Loss, noise and two Friis equations

RF transceiver block diagram

Common RF transceiver includes:

- RX chain
- TX chain
- One or more antennas

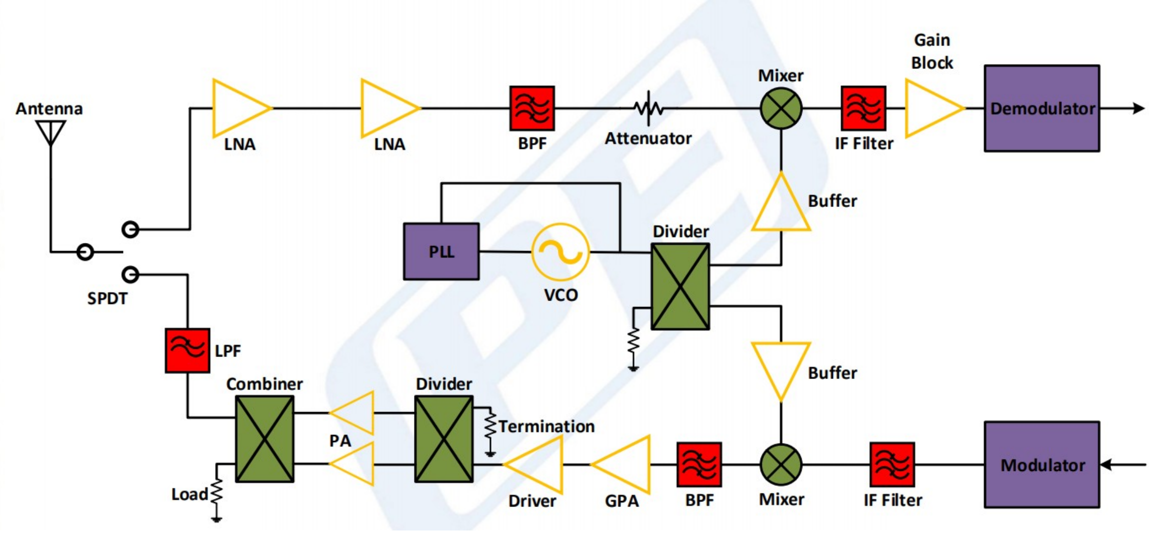

Image source:

www.pasternack.com/pages/Technical-Charts/RF-Transceiver.pdf

RF transceiver block diagram

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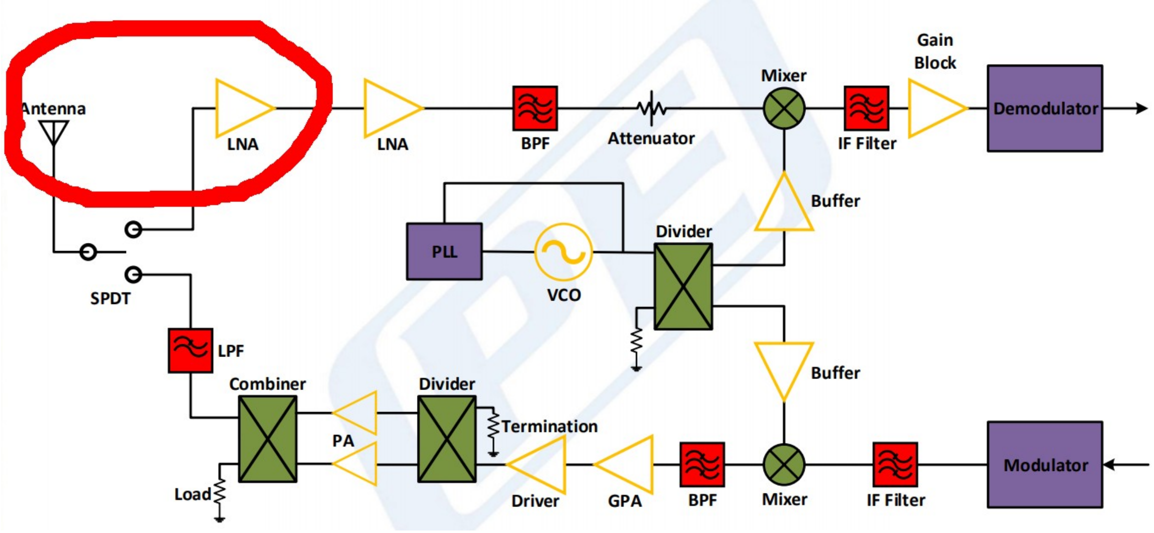


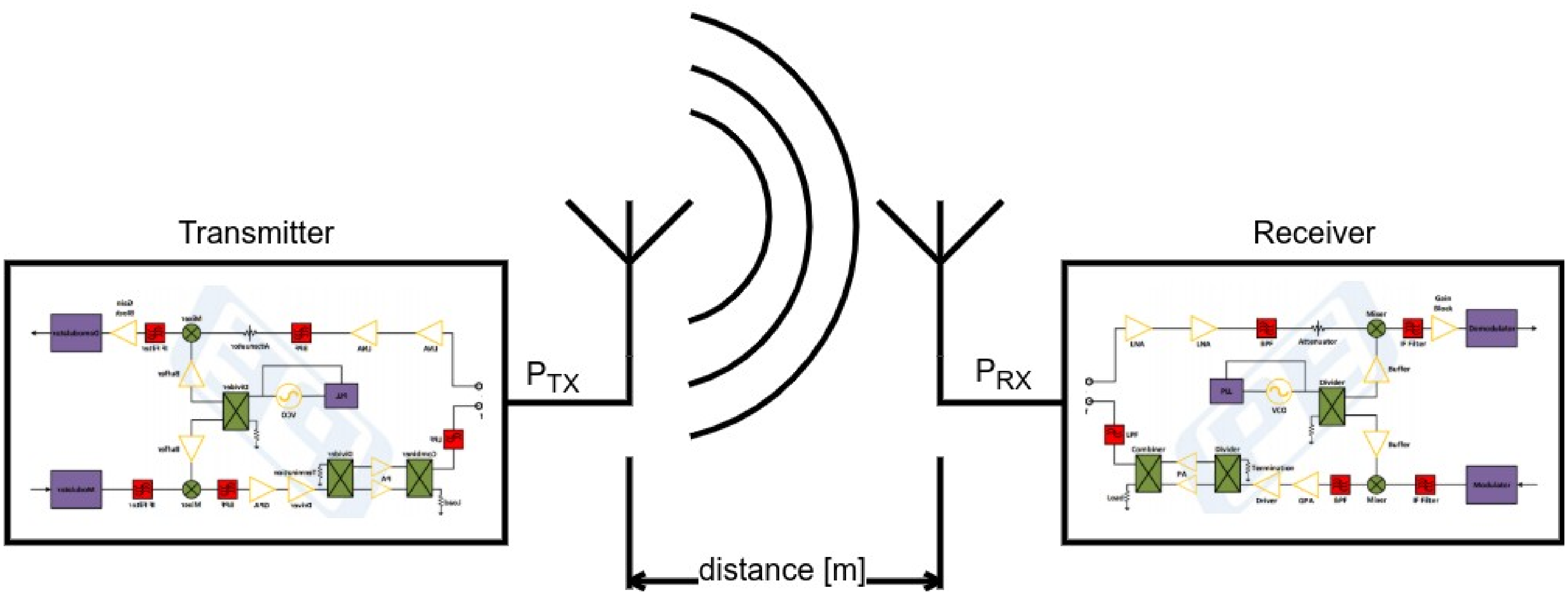
Image source:

www.pasternack.com/pages/Technical-Charts/RF-Transceiver.pdf

RF link budget

Common RF communication system consists of one or several transceivers.

It is important to determine relation between transmitted power, distance and received power to design system properly.



RF link budget

Friis transmission equation is often used to calculate received signal power:

$$P_{RX} = P_{TX} \cdot D_{TX} \cdot D_{RX} \cdot \left(\frac{\lambda}{4\pi d}\right)^2,$$

where

- P_{RX} – received power [W]
- P_{TX} – transmitted power [W]
- D_{RX} – receiver antenna directivity
- D_{TX} – transmitter antenna directivity
- λ – wavelength of signal [m]
- d – distance between RX and TX [m]

RF link budget logarithmic form

Example of RF link budget calculation:

P_{TX} = 1 W, D_{TX} = 10, D_{RX} = 1, d = 100 m, f=800 MHz

$$P_{RX} = 1 \cdot 10 \cdot 1 \cdot \left(\frac{0.375}{4\pi \cdot 100}\right)^2 = 0.0000009\,W = 0.9\,uW$$

The logarithmic form of the equation allows you to simplify calculations, which consist of a large number of arguments and a lot of multiplications:

- W → dBm
- Ratio → dB
- Multiplication → Summation
- Division → Subtraction

RF link budget logarithmic form

Logarithmic conversion formulas:

- dB basic formula

$$D_P = 10 \cdot lg \frac{P_2}{P_1}$$

- W $\rightarrow$ dBm conversation formula

$$P[dBm] = 10 \cdot lg \frac{P[W]}{0.001 W}$$

- Friis equation logarithmic form

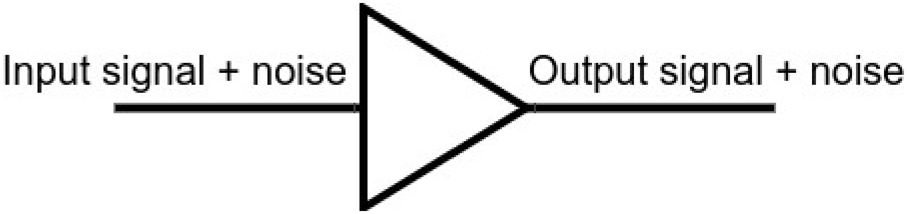
$$P_{RX}[dBm] = P_{TX}[dBm] + D_{TX}[dB] + D_{RX}[dB] + \left(\frac{\lambda}{4 \pi d}\right)^2 [dB]$$

- Previous example in logarithmic form:

$$P_{RX}[dBm] = 30[dBm] + 10[dB] + 0[dB] + (-70.5)[dB] = -30.5[dBm]$$

Noise figure

Noise figure is a measure of degradation of the signal-to-noise ratio (SNR) in a signal chain.



SNR degradation on QPSK constellation

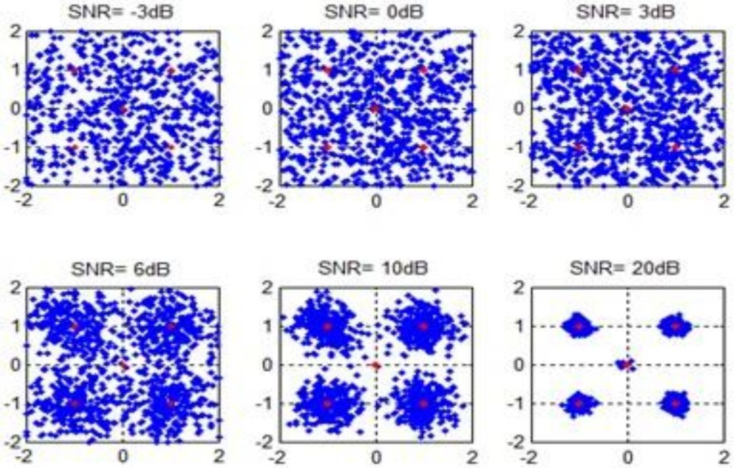


Image source:

https://docplayer.net/45205148-Dsp-based-phase-lock-loops-for-carrier-and-timing-recovery-at-low-signal-to-noise-ratio-a-thesis-presented-to-the-faculty-of.html

Noise figure

Noise figure formula:

$$NF = 10 \cdot lg \frac{S_i / N_i}{S_o / N_o} = SNR_i[dB] - SNR_o[dB]$$

NF of ideal element is 0 dB. In fact it is always >0 dB

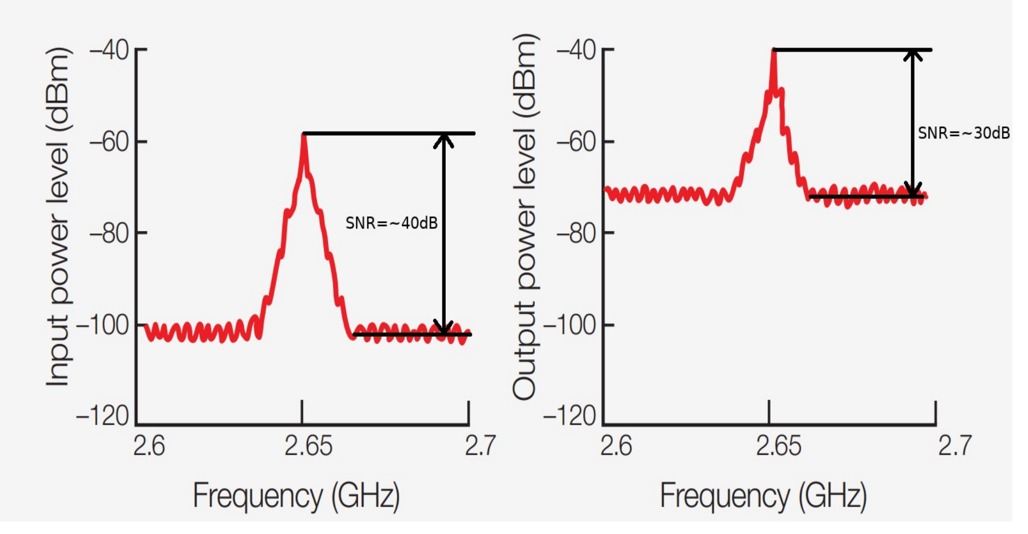


Image source:

https://literature.cdn.keysight.com/litweb/pdf/5952-8255E.pdf

Noise figure

In noise-sensitive applications low-noise amplifiers (LNA) are used.

Noise figure is usually described in amplifier datasheet.

There are 2 datasheet parameter tables for general-purpose amplifier (on the left picture) and for LNA (on the right picture) for example

Parameter	Vcc = +5V			Units
	Min.	Typ.	Max.	
Frequency Range	DC - 6			GHz
Gain	14	17	20	dB
Gain Variation Over Temperature		0.02	0.03	dB/°C
Input Return Loss		7		dB
Output Return Loss		6		dB
Reverse Isolation		30		dB
Output Power for 1 dB Compression (P1dB) @ 1.0 GHz	11	14		dBm
Saturated Output Power (Psat) @ 1.0 GHz		15		dBm
Output Third Order Intercept (IP3) @ 1.0 GHz	24	27		dBm
Noise Figure		6.5		dB
Supply Current (Icc)		50		mA

Parameter	Min	Typ.	Max
Frequency Range	0.7 - 2.2		
Gain	10	13	
Gain Variation Over Temperature		0.01	0.02
Input Return Loss		12	
Output Return Loss		12	
Reverse Isolation		20	
Output Power for 1 dB Compression (P1dB)	19	21	
Output Third Order Intercept (IP3)	35	[illegible]	
Noise Figure		2.3	
Supply Current (Icq)	90	[illegible]	120

Image sources:

https://www.analog.com/media/en/technical-documentation/data-sheets/hmc313.pdf

https://www.analog.com/media/en/technical-documentation/data-sheets/hmc639.pdf

Noise figure

Noise figure of passive device (e.g. filter, cable, switch, attenuator) is equal to its loss

For example, 4 inch long trace can attenuate Wi-Fi 5GHz signal by 3 dB and add 3 dB noise due to noise figure

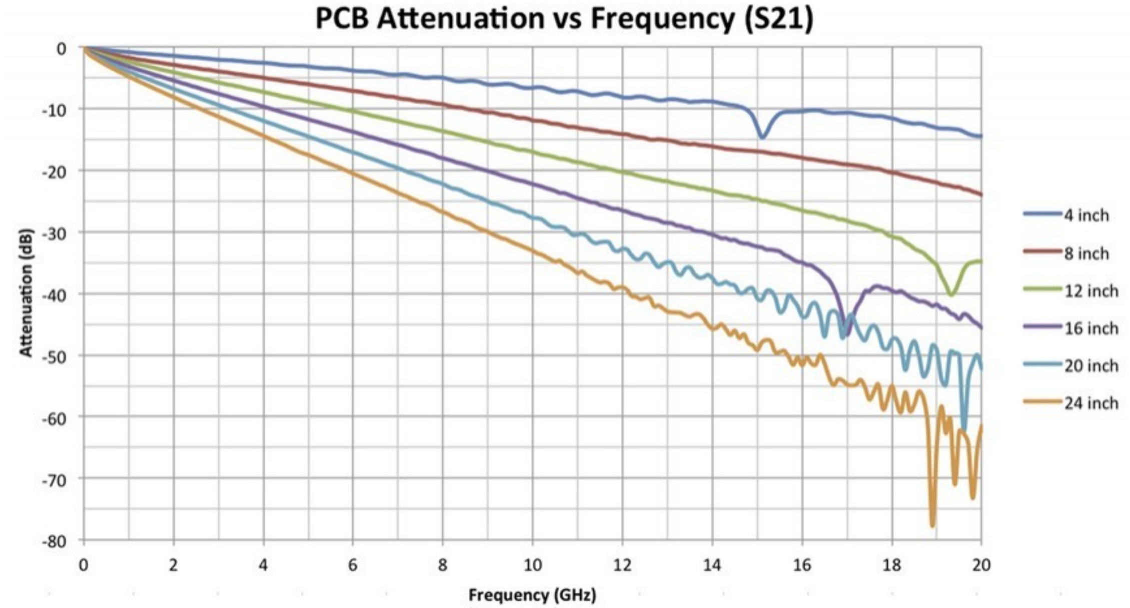
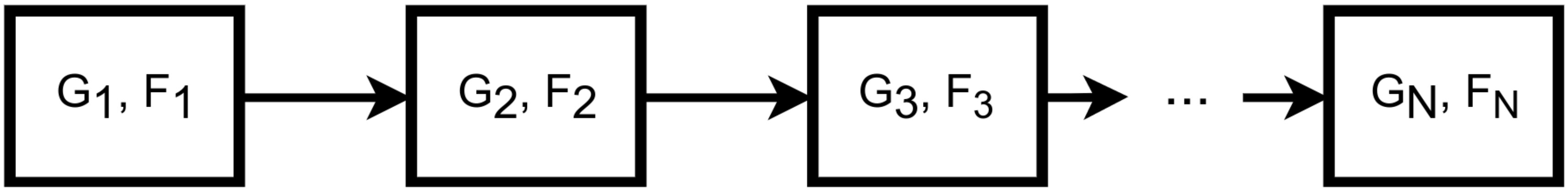


Image source:

http://signal-processing.mil-embedded.com/articles/can-pcb-handle-speed/

Noise figure

Friis formula for cascaded devices



$$G = G_1 + G_2 + G_3 + ... + G_n$$

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + ... + \frac{F_n - 1}{G_1 G_2 G_3 ... G_N},$$

where

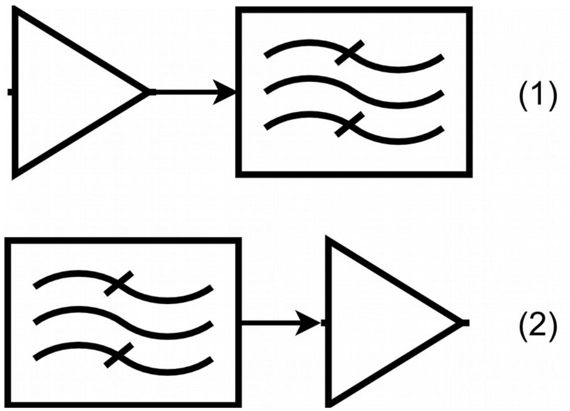
F_N is device noise factor (noise figure converted to ratio)

G_N is device gain (linear, not in dB)

This formula shows that first device noise factor (i.e. noise figure) and gain are most important for overall system noise factor

Noise figure

Let’s consider a simple GPS-receiver input circuit consists of two elements: low noise amplifier and band-pass filter. There are two variants of cascade connection for two elements:



Device	Description	NF, dB	G, dB
LNA	BGU7004 (LNA for GPS application)	0.85	16.5
Band-pass filter	SF1186B-2 (BPF for GPS application)	2.7	-2.7
(1)	LNA + BPF	0.92	13.8
(2)	BPF + LNA	3.55	13.8

Noise figure of system decreased by ~2.6 dB (almost 2 times) due to components rearrangement. BTW, BPF+LNA connection has some pros (i.e. better out-of-band signal immunity)

Noise figure

Conclusions

- It is important to calculate noise figure of RX chain for noise-sensitive applications
- It is important to place LNA as close to the antenna as possible
- Active antenna can be used to reduce noise figure of receiver
- Properly designed RX chain can increase range of wireless connection and increase battery life

Matching networks

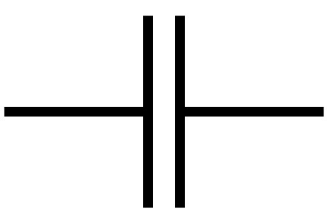
Complex impedance

Impedance is the measure of current response when a voltage is applied. It can be represented in a complex form:

$$Z = R + j \cdot X$$

$$Z = R \left(X = 0 \right)$$

$$Z = j \cdot \omega \cdot L \left(R = 0 \right)$$



$$Z = \frac{1}{j \cdot \omega \cdot C} \left(R = 0 \right)$$

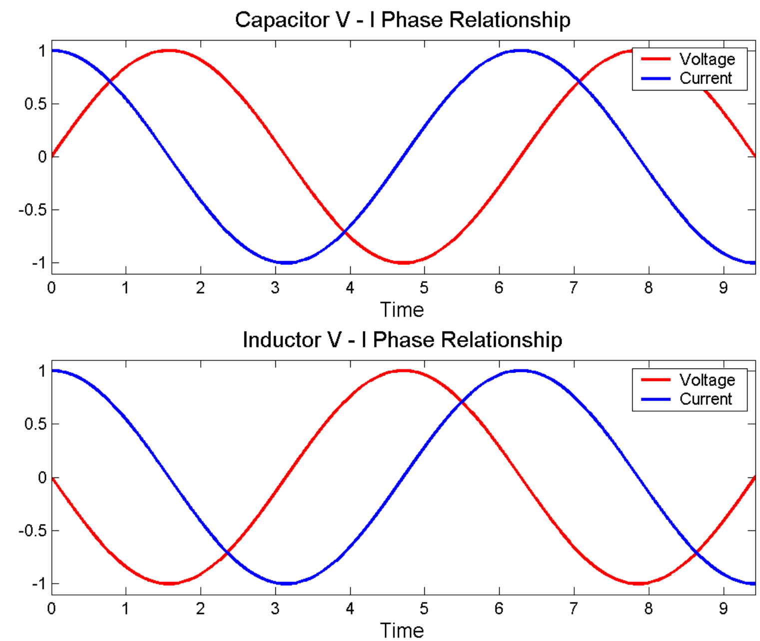


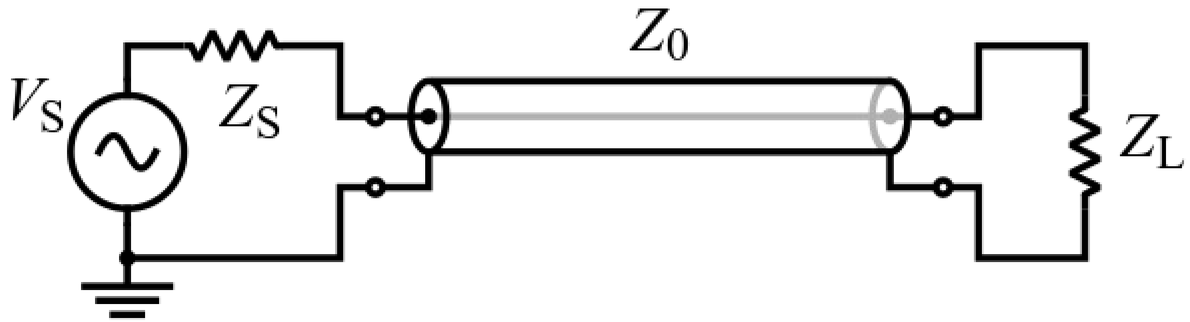
Image source:

https://en.wikipedia.org/wiki/Electrical_impedance

Matching networks

Complex impedance

Any system can be represented as a source with output impedance of Z_S, load with impedance of Z_L and a transmission line with characteristic impedance of Z_0



There is an maximum power transfer theorem: **to obtain maximum power from a source, the resistance of the load must equal the resistance of the source.**

Image source:

https://en.wikipedia.org/wiki/Characteristic_impedance

Matching networks

Transmission lines

Transmission line is any structure designed to conduct AC signal at a frequency high enough that their wave nature must be taken into account.

Main parameter is characteristic impedance Z_0

$$Z_0 = \frac{V}{I},$$

where V and I are voltage and current respectively of a wave propagating along the line.

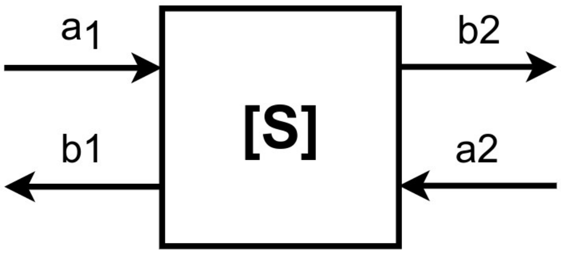
Examples:

- USB-cable (90Ω impedance);
- Coaxial TV cable (75Ω impedance);
- Coaxial RF cable (50Ω impedance);

Matching networks

S-parameters

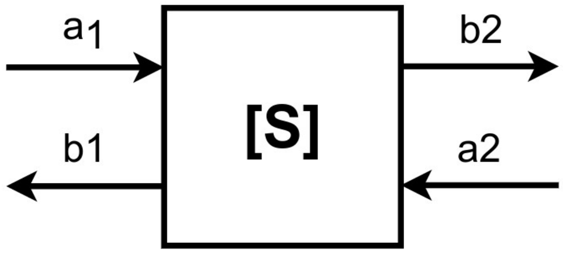
Most of RF devices (amplifier, filter, attenuator etc) can be represented as a two-port network. S-parameters show relationship between power of incident (a_1 and a_2) and reflected waves (b_1 and b_2)



$$S_{mn} = \frac{b_m}{a_n}$$

Matching networks

S-parameters example



$$S_{21}=\frac{b_2}{a_1}=G$$ - gain

$$S_{11}=\frac{b_1}{a_1}=IRC$$ - input reflection coefficient

$$S_{22}=\frac{b_2}{a_2}=ORC$$ - output reflection coefficient

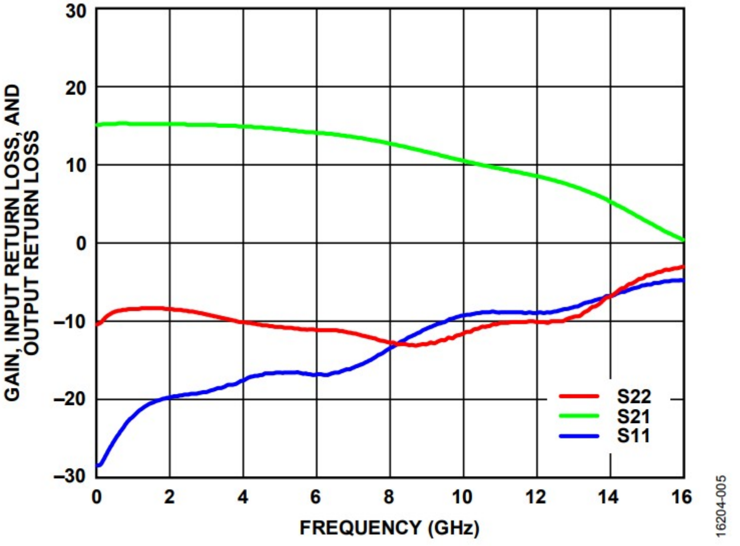
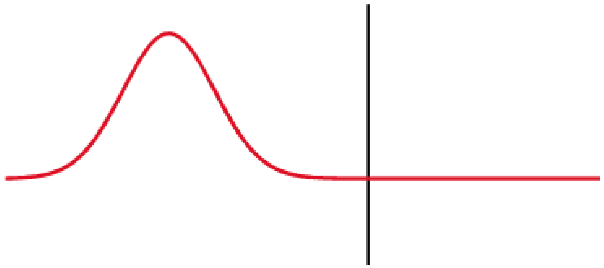


Image source:

https://www.analog.com/media/en/technical-documentation/data-sheets/HMC788A.pdf

Matching networks

Reflection coefficient



Reflection coefficient shows how much power of wave is reflected by device input.

The aim of circuit matching is to decrease reflection coefficient

Image source:

https://en.wikipedia.org/wiki/Reflection_coefficient

Matching networks

Smith chart

Smith chart shows element impedance normalized to desired impedance on a polar plot.

$$z = \frac{Z_L}{Z_o}$$

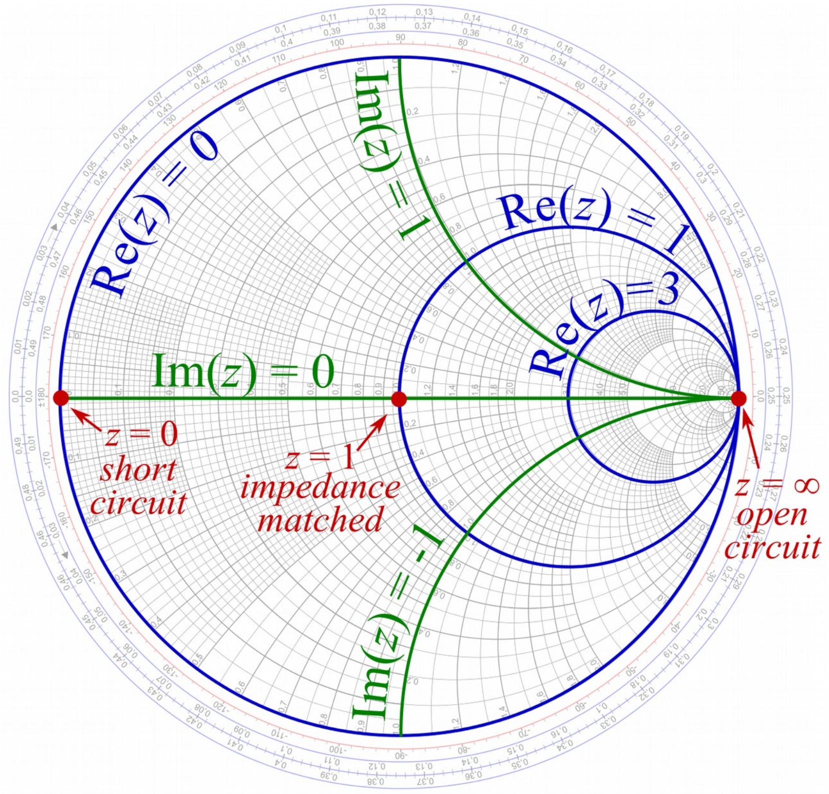
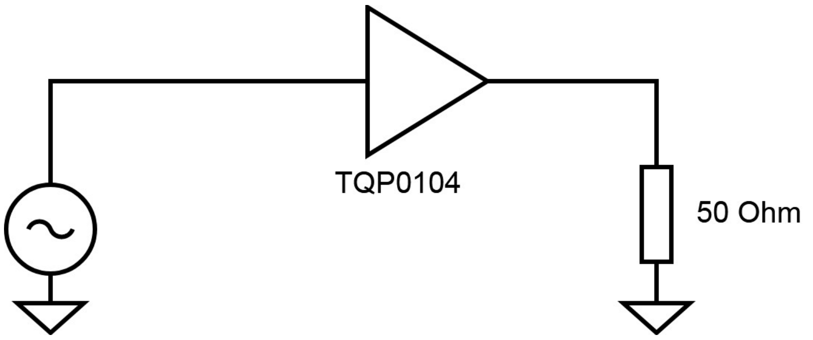


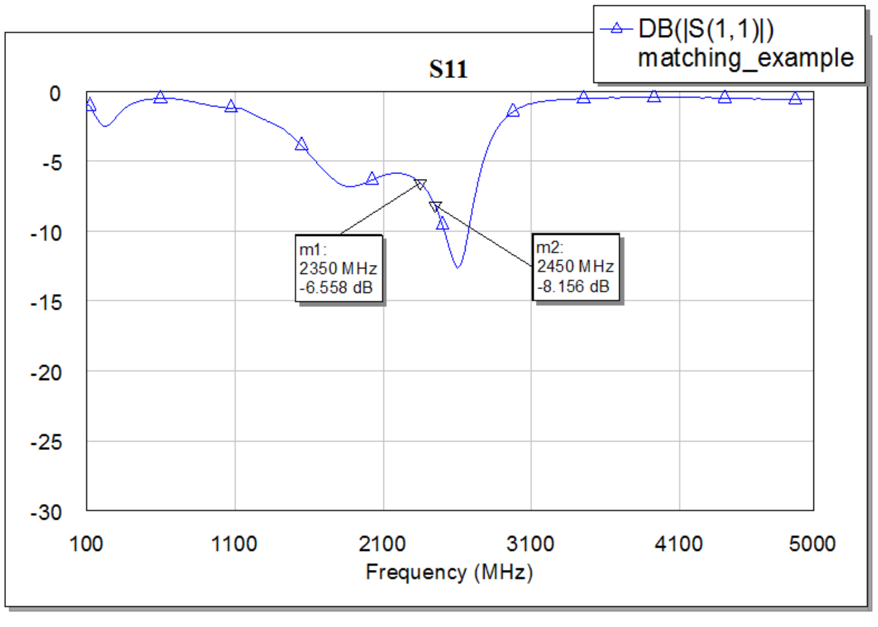
Image source:

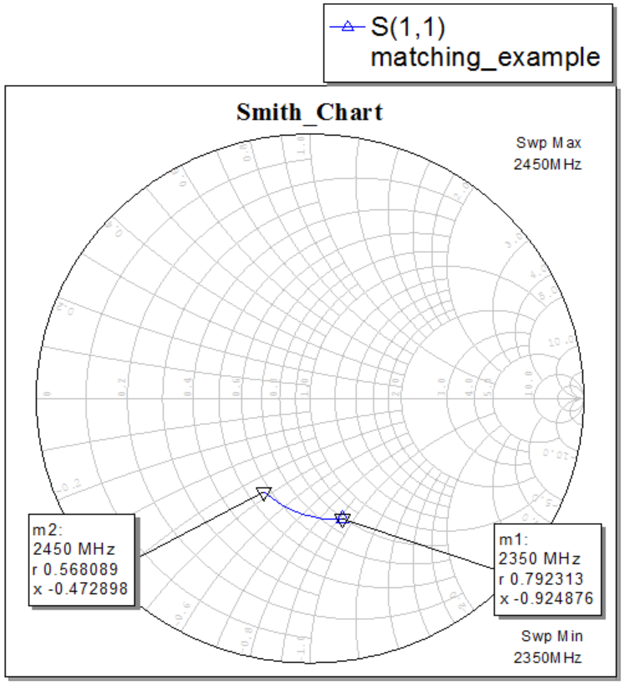
https://en.wikipedia.org/wiki/Smith_chart

Matching networks

Unmatched case







Matching networks

L-matching network

Consists of two components connected in L-shape

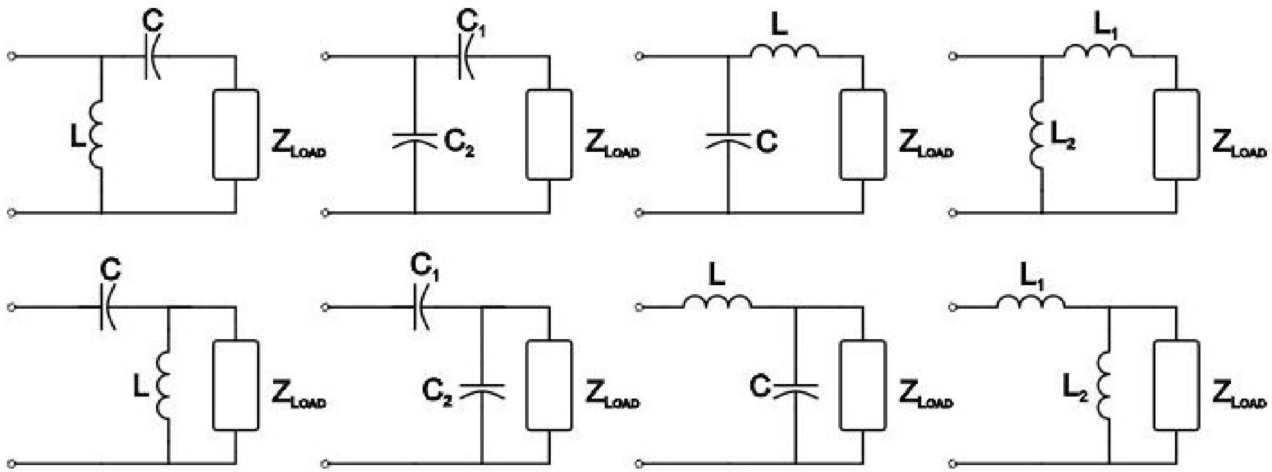


Image source:

https://www.allaboutcircuits.com/textbook/radio-frequency-analysis-design/selected-topics/understanding-matching-networks/

Matching networks

Pi-matching network

Consists of three components connected in π-shape

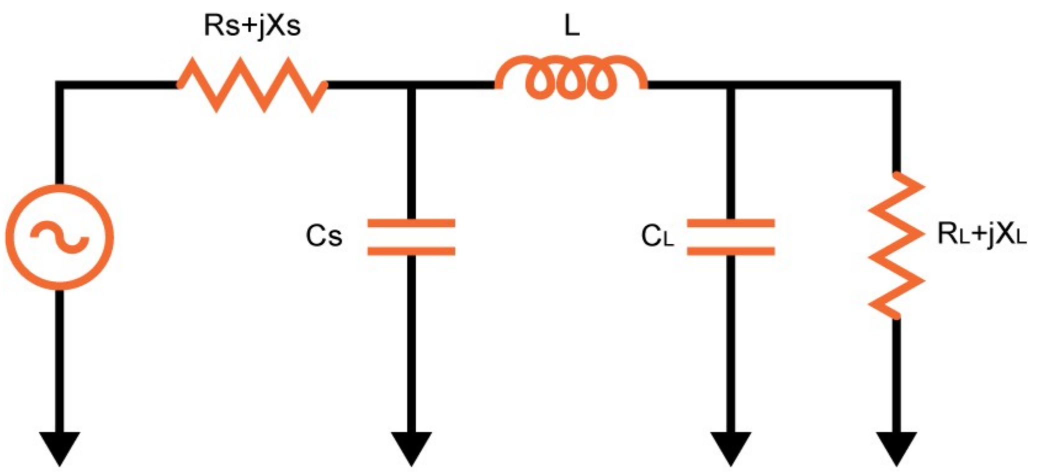
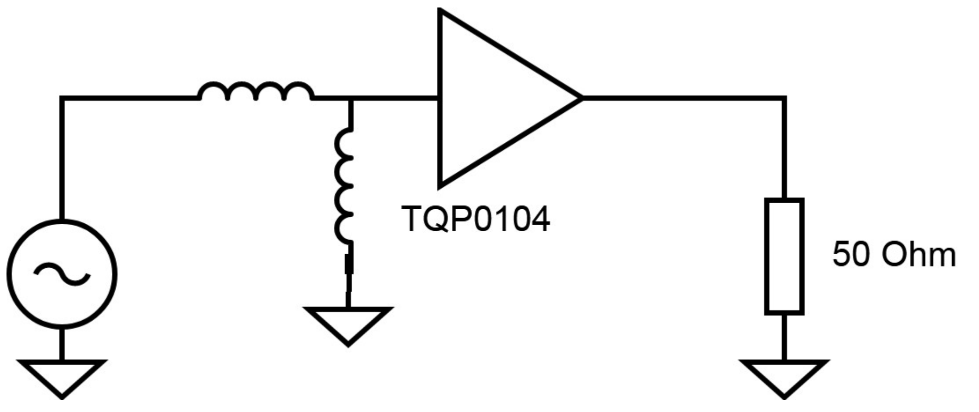


Image source:

https://www.allaboutcircuits.com/tools/pi-match-impedance-matching-calculator/

Matching networks

Matching example



Matching networks

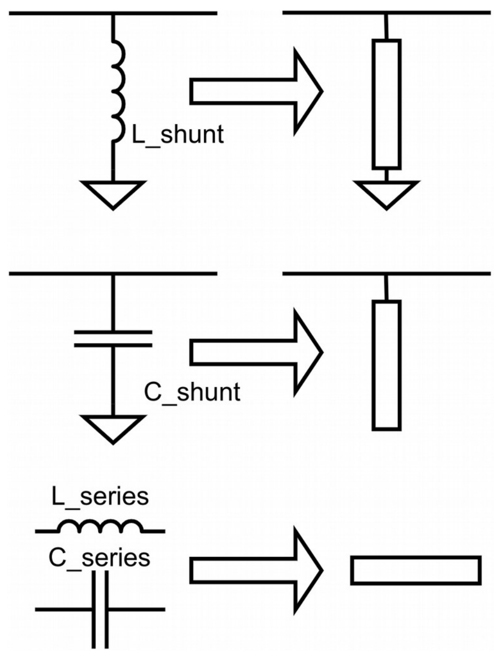
Transmission line matching

Any reactive component can be replaced with a transmission line segment ("distributed element")

$$X_{LUMPLED}=\omega\cdot L$$

$$X_{LUMPLED}=\frac{1}{\omega C}$$

$$X_{LUMPLED}=\omega\cdot L$$
$$X_{LUMPLED}=\frac{1}{\omega C}$$



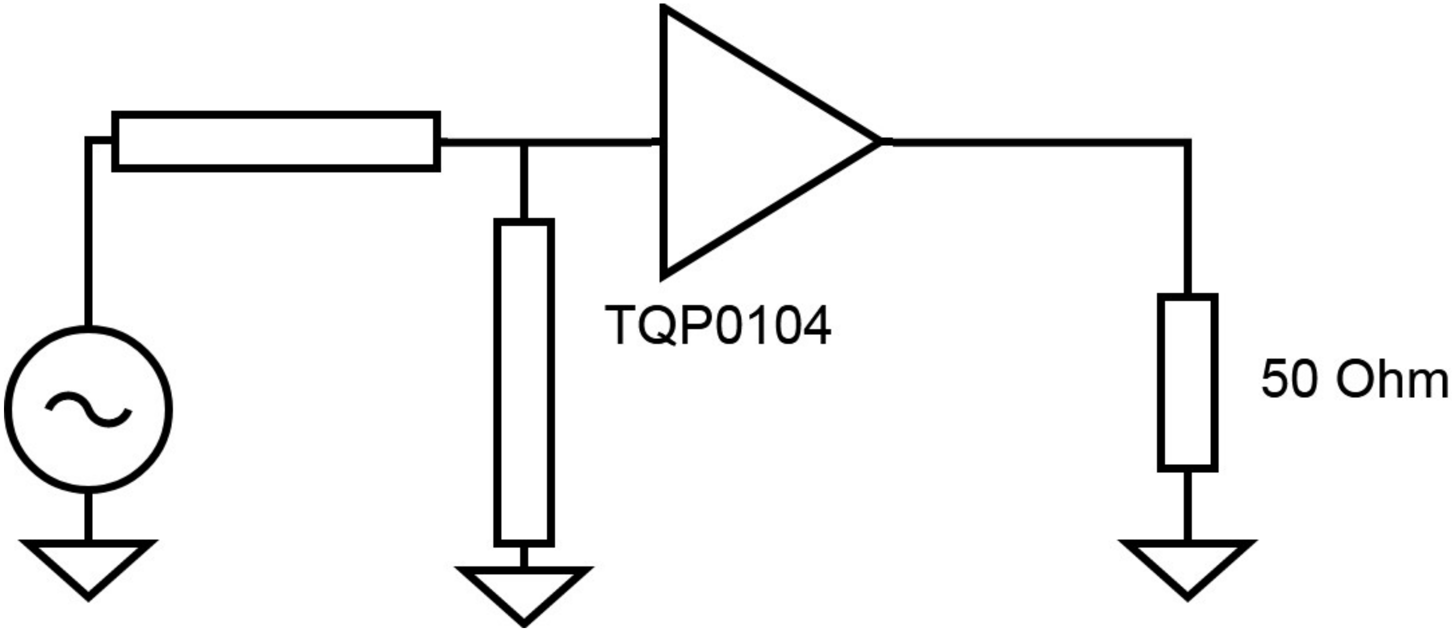
$$X_{DISTRIBUTED}=Z_0\cdot\tan\left(\frac{2\cdot\pi\cdot l}{\lambda}\right)$$

$$X_{DISTRIBUTED}=Z_0\cdot\cot\left(\frac{2\cdot\pi\cdot l}{\lambda}\right)$$

$$X_{DISTRIBUTED}=Z_0\cdot\sin\left(\frac{2\cdot\pi\cdot l}{\lambda}\right)$$

Matching networks

Transmission line matching



Noise figure

Conclusions

- Simple matching circuits (L- and Pi-pad) can provide good matching in narrow band only
- Length of transmission line is important for matching and transmission line should be taken into account at matching circuit design phase
- There is a lot of parameters which are difficult to factor at design phase so it is better to verify all RF-solutions at prototypes
- S-parameters and Smith chart can make RF-issues solving easier

Thank You!

dB conversion

	Power ratio	Voltage ratio
-20 dB	0.01	0.1
-10 dB	0.1	0.32
-3 dB	0.50	0.71
-1 dB	0.74	0.89
0 dB	1	1
1 dB	1.26	1.12
3 dB	2.00	1.41
10 dB	10	3.16
20 dB	100	10
$n \cdot 10$ dB	10^n	$10^{n/2}$