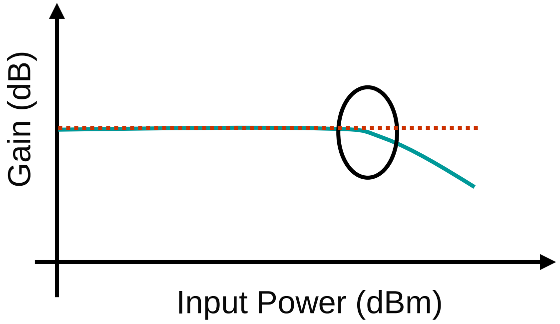


Gain compression



$$P_{diss} + P_{out} = P_{in} + P_{DC}$$

$$G = 1 + \frac{P_{DC} - P_{diss}}{P_{in}}$$



- The gain of a power amplifier is constant over a range of low input power levels – this is its linear region of operation.
- The PA can not maintain a constant gain above a certain power level → gain starts decreasing, the PA starts getting compressed and finally saturates (non-linear region of operation).

PA Design example

We need to design a power amplifier with an output power of 10 W, a power gain of 16.4 dB, a drain efficiency of 26% and a supply voltage of 28 V at 2 GHz. Calculate the following:

- Required input power

- Required DC drain current

- Power added efficiency

Answers: 230 mW, 1.37 A, Power Added Efficiency: 25 %

Reminder

Absolute power levels are expressed in decibels, with a reference power level (usually us1 mW and 1W)

For reference value of 1 mW → dB**m**.

For reference value of 1 W → dB**W**.

dBm to Watt Power Conversion

$$P_{(W)} = \frac{10^{P(dBm)/10}}{1000}$$

$$P_{(dBm)} = 10 * log10(P/1mW)$$

dBW to Watt Power Conversion

$$P_{(W)} = 10^{P(dBW)/10}$$

$$P_{(dBW)} = 10 * log10(P/1W)$$

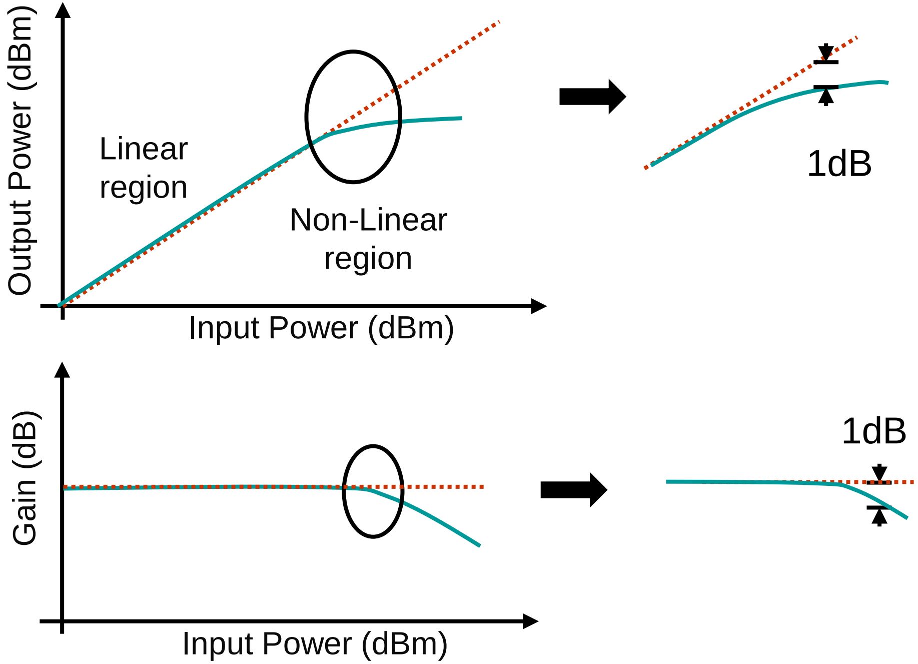
Gain and propagation losses (generally variables that express **ratios**) can be expressed in dB form.

$$G = 10^{G_{(dB)}/10}$$

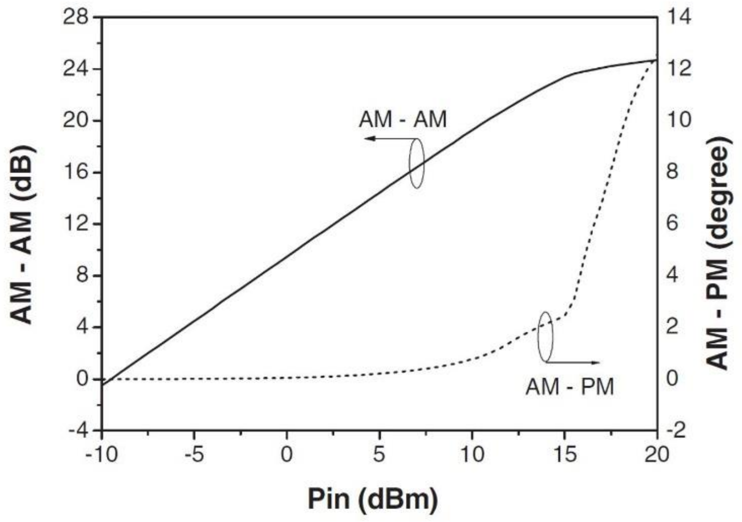
$$G_{(dB)} = 10 * \log_{10}(G)$$

1 dB compression point

The 1 dB compression point is a measure of the PA distortion and refers to the power at which the output power is 1 dB less than what it should ideally be if the system was linear.



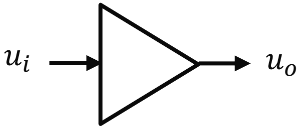
AM-PM distortion



- The **AM–AM** curve of a power amplifier shows the relationship between the output amplitude and the input amplitude at the fundamental frequency. Based on the AM-AM curve, we can extract the 1-dB compression point (P_{1dB}).
- The **AM-PM** distortion curve refers to the phase variation due to the input power variation. This metric is very important for phase modulated signals (such as QPSK), as the phase deviation increases the bit error rate (BER) in digital communications

Source: P. Colantonio, F. Giannini, E. Limiti, High efficiency RF and microwave solid state power amplifiers

Harmonics



For a sinusoidal input signal u_i, the output $u_o$will be:

$$u_o = a_o + a_1 u_i + a_2 {u_i}^2 + \cdots + a_n {u_i}^n$$

For a single-frequency sinusoidal input signal ($u_i = Acos(\omega_o t)$), at the output of the PA we get:

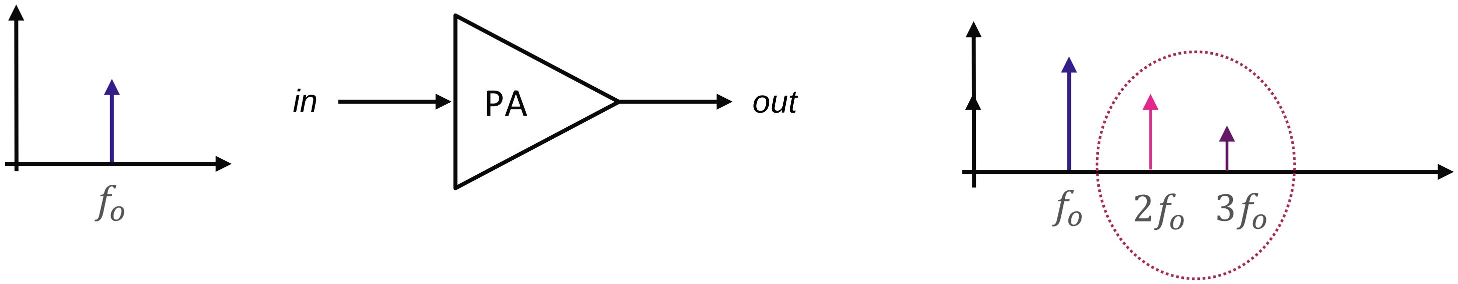
$$\underbrace{u_o = a_o}_{constant} + \underbrace{a_1 Acos(\omega_o t))}_{freq.component\ at\ f_o} + \underbrace{a_2\,(Acos(\omega_o t))^2}_{freq.component\ at\ 2f_o} + \ldots + \underbrace{a_n (Acos(\omega_o t))^n}_{freq.component\ at\ nf_o}$$

The output spectrum of the power amplifier consists of:

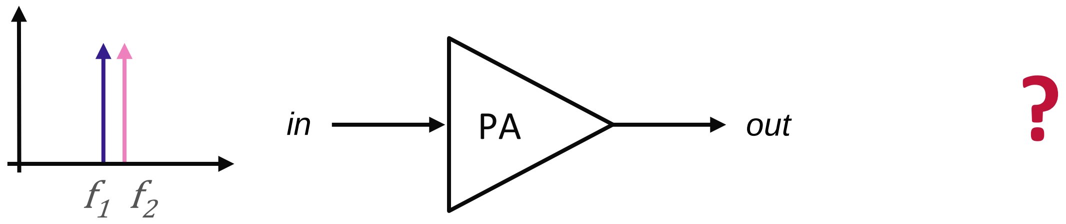
- a DC offset at the output port
- a signal at the original f_o (fundamental frequency) and
- multiples of the fundamental frequency ($n\ \mathrm{f}_o$) → harmonics

Harmonics

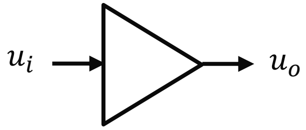
The harmonics are typically far from the fundamental frequency and can be easily filtered .



What will be the output of the PA in the case of two input signals?



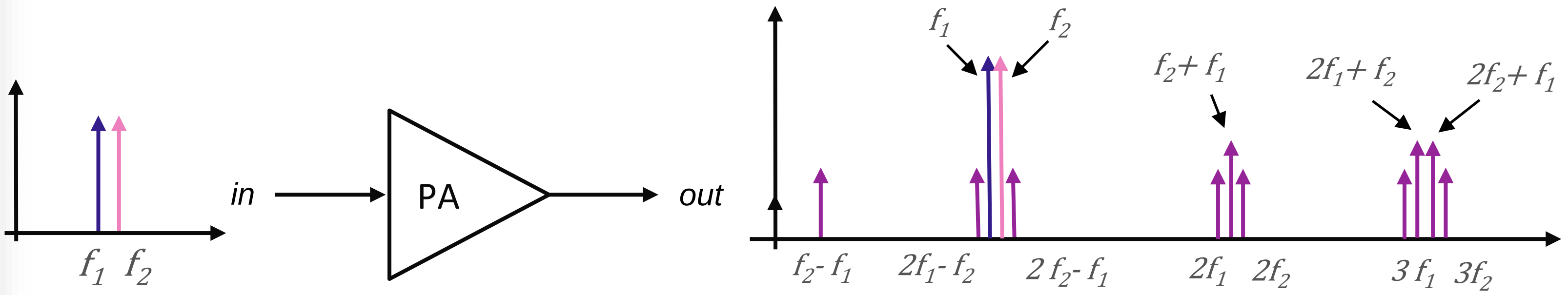
Intermodulation Products



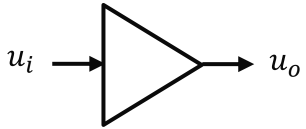
Let's consider a two-tone input signal $u_i = \mathrm{A}\cos(\omega_1 t) + A\cos(\omega_2 t)$ at the input of the power amplifier, then:

$$u_o = \underset{\text{constant}}{a_o} + \underbrace{a_1 A(\cos(\omega_1 t) + \cos(\omega_2 t))}_{\text{original freq.}} + \underbrace{a_2 A^2(\cos(\omega_1 t) + \cos(\omega_2 t))^2}_{\text{freq. comp. at } (f_1+f_2)\ \&\ (f_2-f_1)} + \underbrace{a_3 A^3(\cos(\omega_1 t) + \cos(\omega_2 t))^3}_{\text{freq. comp. at } (2f_1+f_2)\ \&\ (2f_1-f_2)} + \cdots$$

… and other frequency components at $\mathrm{f}_1, 3\mathrm{f}_1, \mathrm{f}_2, 3\mathrm{f}_2, 2\mathrm{f}_1 + \mathrm{f}_2, 2\mathrm{f}_2 + \mathrm{f}_1$



Intermodulation Products



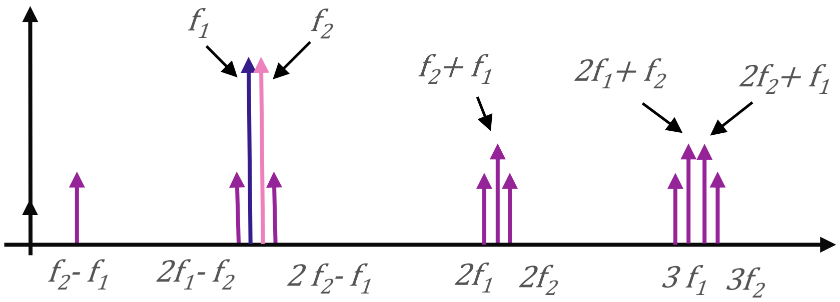
Let's consider a two-tone input signal $u_i = A\cos(\omega_1 t) + A\cos(\omega_2 t)$, at the input of the power amplifier, then:

$$u_o = a_o + \underbrace{a_1 A(\cos(\omega_1 t) + \cos(\omega_2 t))}_{\text{original freq.}} + \underbrace{a_2 A^2(\cos(\omega_1 t) + \cos(\omega_2 t))^2}_{\text{freq. comp. at } (f_1+f_2)\ \&\ (f_2-f_1)} + \underbrace{a_3 A^3(\cos(\omega_1 t) + \cos(\omega_2 t))^3}_{\text{freq. comp. at } (2f_1+f_2)\ \&\ (2f_1-f_2)} + \cdots$$

constant

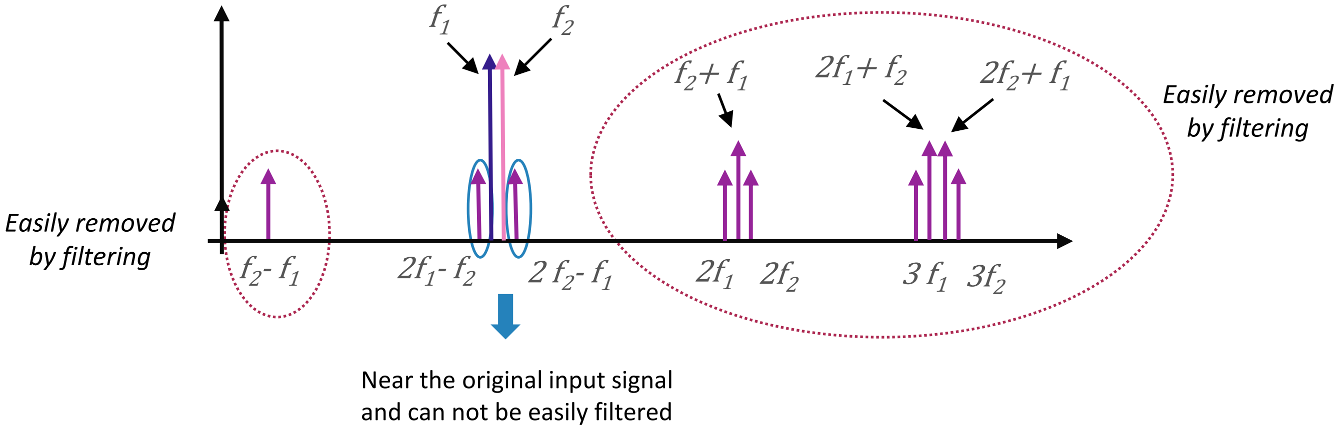
… and other frequency components at $f_1, 3f_1, f_2, 3f_2, 2f_1 + f_2, 2f_2 + f_1$

- The output spectrum of the PA consists of harmonics in the form of $mf_1 + nf_2$ where m, n = 0, ±1, ±2, ±3... → these combinations of the two input frequencies are called intermodulation (IMD) products.
- The order of a given intermodulation product is defined as |m| + |n|.



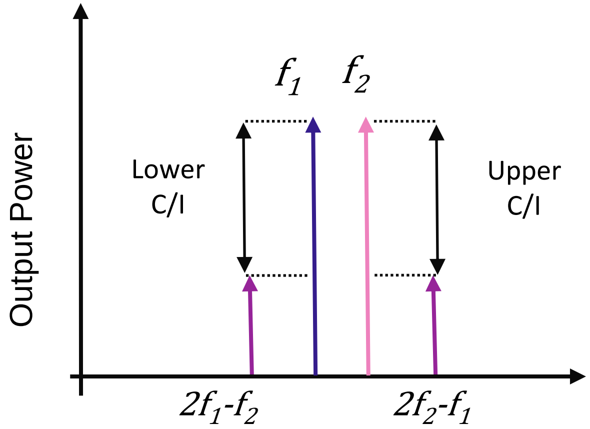
Output spectrum of 2nd & 3rd order two-tone intermodulation products

Intermodulation Products



Output spectrum of second and third order two-tone intermodulation products

Carrier to Intermodulation Ratio

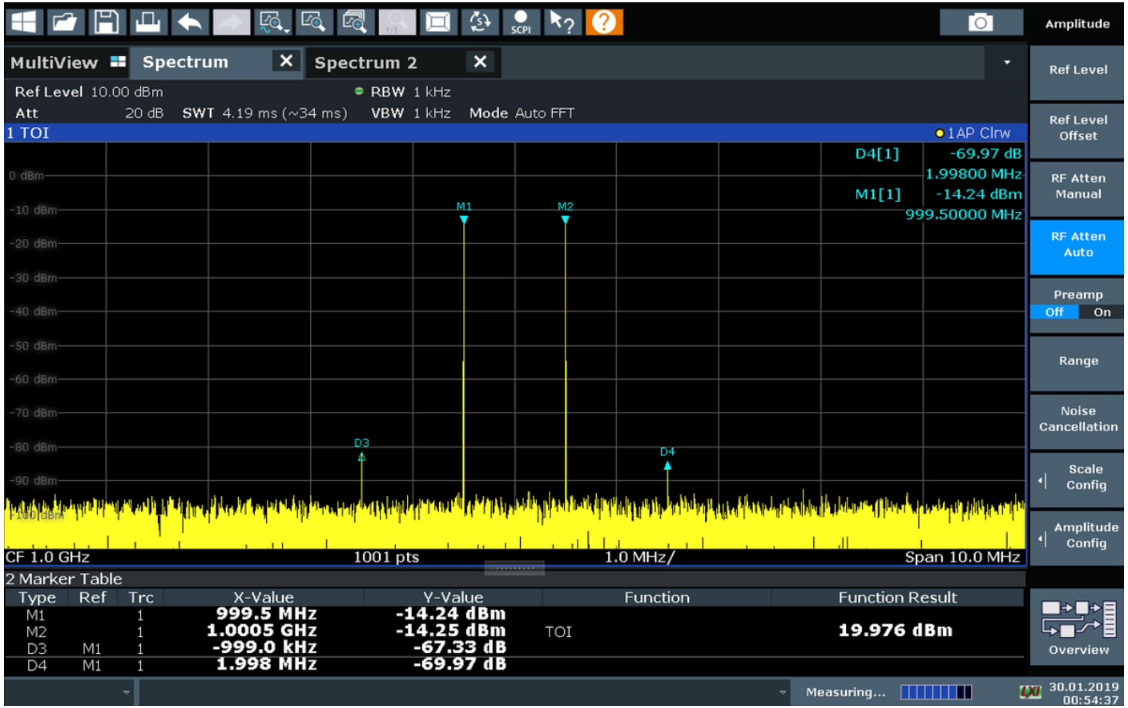


$$C/I = \frac{P_{out(fund)}}{P_{IMD}}$$

The carrier to intermodulation ratio is defined as the ratio of the power at the fundamental frequency and the intermodulation (IMD) output power.

This measure is usually described in **dBc**, meaning decibels below carrier.

Intermodulation Products



Source: https://upload.wikimedia.org/wikipedia/commons/1/15/Two_carrier_3rd_order_intermod_measurement.png

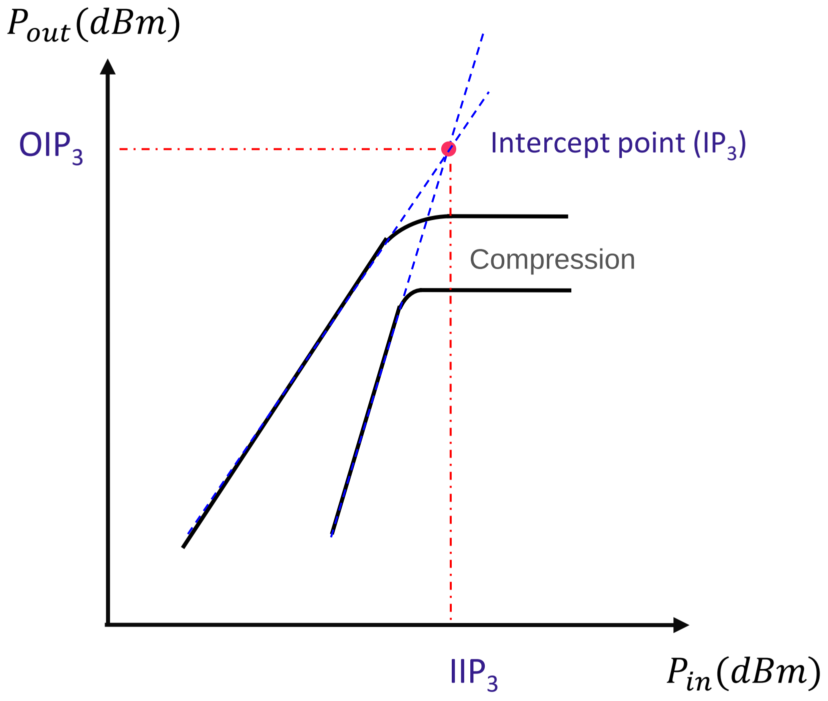
Intercept Point

$$u_o = a_o + a_1 V_o(\cos(\omega_1 t) + \cos(\omega_2 t)) + a_2 {V_o}^2(\cos(\omega_1 t) + \cos(\omega_2 t))^2 + a_3 {V_o}^3(\cos(\omega_1 t) + \cos(\omega_2 t))^3 + \cdots$$

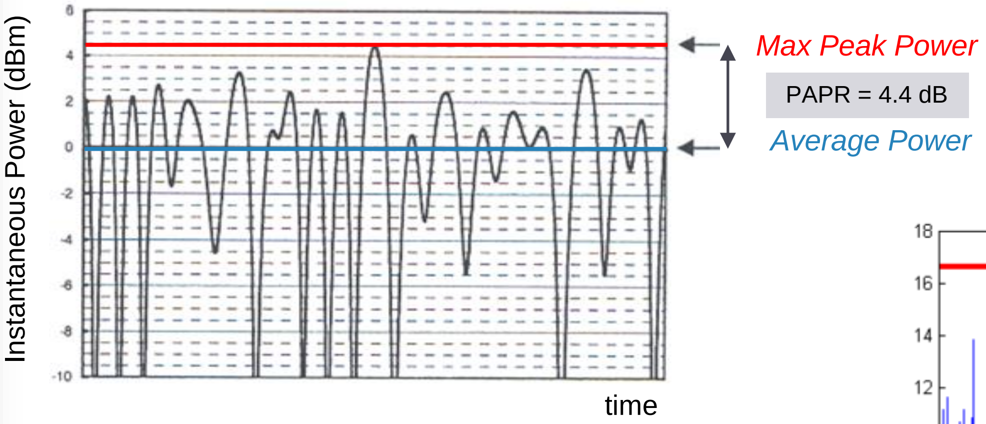
- For low input power levels, the 3rd order intermodulation products will be ‘relatively small’.
- As the input power increases, the power level of the 3rd order intermodulation product will increase quickly.
- There is one theoretical point where the the 3rd order intermodulation product will be equal with the power of the fundamental frequency → 3rd order intercept point (IP_3 or TOI)
- We can find the 3rd order intercept point graphically by plotting the output power at the fundamental frequency and third-order products versus input power (log scale).

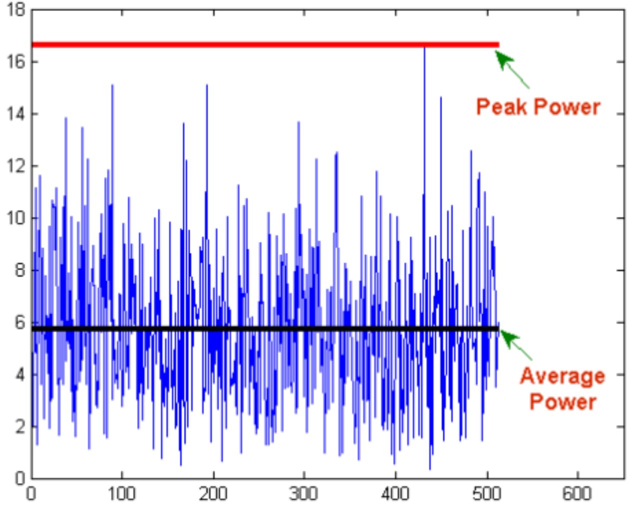
Intercept Point

- The extension of the idealized response of the power amplifier behavior is shown with dotted lines.
- The hypothetical intersection point where the fundamental frequency and the third-order powers would be equal is the third-order intercept point (IP_3).
- The third-order intercept point may be specified as either an *input power level* (*IIP_3*), or an *output power level* (*OIP_3*).



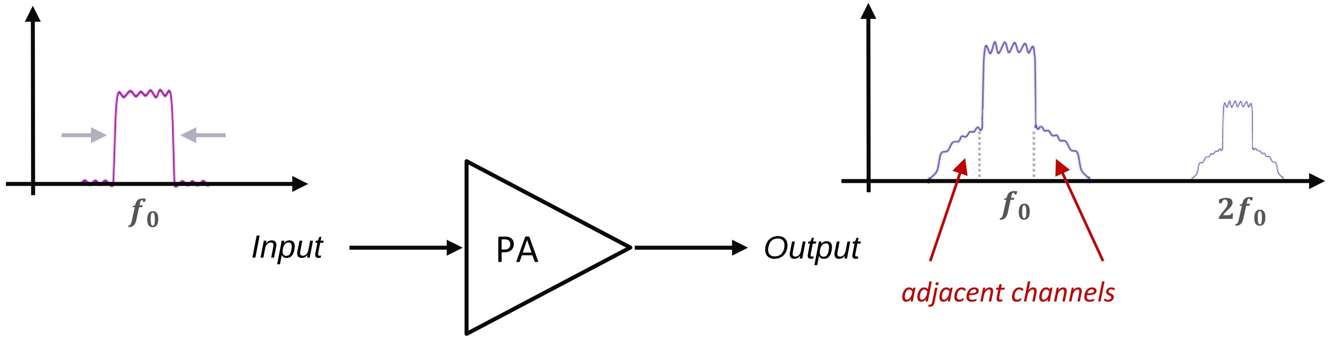
Adjacent Channel Power Ratio





Current wireless communication systems do not use single-tone or two-tone signals … but modulated signals with high peak to average power ratio (PAPR).

Adjacent Channel Power Ratio



The non-linearity of the power amplifier can distort the input signal and can cause interference at the adjacent channels (due to spectral regrowth).

Adjacent Channel Power Ratio

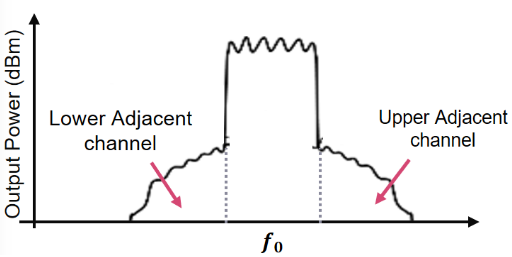
- The adjacent channel power ratio (ACPR) or adjacent channel leakage ratio (ACLR) is a metric for the spectrum regrowth in the adjacent channels.

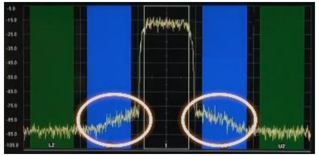
- $ACLR_L$ is the ratio between total output power measured in the fundamental zone (P_o), and the lower adjacent-channel power (P_{LA})

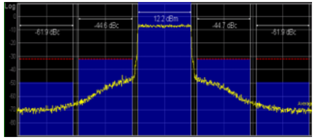
$$ACPR_L = \frac{P_o}{P_{LA}}$$

- $ACLR_U$ is the ratio between total output power measured in the fundamental zone (P_o), and the upper adjacent-channel power (P_{UA})

$$ACPR_U = \frac{P_o}{P_{UA}}$$

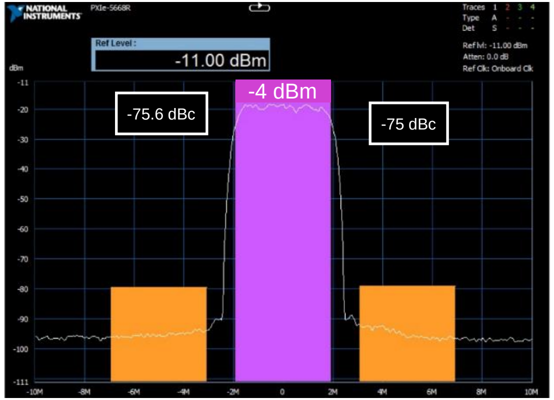






Source: https://www.anritsu.com/

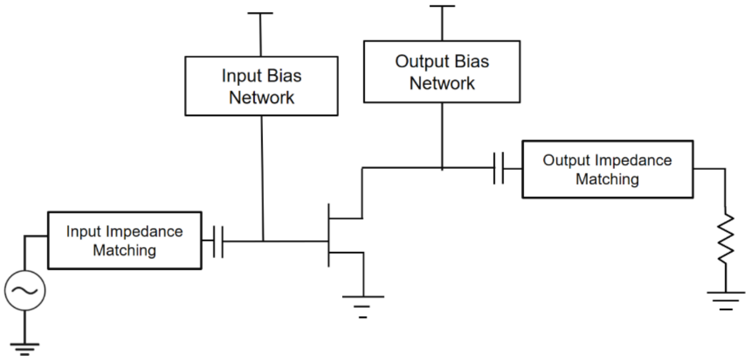
Adjacent Channel Power Ratio



ACPR is expressed in dBc to show the difference between the desired signal and the leakage at the adjacent channel.

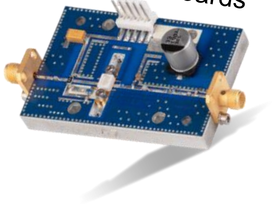
Source: https://www.ni.com

Power Amplifier Topology (simple)

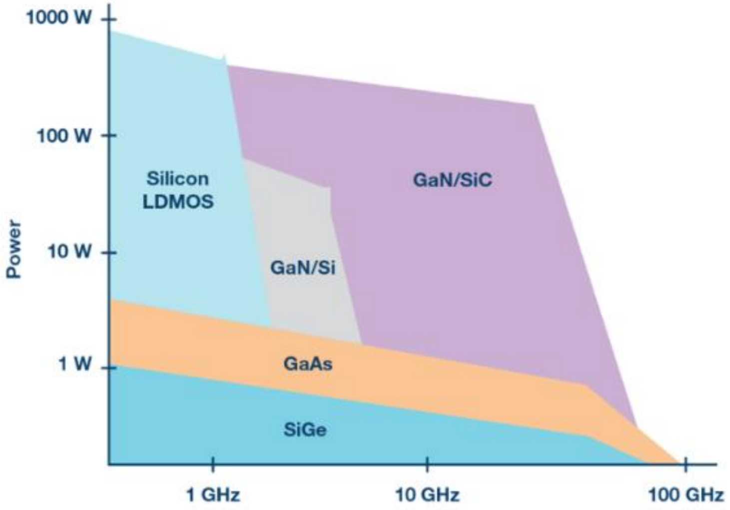


Schematic of power amplifier

Example of commercial PAs boards



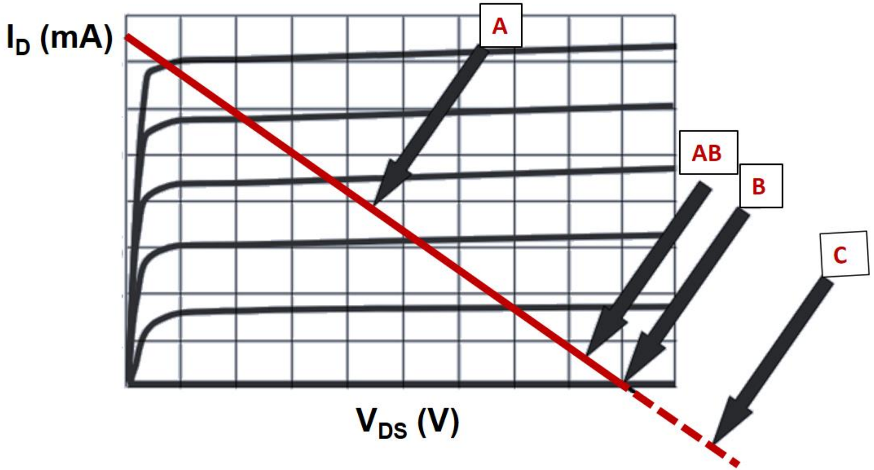
Transistor technology



Transistor technology selection:
* frequency
* power

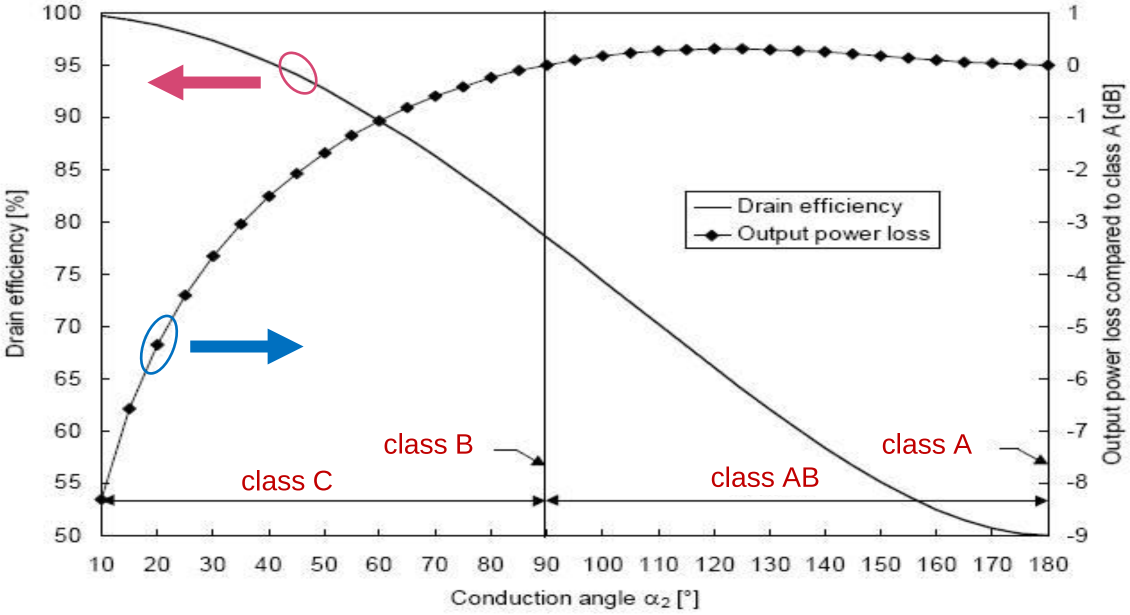
Another Important design specification: the polarization class

Power Amplifier classes



PA class choice : trade off between output power and efficiency

Efficiency and output power



Classes of operation

Class A amplifier

- transistor is biased to conduct over the entire range of the input signal cycle
- theoretical maximum efficiency: **50%**
- low noise amplifiers (LNA) and small-signal PAs typically class A

Class B amplifier

- transistor is biased to conduct only half of the input signal cycle
- two complementary transistors typically used in class B push-pull amplifier to provide amplification over the entire cycle
- theoretical maximum efficiency: **78%**

Classes of operation

Class AB amplifier

- transistor biased to conduct for more than half of the input signal cycle
- combination of class A and B:

  more efficient than class A power amplifier

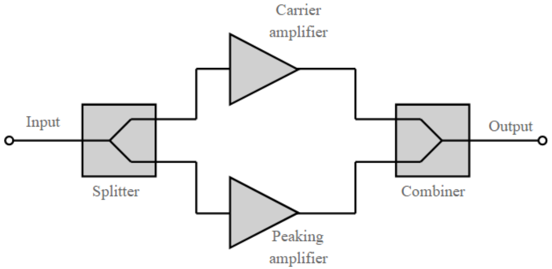
  more linear than class B amplifier

Class C amplifier

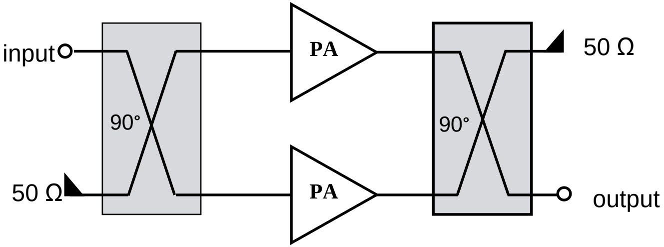
- transistor near cut off for more than half of the input signal cycle
- theoretical maximum efficiency: 100%

Class D, E….

More power amplifier topologies…



Doherty amplifier



Balanced amplifier

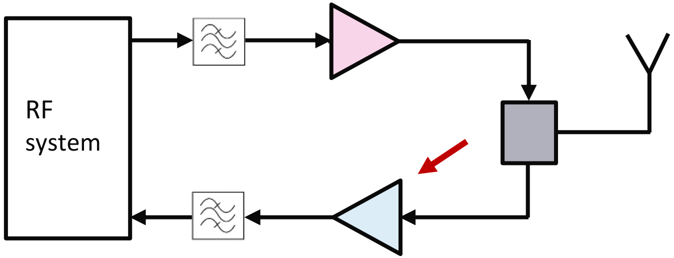
Outline

- Power Amplifier (PA)
- Low Noise Amplifier (LNA)
- Antennas
- Duplexer/ Switch

Low Noise Amplifier (LNA)

The Low Noise Amplifier (LNA) is an amplifier typically found at the receiver path of a transceiver.

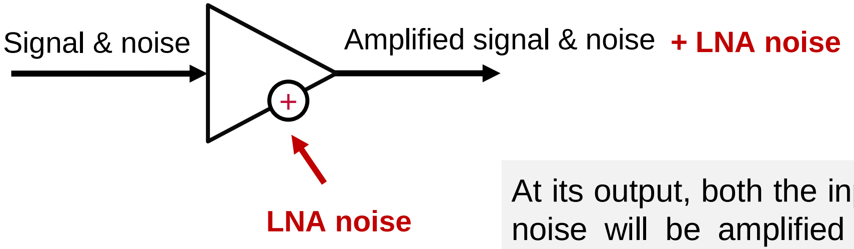
Its role is to amplify the low-power received signal to the desired level with the addition of minimum noise!



Key performance parameters are the gain, efficiency, linearity and <u>noise figure</u>…

Low Noise Amplifier

The signal at the input of the LNA contains the desired signal plus some unwanted noise.



At its output, both the input signal and noise will be amplified by the same amount (gain). However, the noise of the LNA will appear at the output as well.

Signal to Noise Ratio

$$SNR = \frac{P_s}{P_N} = \frac{signal\ power}{noise\ power}$$

Low Noise Amplifier

- The noise factor measures the change (degradation) of the Signal to Noise Ratio (SNR) between the input and output of the LNA.
- The noise figure (NF) is the log scale of the noise factor.

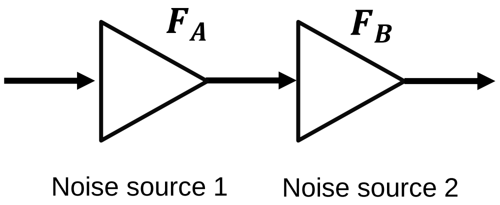
Noise Factor (F)

$$F = \frac{SNR_{in}}{SNR_{out}}$$

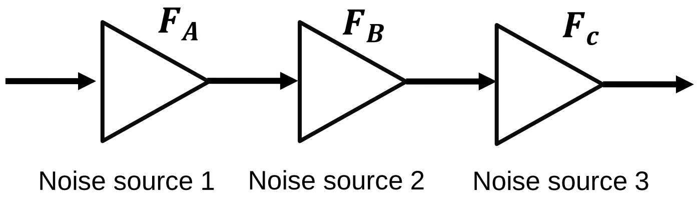
Noise Figure (NF)

$$NF = 10\log_{10}(F) = 10\log_{10}\left(\frac{SNR_{in}}{SNR_{out}}\right)$$

Cascaded Topology



$$F_{tot} = F_A + \frac{F_B - 1}{G_A}$$

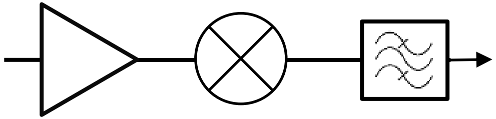


$$F_{tot} = F_A + \frac{F_B - 1}{G_A} + \frac{F_C - 1}{G_A G_B}$$

- In a cascaded system where many stages are connected together (LNAs, filters etc), the overall noise figure should be calculated.
- The performance of the first stage is the most important

Cascaded Noise Figure Example

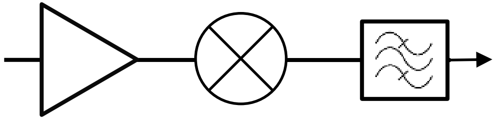
Calculate the overall gain and noise figure



Amplifier NF=3 dB
G=10 dB
Mixer conversion loss= 7 dB
Filter insertion loss 4 dB

Cascaded Noise Figure Example

Calculate the overall gain and noise figure



Amplifier NF=3 dB G=10 dB Mixer conversion loss= 7 dB Filter insertion loss 4 dB

Solution

$$F_{chain} = F_A + \frac{F_B - 1}{G_A} + \frac{F_C - 1}{G_A G_B}$$

$$F_{chain} = 10^{(3/10)} + \frac{10^{(7/10)}-1}{10^{(10/10)}} + \frac{10^{(4/10)}-1}{10^{(10/10)}10^{(-7/10)}} = 3.15$$

$$NF = 10log10(3.15) = 5\ dB$$

$$G_{chain} = 10 - 7 - 4 = -1\ dB$$

LNA Perfomance Examples

- Perfomance of two commercial wideband LNAs (ADL8104 and PMA-545+)

0.4 GHz TO 0.6 GHz FREQUENCY RANGE

V_{DD} = 5 V, total supply current (I_{DQ}) = 150 mA, R_{BIAS} = 90.9 Ω, and T_A = 25°C, unless otherwise noted.

Table 1.

Parameter	Min	Typ	Max	Unit	Test Conditions/Comments
FREQUENCY RANGE	0.4		0.6	GHz	
GAIN	11.5	14		dB	
Gain Variation over Temperature		0.036		dB/°C	
NOISE FIGURE		3.5		dB	
RETURN LOSS					
Input		12		dB	
Output		13		dB	
OUTPUT					
OP1dB	16.5	19		dBm	
Saturated Output Power (P_{SAT})		21		dBm	
OIP3		32		dBm	Measurement taken at output power (P_{OUT}) per tone = 5 dBm
OIP2		50		dBm	Measurement taken at P_{OUT} per tone = 5 dBm
POWER ADDED EFFICIENCY (PAE)		18		%	Measured at P_{SAT}

ADL8104

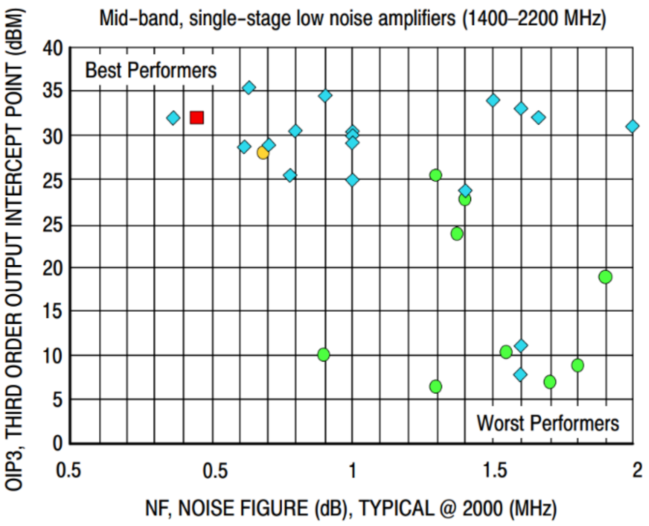
Electrical Specifications[1] at 25°C, Zo=50Ω, *(refer to characterization circuit)*

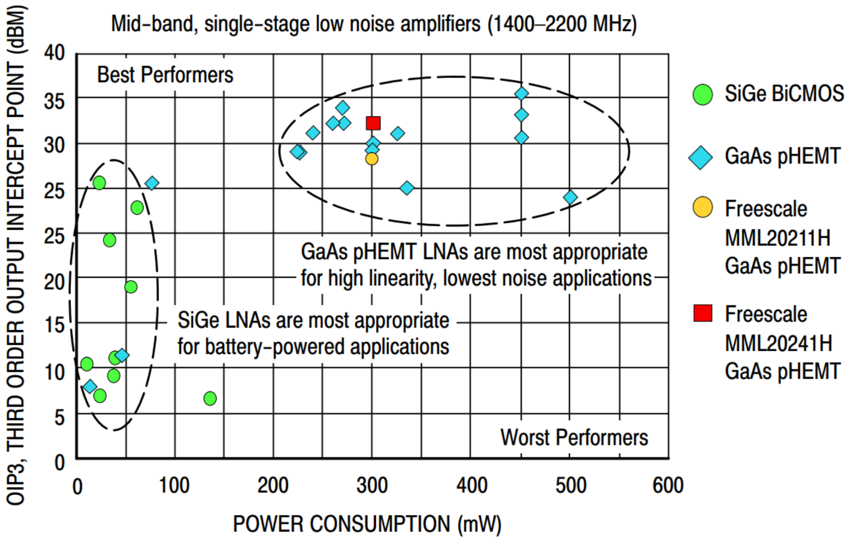
Parameter	Condition (GHz)	Min.	Typ.	Max.	Units
Frequency Range		0.05		6.0	GHz
DC Voltage (V_d)			3.0		V
DC Current (I_d)[6]		65	80	98	mA
DC Current (I_{Rbias})			5.6		mA
Noise Figure	0.05		1.3	—	dB
	0.5		0.8	—	
	1.0		0.8	—	
	2.0		1.0	1.3	
	3.0		1.2	—	
	4.0		1.5	—	
	5.0		2.0	—	
	6.0		2.4	—	
Gain	0.05	—	26.1	—	dB
	0.5	—	23.3	—	
	1.0	—	19.4	—	
	2.0	12.7	14.2	15.6	
	3.0	—	11.1	—	
	4.0	—	8.9	—	
	5.0	—	7.0	—	
	6.0	—	5.5	—	
Output Power @ 1 dB compression [2]	0.05	—	19.6		dBm
	0.5	—	19.9		
	1.0	—	19.3		
	2.0	18.3	20.3		
	3.0	—	20.1		
	4.0	—	20.7		
	5.0	—	20.0		
	6.0	—	21.2		

PMA-545+

Source: Analog Devices & Mini-circuits

LNA Technology





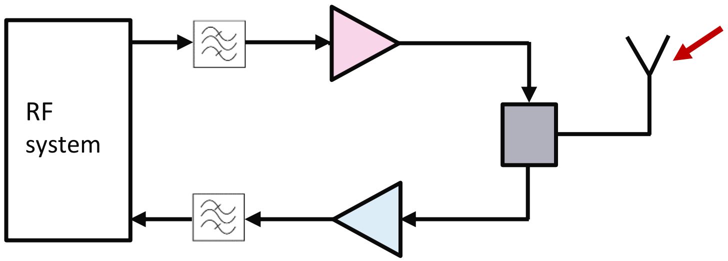
Source: https://www.nxp.com/

Outline

- Power Amplifier (PA)
- Low Noise Amplifier (LNA)
- Antennas
- Duplexer/ Switch

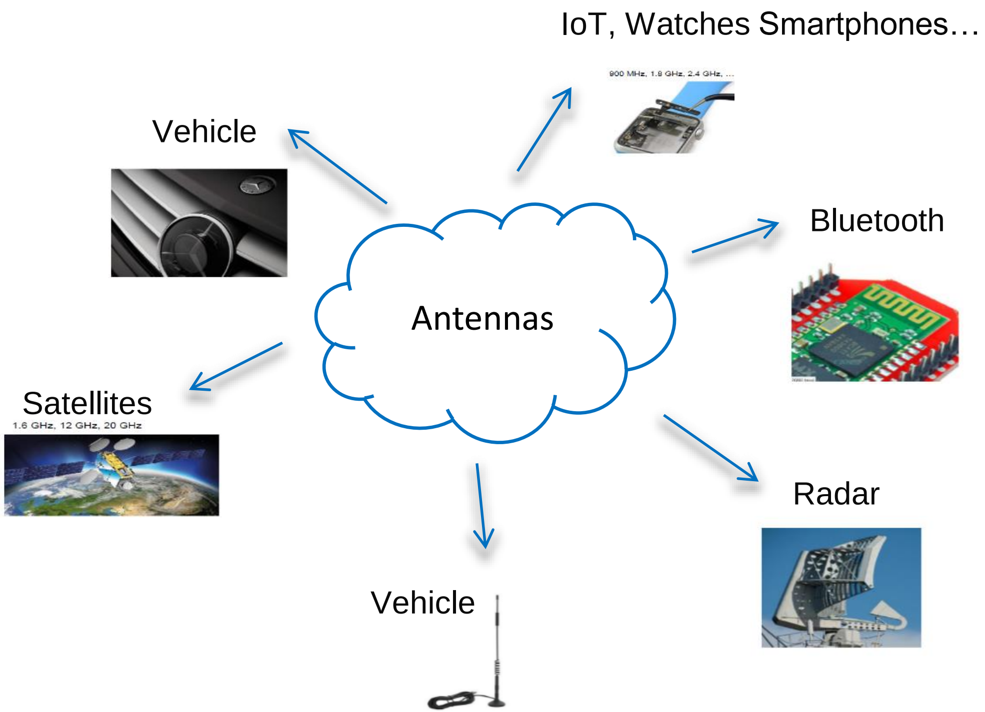
Antennas

- **Antennas** are responsible for the transmission and reception of the radio waves.There is a range of antenna types (e.g. wire antennas, microstrip antennas, reflector antennas).



Key performance parameters are the bandwidth, gain, efficiency and radiation pattern…

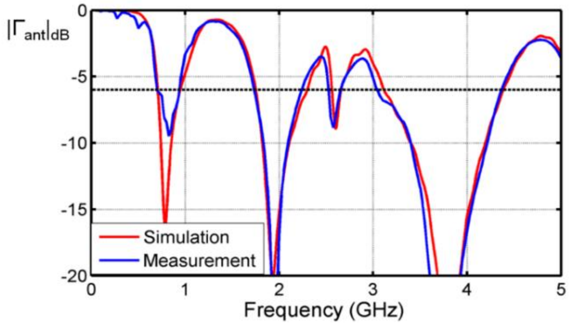
Antennas Applications

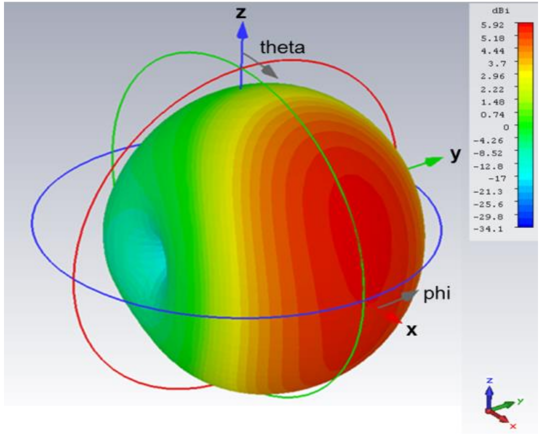


Antennas are everywhere!

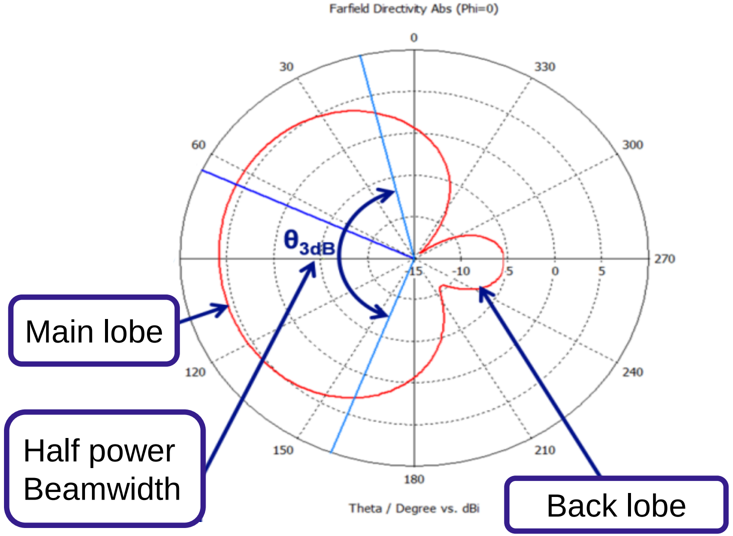
Antennas Design Parameters

- Examples of antenna design parameters: bandwidth, gain and radiation pattern.
- The radiation pattern of an antenna defines how the radiated power varies in space.

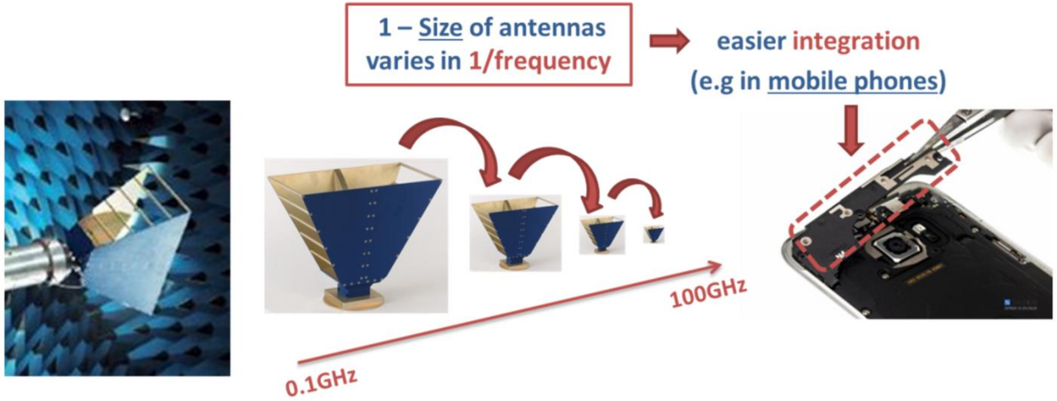




Radiation pattern



Antennas


1 – Size of antennas
varies in 1/frequency
easier integration
(e.g in mobile phones)
0.1GHz
100GHz

Antennas Samsung's Galaxy S8 & Apple Watch 2

- Samsung's Galaxy S8: antennas for Bluetooth, GPS, Wi-Fi, and NFC communications, at least four LTE cellular antennas.

- Apple Watch 2 (bottom): the group of antennas (removed) includes Wi-Fi, Bluetooth, and GPS, newer models include LTE cellular antennas.

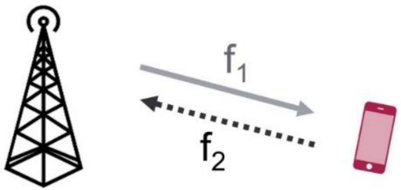
Source: https://spectrum.ieee.org/

Outline

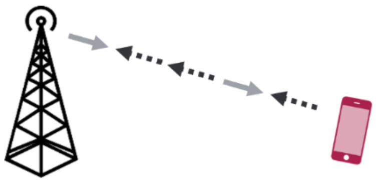
- Power Amplifier (PA)
- Low Noise Amplifier (LNA)
- Antennas
- Duplexer/ Switch

FDD and TDD systems: design difference

FDD system



TDD system

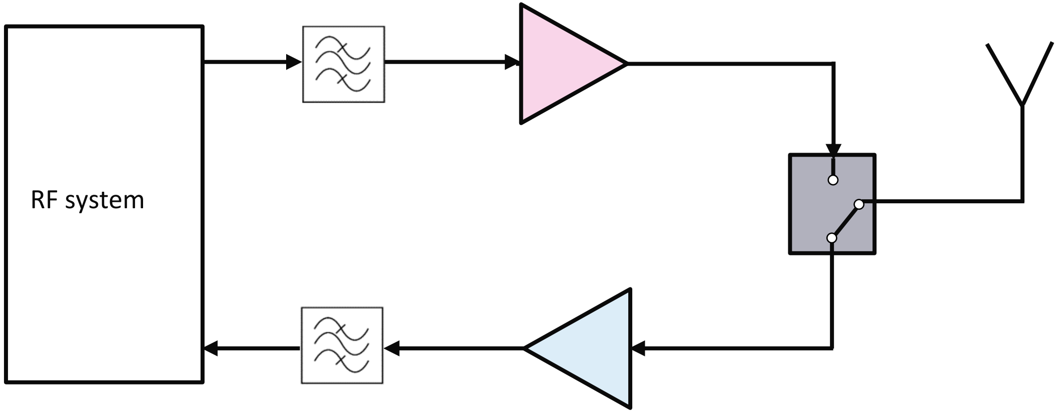


In a Frequency Division Duplex system, a duplexer can be used to separate the signals paths for the transmitter and the receiver.

In a Time Division Duplex system, an RF switch can be used (same Tx & Rx frequency).

Tx/Rx Switch

In TDD systems, a Tx/Rx switch can be used to connect the antenna at the output of the transmitter and the receiver chain.



Key performance parameters are the insertion loss, isolation (signal leakage between the Tx and Rx) and switching speed…

Tx/Rx Switch

- A key parameter for the operation of a Tx/Rx switch is the switching speed.
- The switching speed can be calculated based on the time required to change from the ‘off-state’ to the ‘on-state’ or from ‘on-state’ to the ‘off-state’.

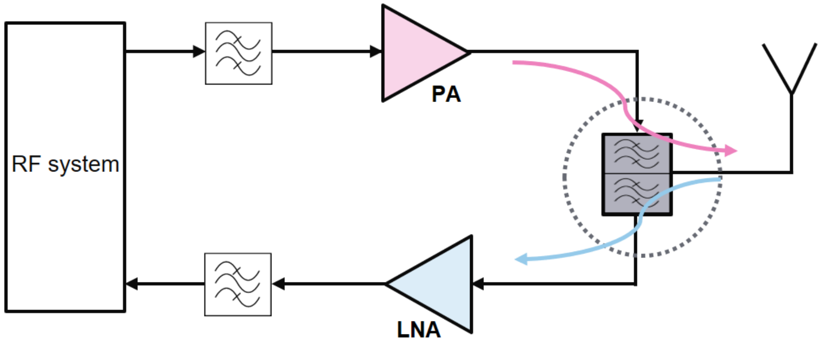
Transmit RF switching time	tsw	10% to 90% RF on, repetition rate = 0.1 MHz, @ 2.6 GHz		250		ns

Example of commercial RF switch

Source: Skyworks - SKY12215-478LF

Duplexer

A duplexer is a three port device that allows the transmitter and the receiver operating at different frequencies to share the same antenna (typically the transmit and receive frequency are quite ‘close’).



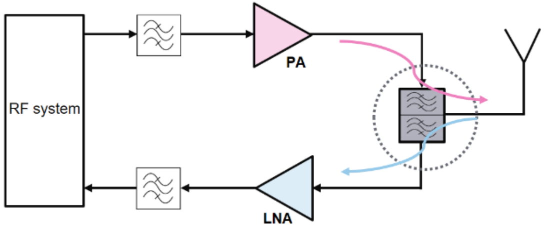
Key performance parameters are the insertion loss, isolation…

Duplexer Insertion Loss

The duplexer is one of the most important components for both the Tx and Rx chain.

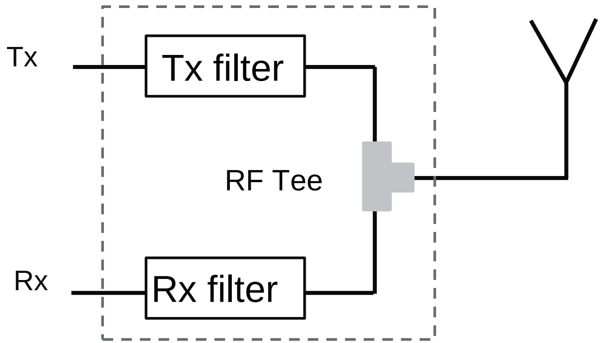
What does duplexer high insertion loss mean for the transmitter?

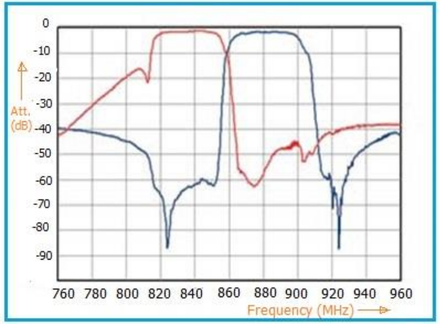
What does duplexer high insertion loss mean for the receiver?



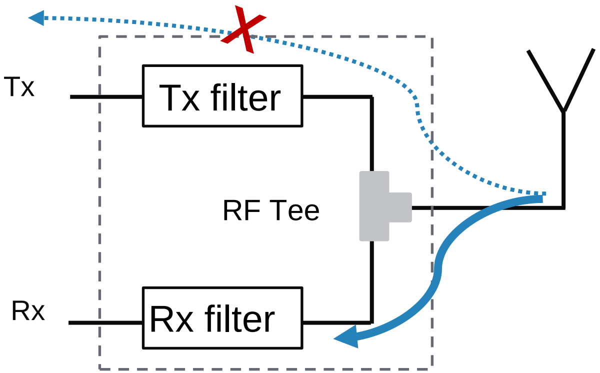
Duplexer

Very selective band pass filters are required to separate uplink and downlink signals

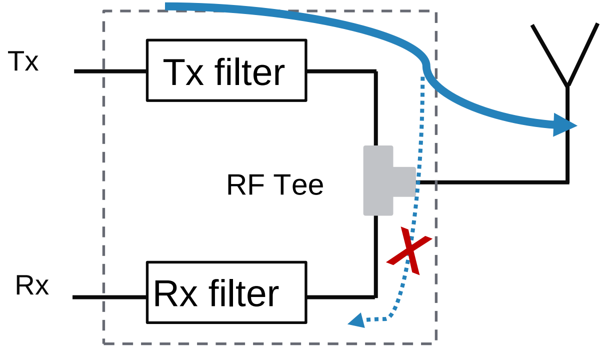




Duplexer Isolation

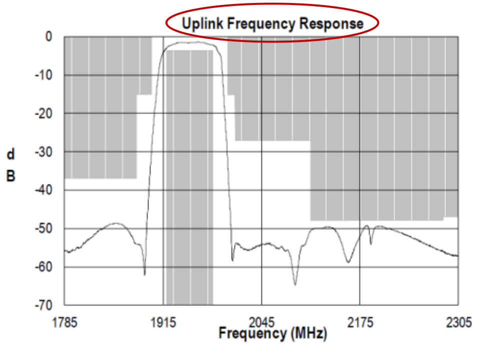


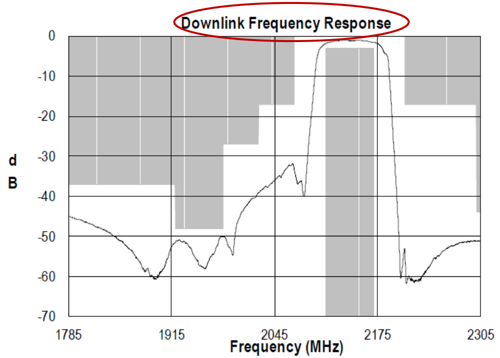
Duplexer Isolation



Duplexer performance example

LTE Band Number	Uplink (MHz)	Downlink (MHz)	Passband Width (MHz)	Duplexer Gap (MHz)
1	1920 - 1980	2110 - 2170	60	130





Electrical Specifications [1, 2] – Band 1 Uplink

Parameter [3]	Conditions	Min	Typ [4]	Max	Units
Center Frequency		–	1950	–	MHz
Max Insertion Loss	1920 – 1980 MHz (-40 to +85 °C)	–	2.0	3.8	dB
Average Insertion Loss	1920 – 1925 MHz (-40 to +85 °C)	–	–	3.0	dB
	1925 – 1975 MHz (-40 to +85 °C) (5 MHz sliding Window)	–	–	2.4	dB
	1975 – 1980 MHz (-40 to +85 °C)	–	–	2.7	dB
Lower Band edge [5]	3.5dB	–	–	1920	MHz
Upper Band edge [5]		1980	–	–	
Amplitude Ripple [6]	1920– 1980 MHz	–	1.5	1.6	dB p-p
	1920 – 1980 MHz (-40 to +85 °C)	–	1.5	2.2	dB p-p
Attenuation [5]	0.9 – 1880 MHz	37	41.6	–	dB
	1880 – 1900 MHz	13	26.9	–	
	2000 – 2010 MHz	13	35.4	–	
	2010 – 2110 MHz	27	50.6	–	
	2110 – 2285 MHz	46.5	49.1	–	
	2285 – 2485 MHz	46	49.2	–	
	2485 – 2690 MHz	43.5	45.4	–	
	2690 – 3400 MHz	22	35.4	–	
	3400 – 3700 MHz	22	24.0	–	
	3700 – 3800 MHz	20	22.0	–	
	3800 – 5850 MHz	13.8	18.5	–	
Source/Load Impedance [7]	Single-ended	–	50	–	Ω

Notes:

Test conditions unless otherwise noted: Temp= +25°C

Electrical Specifications [1, 2] – Band 1 Downlink

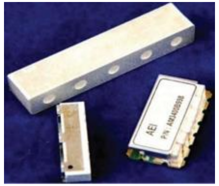
Parameter [3]	Conditions	Min	Typ [4]	Max	Units
Center Frequency		–	2140	–	MHz
Max Insertion Loss	2110 – 2170 MHz (-40 to +85 °C)	–	2.0	3.2	dB
Average Insertion Loss	2110 – 2115 MHz (-40 to +85 °C)	–	–	2.5	dB
	2115 – 2165 MHz (-40 to +85 °C) (5 MHz sliding Window)	–	–	2.4	dB
	2165 – 2170 MHz (-40 to +85 °C)	–	–	2.7	dB
Lower Band edge [5]	3.5dB	–	–	2110	MHz
Upper Band edge [5]		2170	–	–	
Amplitude Ripple [6]	2110– 2170 MHz @ 25 °C	–	1.0	1.2	dB p-p
	2110 – 2170 MHz @ -40 to +85 °C	–	1.0	1.8	dB p-p
Attenuation [5]	0.9 – 1920 MHz	37	40.3	–	dB
	1920 – 1980 MHz	48	50.0	–	
	1980 – 2025 MHz	27	39.3	–	
	2025 – 2070 MHz	17	31.8	–	
	2210 – 2300 MHz	17	51.1	–	
	2300 – 2690 MHz	44	46.2	–	
	2690 – 3400 MHz	27	35.9	–	
	3400 – 4200 MHz	17	33.7	–	
	4200 – 4400 MHz	32	33.6	–	
	5150 – 5850 MHz	15	18.5	–	
Isolation S32	1920—1980Mhz	50	–	–	dB
	2110—2170Mhz	49	–	–	dB

Source: Qorvo - BAW Duplexer - QPQ1282

Filter types

To choose the technology
Trade off : size / frequency / power

cavity & ceramic filter



ceramic filters

cavity & LC filter

ceramic & SAW
(Surface Acoustic Wave) filter

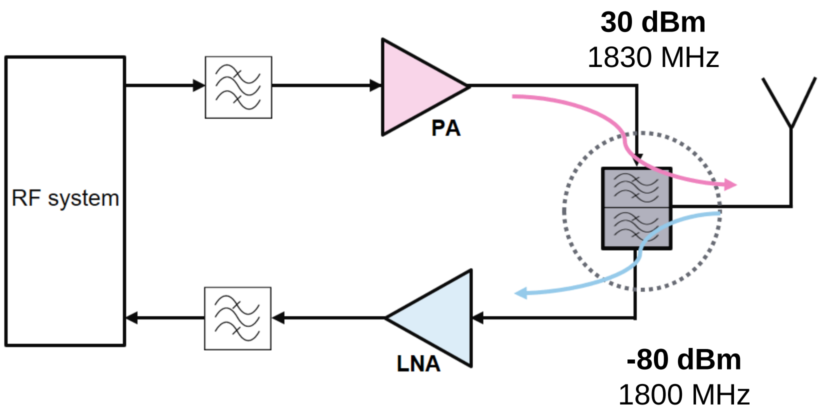
LC filter

Source: http://anatechelectronics.com/

Duplexer Isolation example

Characteristics of the transceiver shown below:

- transmitted power at 1830 MHz : 30 dBm
- receiver power at 1800 MHz : -80 dBm
- 70 dB isolation duplexer



Source: J.C. Pedro, N. Carvalho, Intermodulation Distortion in Microwave and Wireless circuits

Duplexer Isolation example

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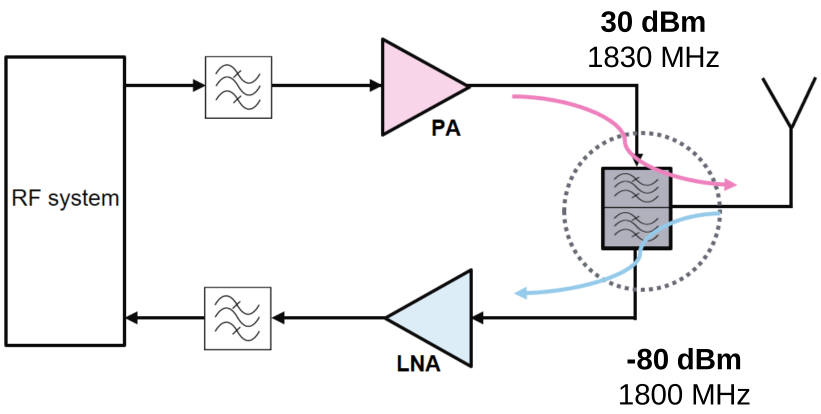
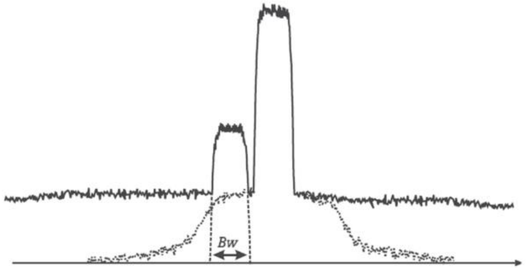


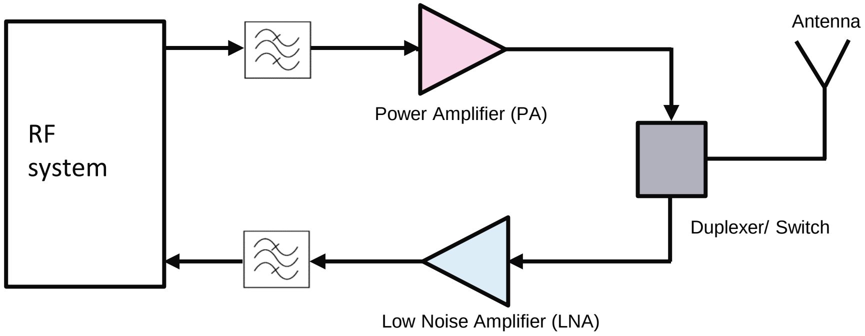


The receiver will be driven by the received signal of -80 dBm plus an interferer of 40 dB stonger!

Source: J.C. Pedro, N. Carvalho, Intermodulation Distortion in Microwave and Wireless circuits

Summary of today's lecture

- Overview of RF front end topology
- Analysis of main RF components:
  - Power Amplifier (PA)
  - Low Noise Amplifier (LNA)
  - Antenna
  - Duplexer/RF switch



Bibliography & Useful Resources

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14 - https://www.mwrf.com/