Antenna Theory and Matching

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Agenda

- Antenna Basics
- Antenna Parameters
- Radio Range and Communication Link
- Antenna Matching Example

What is an Antenna

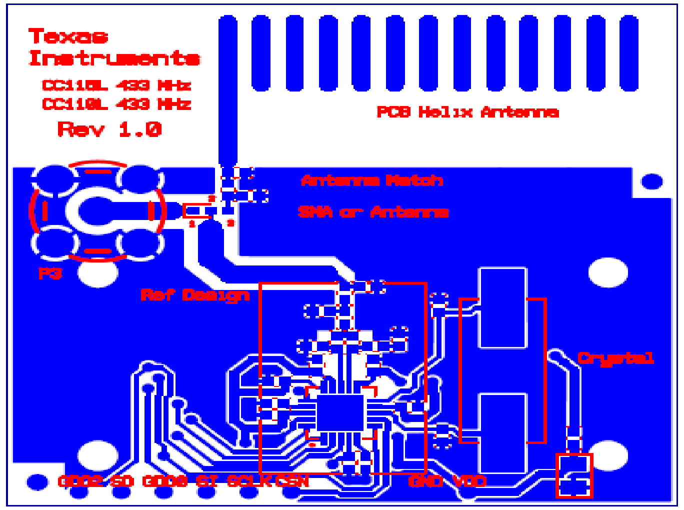
- Converts guided EM waves from a transmission line to spherical wave in free space or vice versa.
- Matches the transmission line impedance to that of free space for maximum radiated power.
- An important design consideration is **matching** the antenna to the transmission line (TL) and the RF source. The quality of match is specified in terms of **VSWR** or **S11**.
- Standing waves are produced when RF power is not completely delivered to the antenna. In high power RF systems this might even cause arching or discharge in the transmission lines.
- Resistive/dielectric losses are also undesirable as they decrease the efficiency of the antenna.

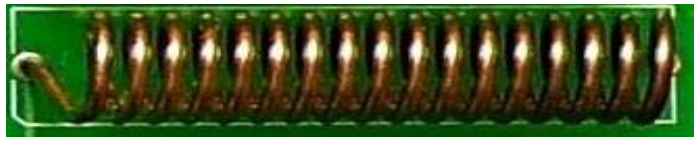
When does radiation occur

- EM radiation occurs when charge is accelerated or decelerated (time-varying current element).
- Stationary charge means zero current ⇒ no radiation.
- If charge is moving with a uniform velocity ⇒ no radiation.
- If charge is accelerated due to EMF or due to discontinuities, such as termination, bend, curvature ⇒ radiation occurs.

Commonly Used Antennas

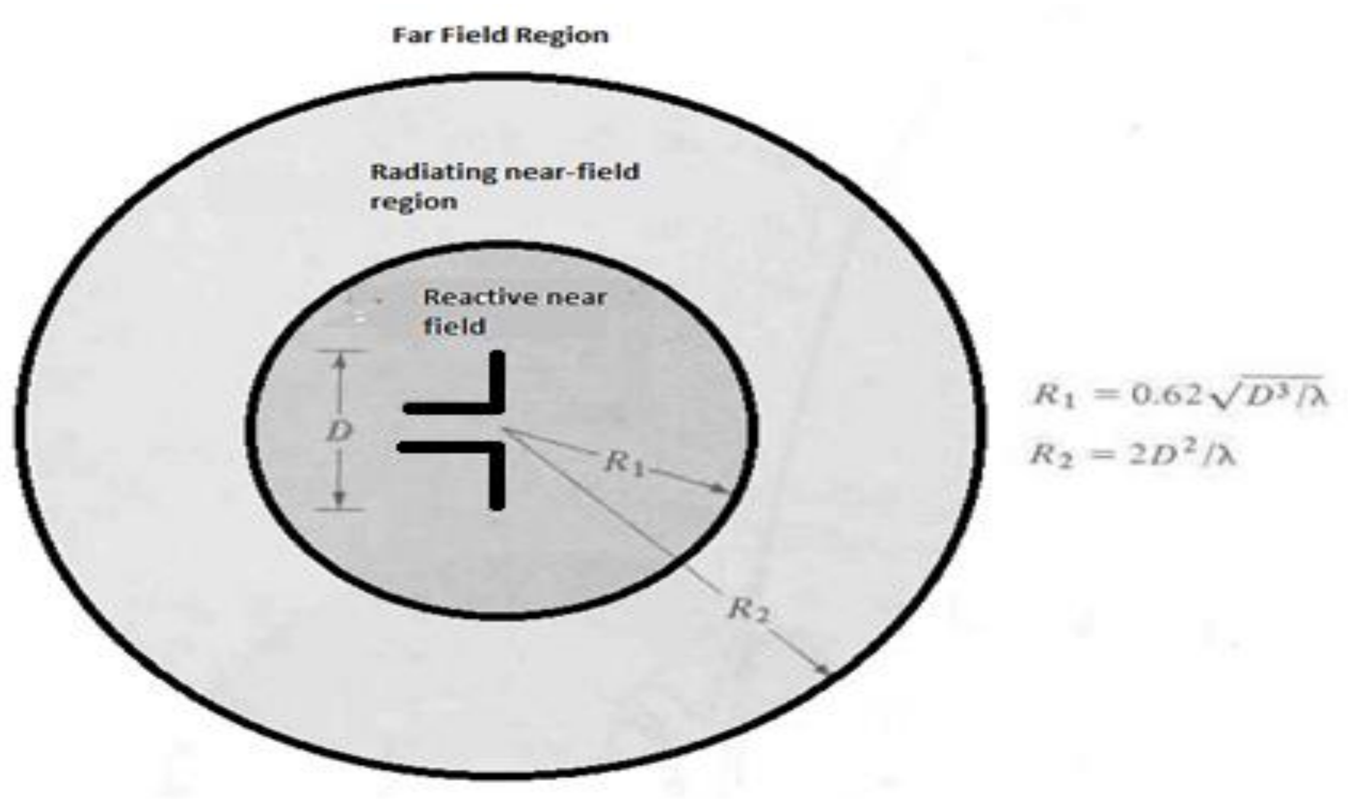
- **PCB antennas**
  - No extra cost
  - Size can be demanding at sub 433 MHz (but we have a good solution!)
  - Good performance at > 868 MHz
- **Whip antennas**
  - Expensive solutions for high volume
  - Good performance
  - Hard to fit in many applications
- **Chip antennas**
  - Medium cost
  - Good performance at 2.4 GHz
  - OK performance at 868-955 MHz
  - Poor performance at 433-136 MHz
- **Wire / Helical antennas**
  - Low cost
  - Good performance
  - Ideal at sub 433 MHz





Antenna Radiation Regions

- Space surrounding the antenna is usually divided in three regions as functions of dimensions and wavelength of operation



Typically we are only interested in the far-field region of the antenna for practical purposes

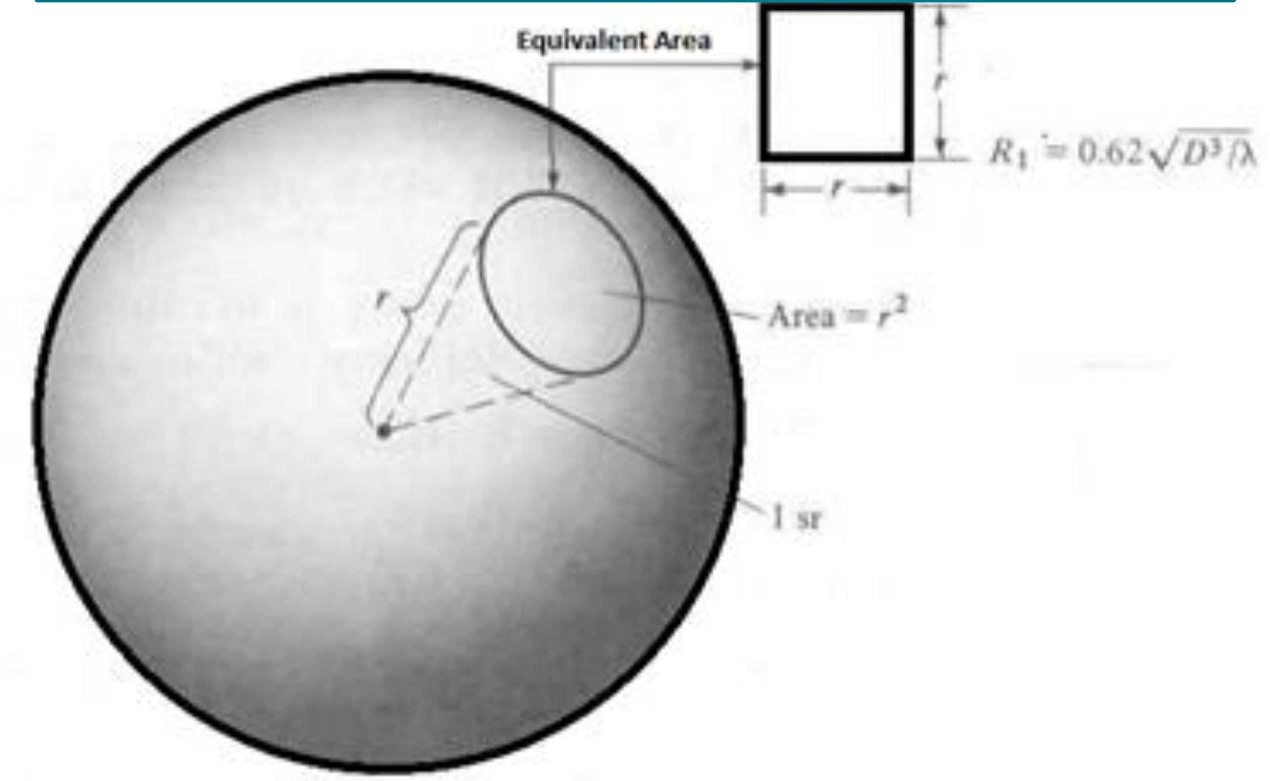
- Electric and magnetic fields are perpendicular to each other
- Electric and magnetic field amplitude drops as 1/r
- E.g a 2 ft diameter dish operating at 10GHz would have the start of far-field region at 24m.

From Balanis

Isotropic radiator

- An isotropic source radiates in all direction uniformly
- The radiated power goes through a sphere in all directions with same intensity
- Power and energy bearing EM waves are used to transport information signals through a wireless medium. **Poynting vector** is a quantity used to describe the power in the EM wave.

Geometry describing a unit solid angle – Steradian.



$$U = \frac{P_{rad}}{4\pi}$$

Where U (W/unit solid angle)is the radiation intensity

A 2W isotropic radiator will have 160nW/m^2 power density at 1km away from source.

Non-Isotropic radiator

- A non-isotropic source doesn't not have same radiation intensity in all direction.
- A non-isotropic antenna concentrates power in a desired direction more than any other.
- Hence, the term **directivity** is associated with non-isotropic sources.
- **Directivity** is the antenna’s ability to focus energy in a desired direction when transmitting or to receiving maximally. An antenna that radiates more or less equally in any orthogonal plane is called an **omnidirectional** antenna where as **isotropic** radiator is a hypothetical lossless antenna radiating in all directions
- **Directivity** is the ratio of radiation intensity of an antenna w.r.t an isotropic radiator.

$$D(\theta,\varphi)=\frac{U(\theta,\varphi)}{U_{avg}}$$

$$U_{\max}=\frac{D.P_{rad}}{4\pi}$$

In general an antenna with 6dBi specification of directivity means that the intensity is 6dB more in the maximum direction of radiation compared with an isotropic antenna

Where U (W/unit solid angle)is the radiation intensity

Non-Isotropic radiator - Example

- What is the power density of a 2W non-isotropic source at 2km if the directivity is 50 in the maximum beam direction?
- What is the directivity in dBi?

$$P_{density} = \frac{D.P_{rad}}{4\pi r^2} = \frac{50 \times 2W}{4\pi \times 2000^2} = 1.97 \times 10^{-6} W/m^2$$

$$D_{dB} = 10\log_{10}(50) = 17dBi$$

Antenna Gain

- **Gain** of an antenna is closely related to directivity and efficiency. Usually antenna gain is a relative quantity which is measured w.r.t a reference radiator. Relative gain is expressed as the ratio of power gain in a given direction to the power gain of a reference antenna.

$$G(\theta,\varphi) = e_r . D(\theta,\varphi)$$

Where e_r is the radiation efficiency = Prad/Pin

An antenna with 90% efficiency and a directivity of 120 would have a gain of

$$G_{dB} = 10 * \log_{10}(G) = 10 * \log_{10}(0.9 * 120) = 20.33 dBi$$

Antenna Gain – Cont'd

- **Gain** of an antenna is proportional to its effective area Ae[m2]
- And inversely proportional to operating wavelength
- Effective area is related to physical area

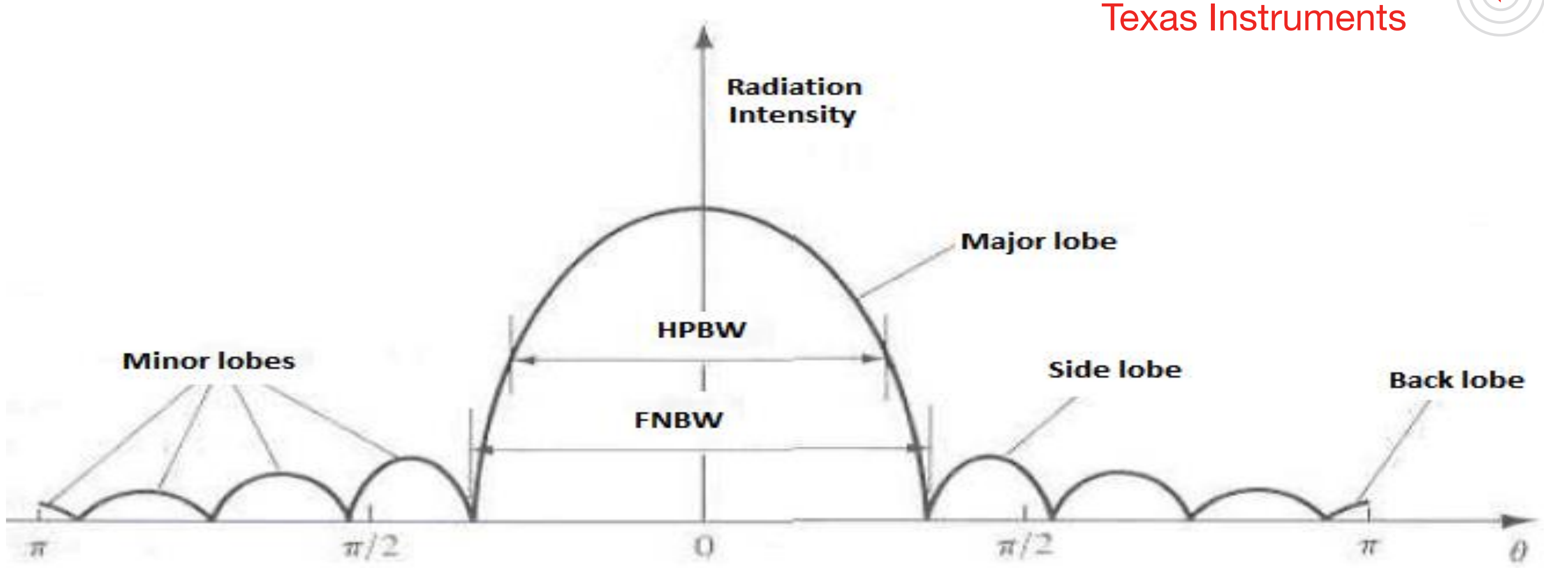
$$G = \frac{4\pi}{\lambda^2} A_e$$

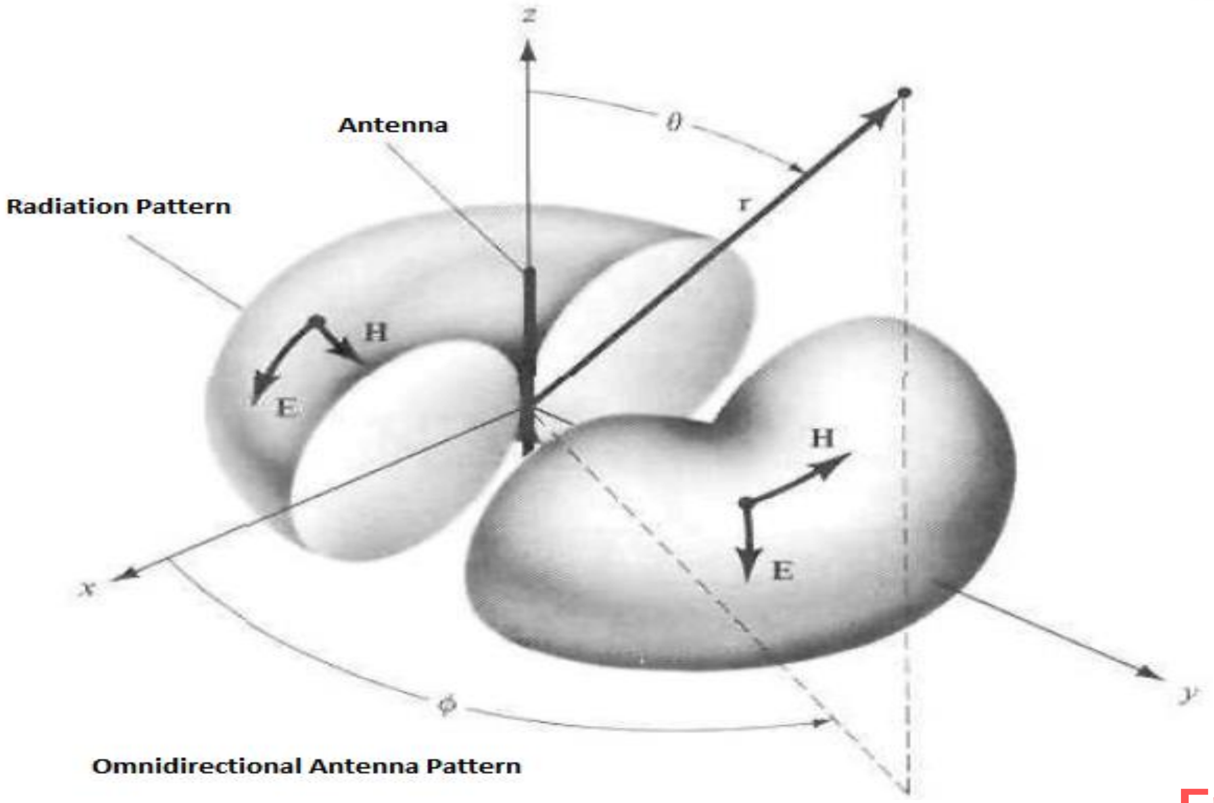
$$A_e = \varepsilon_{ap} A_p$$

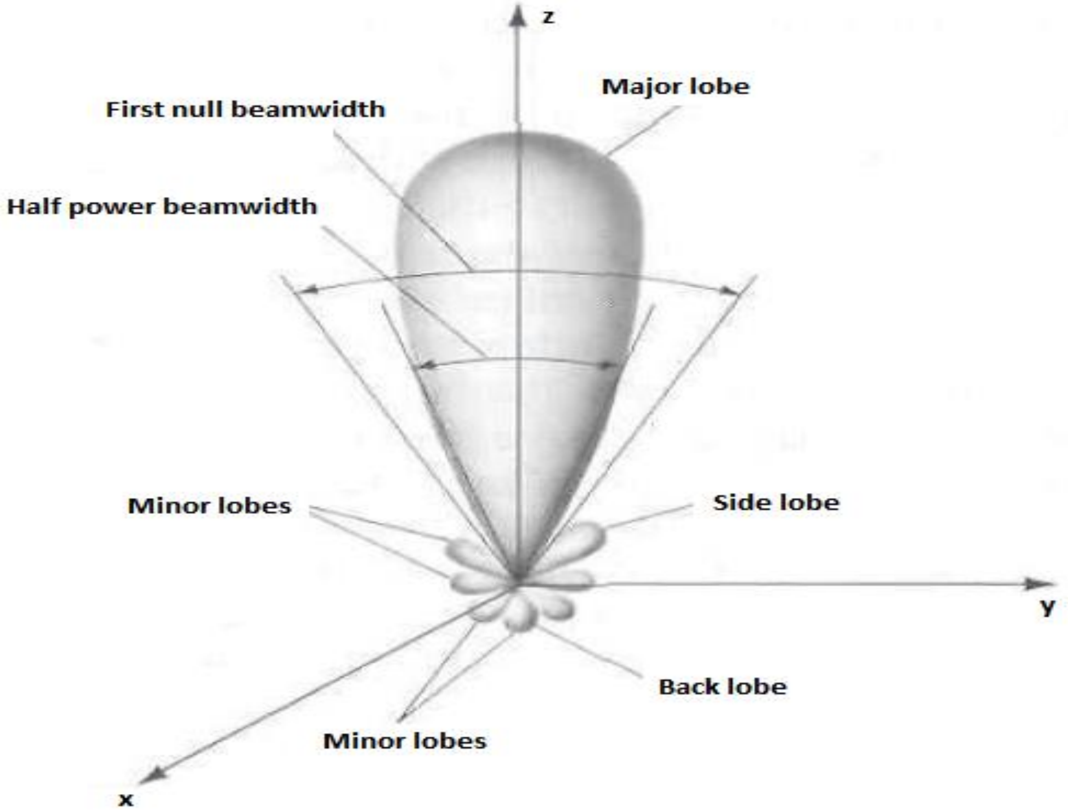
Where ε_{ap} is the aperture efficiency

Radiation pattern

- **Radiation patterns** describe the relative strength of the radiated or received field in various directions from the antenna, at a constant distance. Although EM radiation takes place in 3 dimensions, the patterns documented are a 2-dimensional slice of the 3-dimensional pattern, in the horizontal or vertical planes.







From Balanis

Antenna Radiation Resistance

- The radiation field components from the current element are tangential to the spherical surface and the Poynting vector is perpendicular to the surface indicating radial flow of power from the current element. The average power in W/m^2 is one half the product of the fields:

$$P = \frac{\eta I_m^2 \sin^2 \theta dl^2}{8r^2\lambda^2}$$

- Total power being radiated is the surface integral of the Poynting vector over the surrounding surface usually a sphere

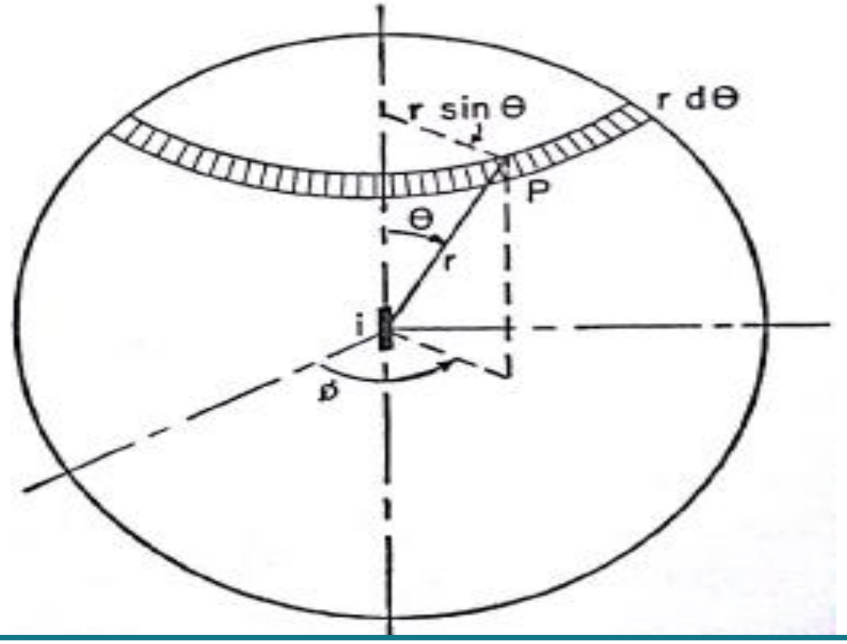
$$da = 2\pi r^2 \sin\theta d\theta$$

$$W = \int_S P.da = \frac{\pi \eta I_m^2 dl^2}{4\lambda^2}\int_0^\pi \sin^3\theta d\theta$$

This is the same power as would be dissipated in a resistance *Rr* by current *Im* in absence of any radiation

$$W = 40\pi^2 I_m^2 \left(\frac{dl}{\lambda}\right)^2$$

$$R_r = \frac{2W}{I_m^2} = 80\pi^2\left(\frac{dl}{\lambda}\right)^2$$



Area vector for Poynting vector integration.

From Ryder

Application - Half-Wave Antenna in Space

- One of the simplest antennas and frequently used is half wave long thin wire dipole. Assuming the antenna is far removed from earth and obstacles.
- The current at the end of the antenna has to be zero since there is nowhere for it to go. A sinusoidal distribution exists for a thin straight wire and in figure below and using the center of wire as reference the current along the antenna is

$$i = I_m \cos 2\pi\left(\frac{x}{\lambda}\right); -\lambda/4 \le x \le \lambda/4$$

- Choosing a point **P** far away radius vectors r0 and r1 can be considered parallel with

$$r_1 = r_0 - x\cos\theta$$

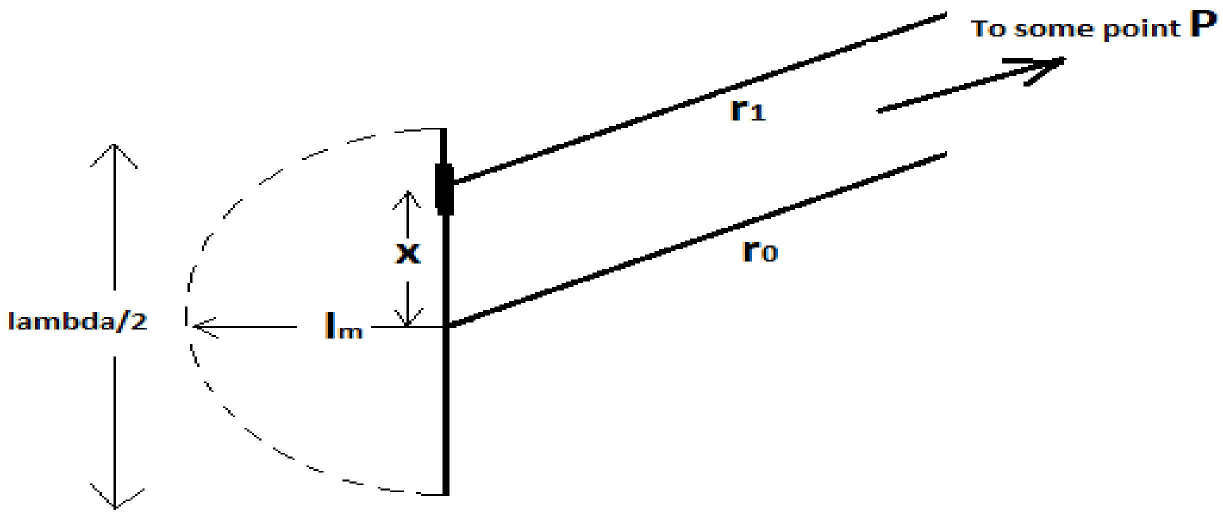
- The r.m.s fields the E and H fields are as follows:

$$H_\phi = \frac{I_{rms}}{2\pi r_0}\left[\frac{\cos(0.5\pi\cos\theta)}{\sin\theta}\right]$$

$$E_\theta = \frac{60 I_{rms}}{r_0}\left[\frac{\cos(0.5\pi\cos\theta)}{\sin\theta}\right]$$

- Fields are mutually at right angles and in time phase.
- Poynting vector using r.m.s values is give by:

$$P = |E_\theta||H_\phi| = \frac{30 I_{rms}^2}{\pi r_0^2}\left[\frac{\cos(0.5\pi\cos\theta)}{\sin\theta}\right]^2$$



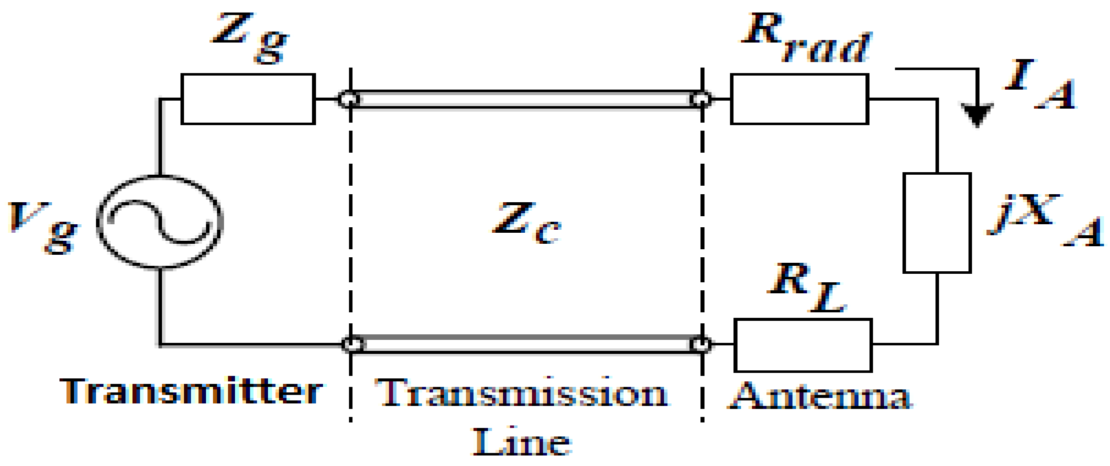
From Ryder

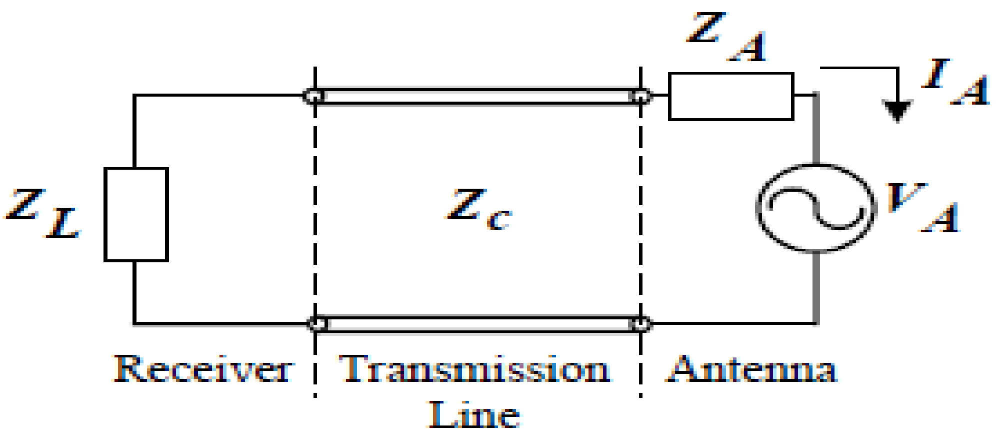
Antenna Polarization

- In order for a TX and RX antenna to have a link, they must have same polarization
- Polarization of a plane wave shows how the instantaneous electric or magnetic filed is oriented at a given point in space.
- Polarization mismatch will cause signal loss
- There are 3 types of polarization:
  - **Linear(vertical or horizontal):** if E or M field vector is always oriented along the same straight line every instance of time
  - **Circular:** if E or M field vector at that point traces out a circular path as a function of time.
  - **Elliptical:** if E or M field vector at that point traces out a elliptical path as a function of time.

Antenna Circuit Models

- Generally an antenna is the transition that interfaces a transmission line to free space as efficiently as possible while maintaining a desired EM distribution pattern in free space.





V_g - voltage-source generator (transmitter);

Z_g - impedance of the generator (transmitter);

R_{rad} - radiation resistance (related to the radiated power as $P_{rad} = I_A^2 \cdot R_{rad}$)

R_L - loss resistance (related to conduction and dielectric losses);

jX_A - antenna reactance.

Antenna impedance: $Z_A = (R_{rad} + R_L) + jX_A$

From Balanis

Radio Link

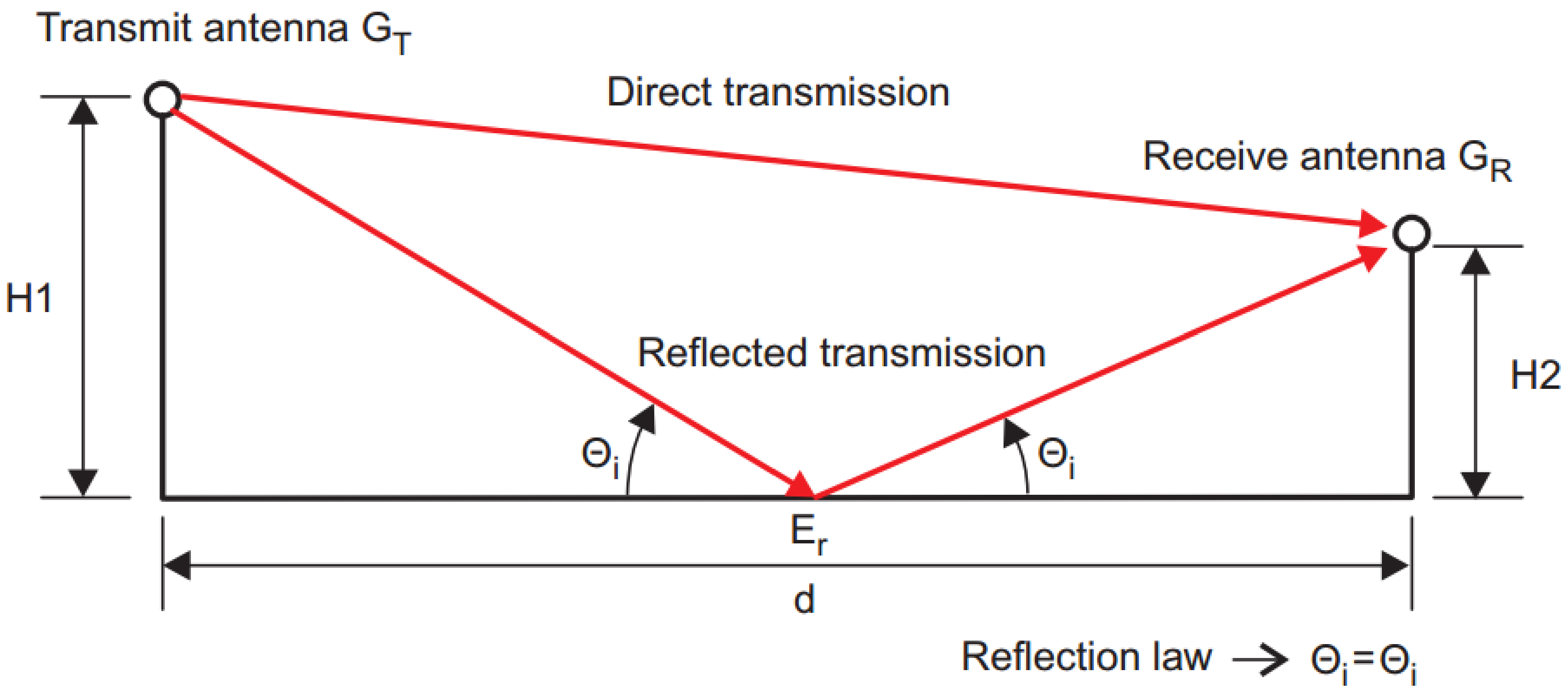
- When setting up a radio link, the maximum range between a transmitter and receiver is often desired.
- Realistic range estimation can be made by employing 2-ray Friis model for RF propagation which can take into account typical building construction materials
- Maximum range can be influenced by:
  - Antenna performance and location
  - Output power of transmitters and reciever sensitivity
  - Unwanted RF jammers
  - The operating frequency
  - Radio configuration
  - Building material between TX and RX

Friis Transmission Equation and Range

TECH DAYS
Texas Instruments

For TX and RX antennas that are matched for polarization and reflection and aligned for maximum directional radiation and reception the ratio of RX power to TX power is given by the following:

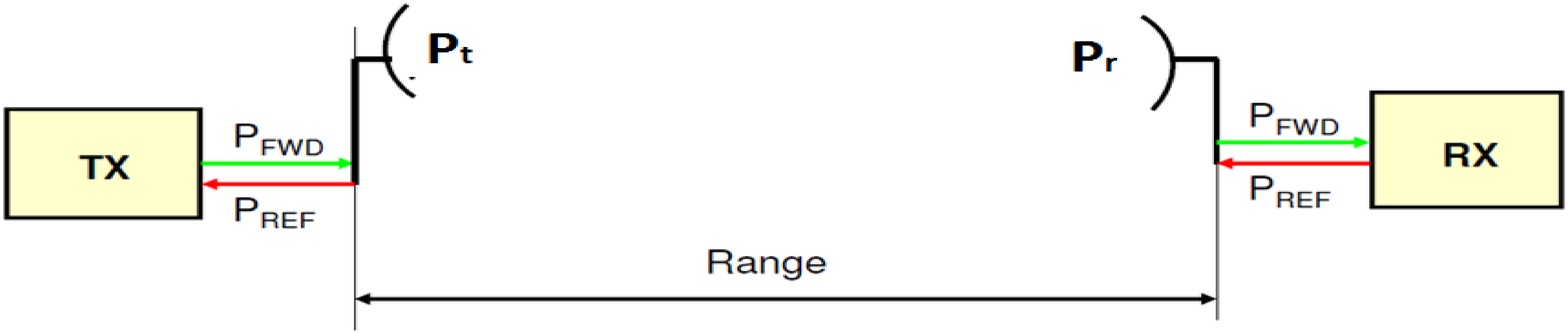
$$\frac{P_r}{P_t} = \left(\frac{\lambda}{4\pi R}\right)^2 G_t G_r$$



Range of LOS Link

By solving Friis formula for R and replacing the received power with minimum detectable signal we can get the expression for maximum range:

$$R_{\max} = \sqrt{\frac{P_t G_t G_r \lambda^2}{(4\pi)^2 P_{\min}}}$$



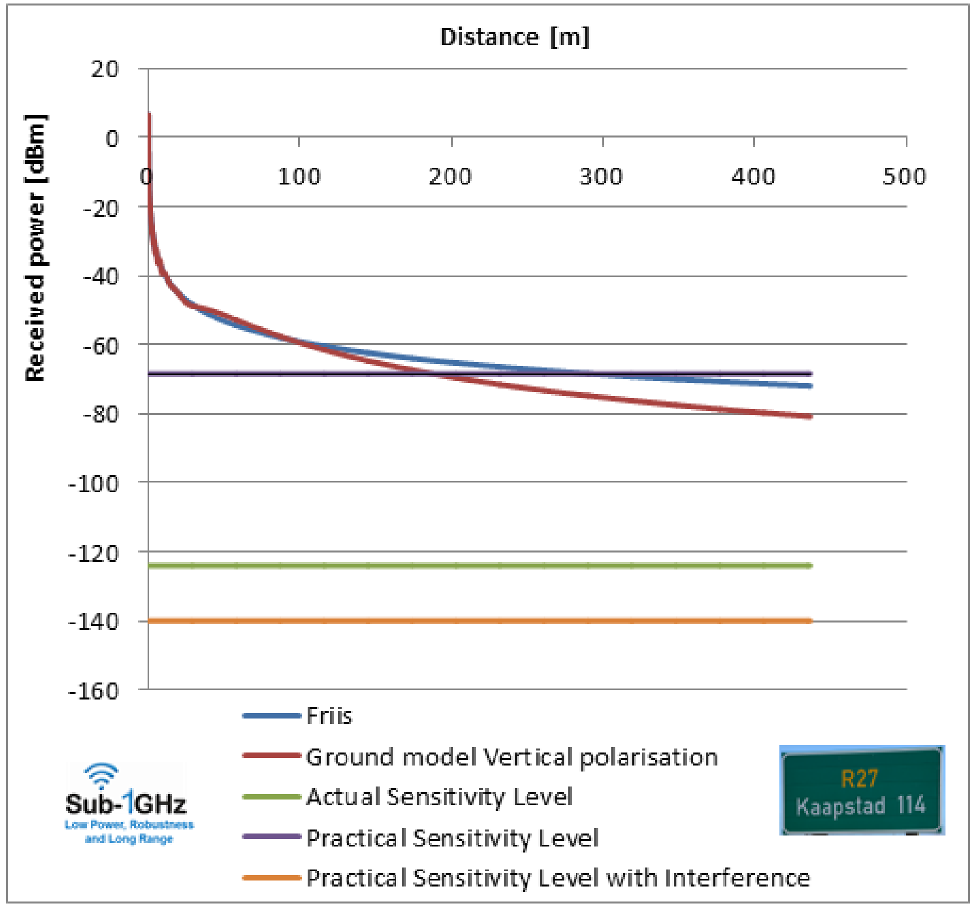
Excel sheet for Range estimation

Friis-Equation and 2-Ray Ground Reflection Model

Antenna locations (height over ground)	Tx: 2.0	Rx: 2.0	m
Maximum LOS based on antenna heights:			10.1 km
Frequency (region)[1]:	868 MHz	High-band Sub-1GHz, Europe, Africa	868 MHz
Antenna position:	Vertical		-
Transmitted power (suplied from transmitter):	14		dBm
Mean Effective Gain (MEG) of Tx antenna:	DN024 - 863-928 MHz (CC_Antenna_DK2_#9)		-0.95 dBi
Mean Effective Gain (MEG) of Rx antenna:	DN024 - 863-928 MHz (CC_Antenna_DK2_#9)		-0.95 dBi
Select ground surface:	Ground		18 ε_r
Interference power level (at antenna port):	No interference		- dBm
Environmental noise floor:	-150 dBm		-150 dBm
Select chip and datarate (sensitivity level):	CC13xx - 0.625 kbps (LRM)		-124.0 dBm
Blocking Level (fc +/- 10MHz):			90.0 dB
Practical sensitivity level:			-68.4 dBm
Practical sensitivity level with Interference:			- dBm
Select Effective Attenuation between Rx and Tx:	Guard band without Antenna Diversity		55.6 dB
Select absorbtion material 1 between Tx and Rx:	7" brick - 2 GHz (7,5 dB)		
Select absorbtion material 2 between Tx and Rx:	1/2" drywall - 500 MHz (0,1 dB)		
Select absorbtion material 3 between Tx and Rx:	8" concrete - 2 GHz (32 dB)		
Link budget:			136.1 dB

Realistic range expectation:	With Interference	Without Interference	Friis
	188 m	**188 m**	**291 m**

1. To be able to enter custom frequency, please enable marcos.



For more info concerning our wireless devices, visit the E2E community

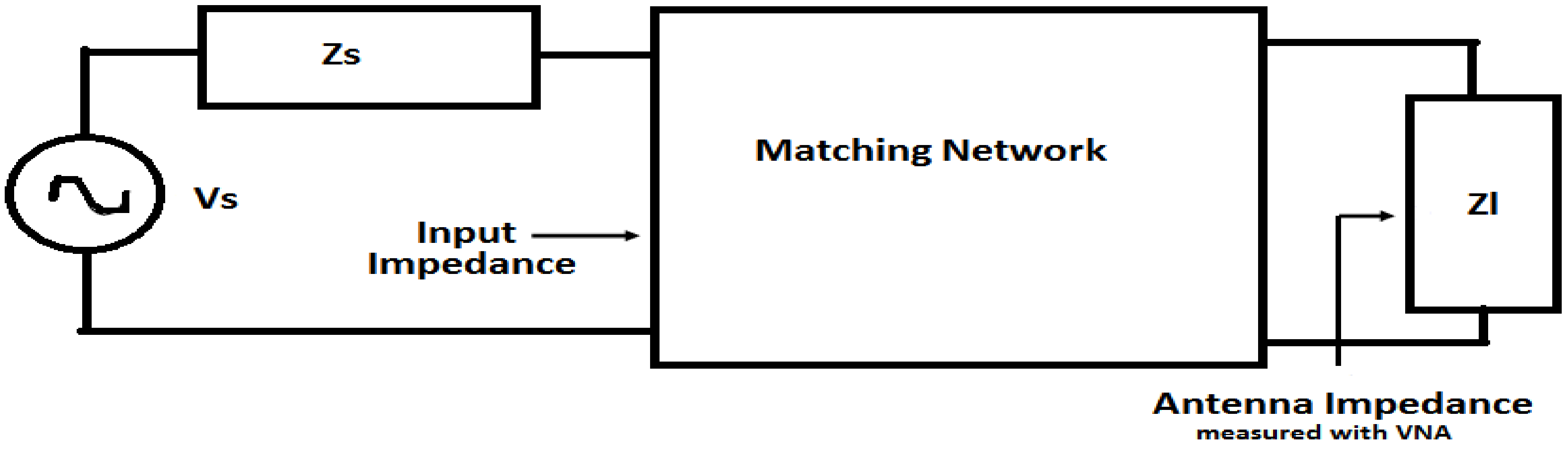
Achieving Optimum Range | Range Debug Check List

CC-Antenna-DK2 | Antenna Selection Guide

Rev 1.15

Antenna Matching

- Only inductors or capacitors should be used for matching.
- Matching circuits, distributed or lumped, have losses due to limited quality factor.
- If an antenna has a reasonable initial resonance, the improvement obtained from the matching circuit will compensate for the loss it introduces



Antenna Matching Consideration

- **Input Impedance** is the impedance presented by the antenna at its terminal. Maximum power is transferred to the antenna during **conjugate** match. Transceivers and their transmission lines are typically designed for 50Ω. If the antenna has an impedance different from 50Ω, then there is a mismatch and an impedance matching circuit is required.
- In **conjugate match**, half of power is dissipated in ***Rg*** of generator and the other half that makes to the antenna, part of it is radiated through the radiation resistance ***Rr*** and rest is dissipated in the ***Rl*** *of* the antenna.
- **Return Loss** is a way of expressing mismatch. It is a logarithmic ratio measured in dB that compares the power reflected by the antenna to the power that is fed into the antenna. The quality of match is specified most often in terms of VSWR or S11 under matched conditions.

$$S_{11} = 20\log(\Gamma) = 20\log\left(\frac{VSWR-1}{VSWR+1}\right)$$

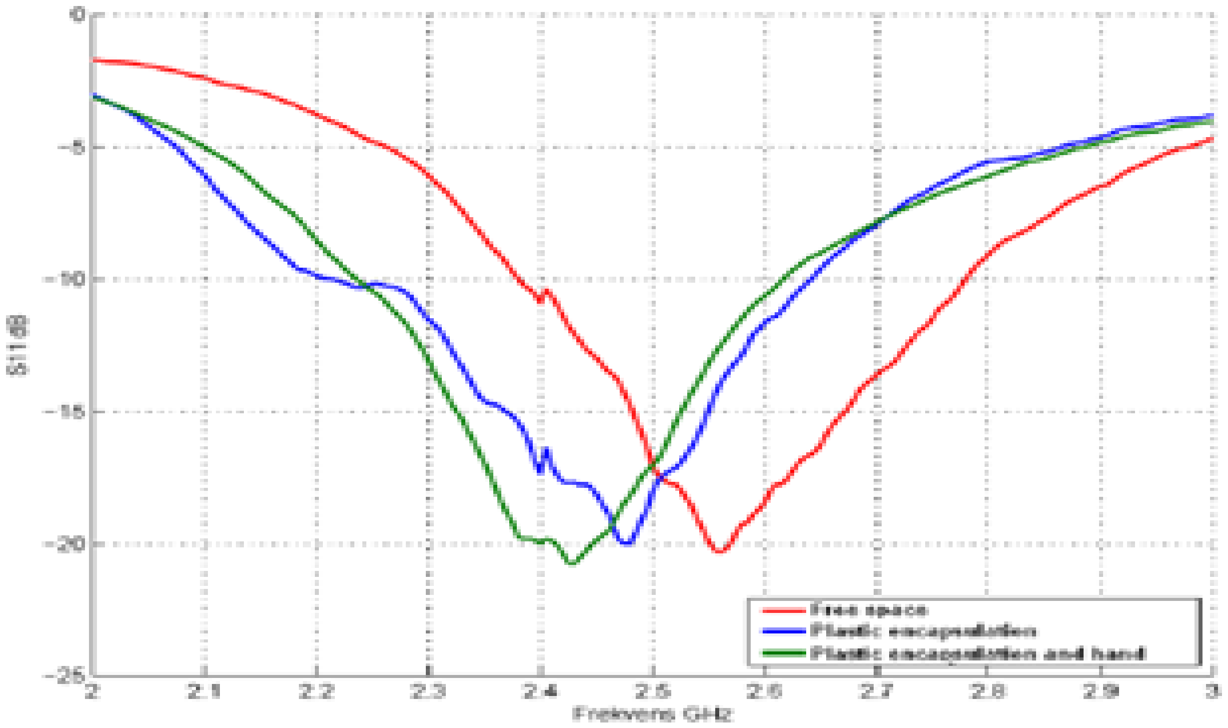
Antenna VSWR and Noise Figure

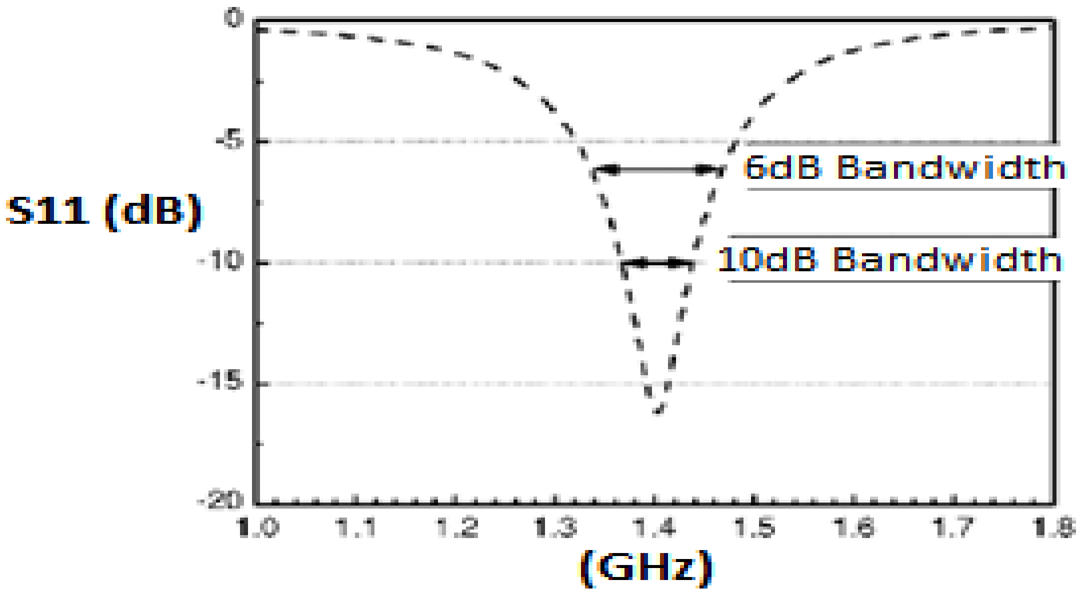
- **Antenna VSWR** changes according to the environment around the antenna and therefore matching conditions can change accordingly. This change in VSWR, if large enough, can disrupt the noise figure of the front end of a receiving system.
- The influence of antenna VSWR on the noise figure(NF) is given by (in dB):

noise factor

$$NF = 10\log\left[1 + \frac{F-1}{2}\left[\frac{1}{\rho} + \rho\right]\right]$$

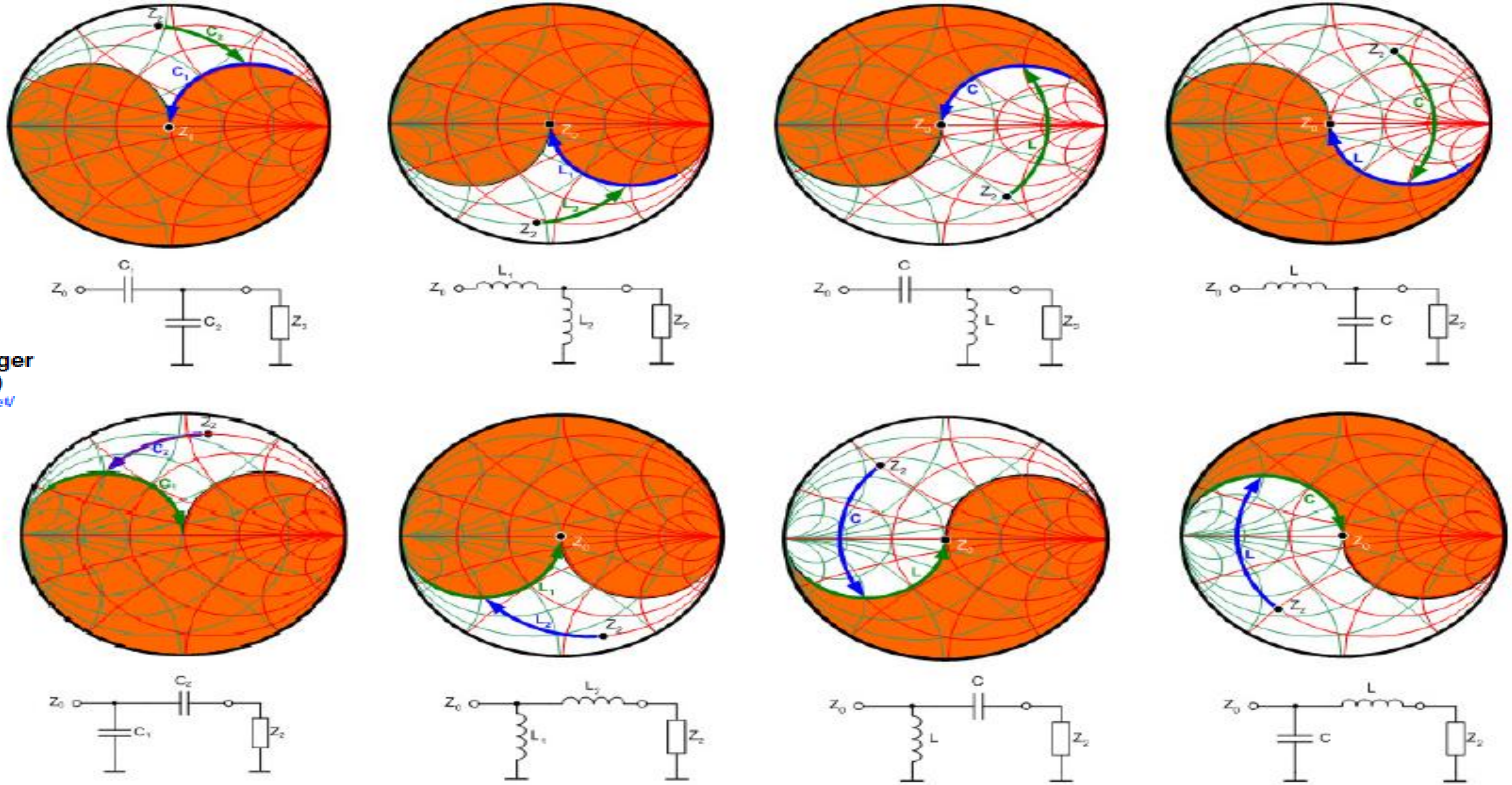
Antenna Bandwidth





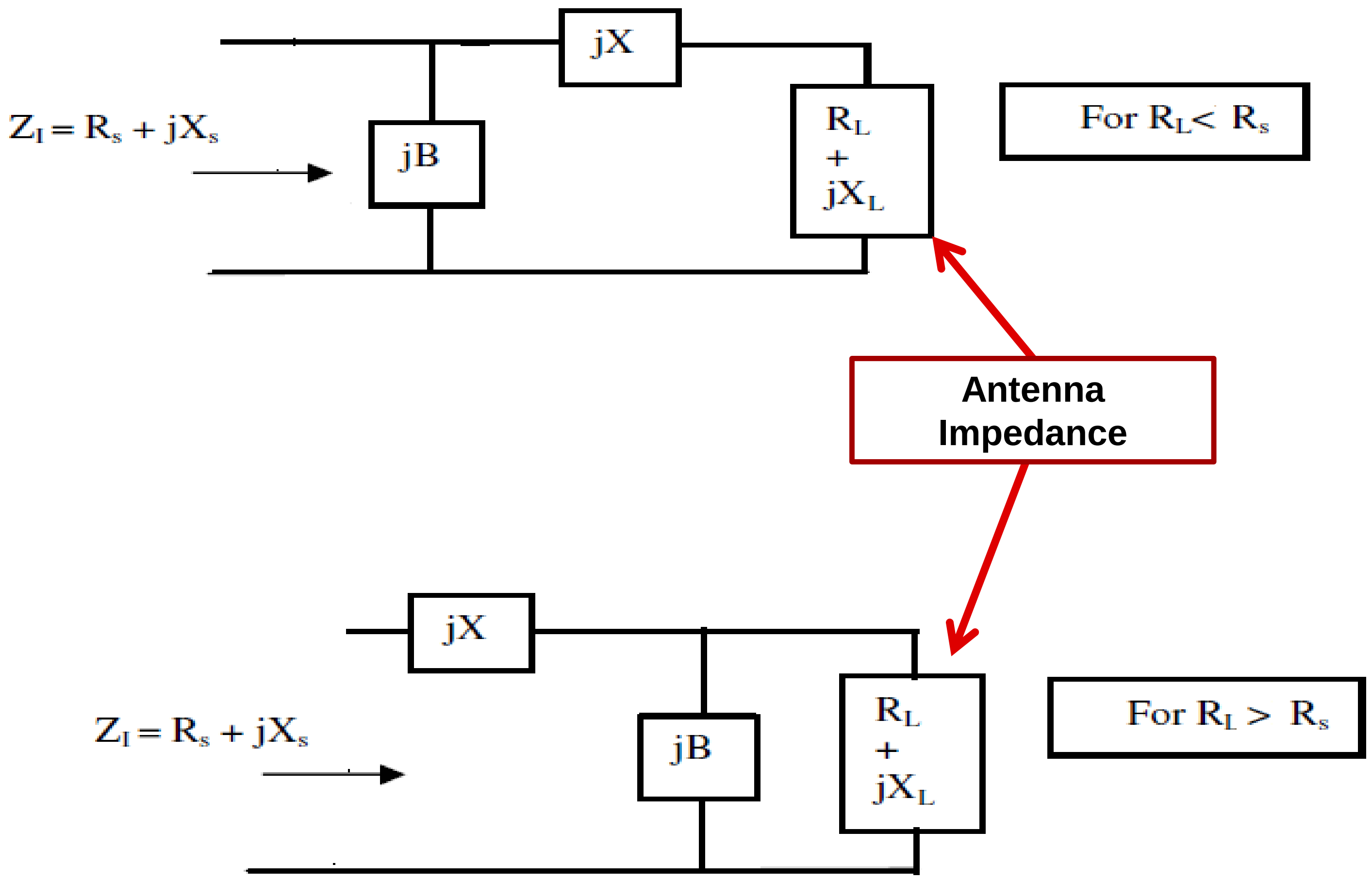
- **Bandwidth** refers to the range of frequencies over which the antenna can operate with acceptable VSWR.
- Typically a BW of operation when VSWR is less than 2:1 is acceptable. This translates to a return loss of about -9.5dB

L-Network can always match the antenna



Material from
Prof. F. Dellsperger
(Bern University)
http://fritz.dellsperger.net/

Analytic Expressions for L-Match



$$B = \frac{-X_S \pm R_S\sqrt{\dfrac{R_S - R_L}{R_L} + \dfrac{X_S^2}{R_L R_S}}}{R_S^2 + X_S^2} \quad (9)$$

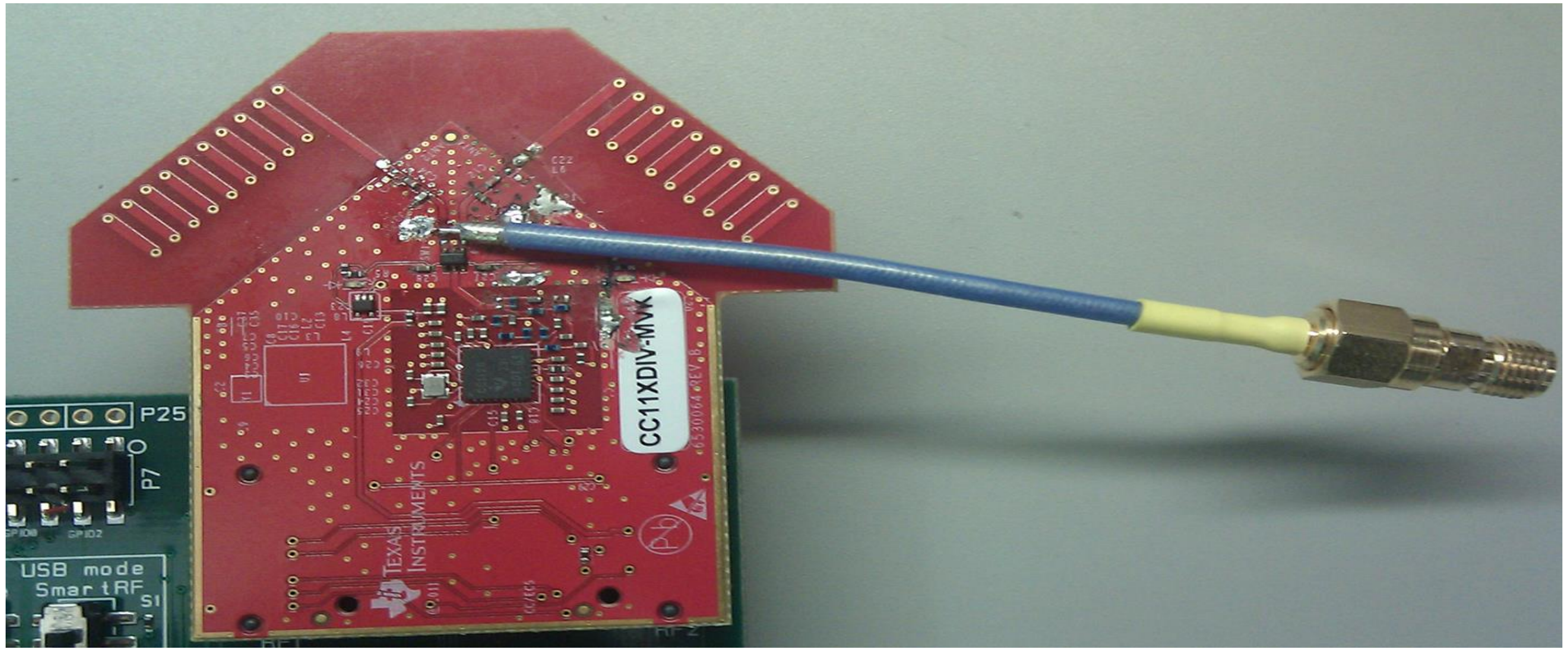
$$X = \frac{B R_S R_L + X_S}{1 + B X_S} - X_L \quad (10)$$

$$B = \frac{-X_L \pm \sqrt{\dfrac{R_L}{R_S}}\sqrt{R_L^2 + X_L^2 - R_S R_L}}{R_L^2 + X_L^2} \quad (11)$$

$$X = \frac{1}{B} + \frac{X_L R_S}{R_L} - \frac{R_S}{R_L B} + X_S \quad (12)$$

Antenna Matching Process

- Semi rigid cables are very useful in this regard for debugging RF.
- First the shielding is soldered onto the ground plane and then the middle conductor is soldered on pads. This minimizes the risk of ripping off pads from PCB.



System Calibration

STEP 1 (Network Analyzer)

Ideal to have dedicated boards that are specifically used just for calibration purposes. Measuring one antenna design would require four boards:

- Open : end connector in air; shield connected to GND1
- Short : end connector to closest GND; shield connected to GND1
- Load: 50ohm calibration, it is useful to use two 100ohm parallel resistors assembled at the end connection point; shield connected to GND1
- Device Under Test (DUT) Board.

Or a more conveint method would be to use port extensions when measuring the DUT which only requires the board to be measured:

- Assemble cable shielding onto an earth plane of the DUT and then measure the length of the cable with OPEN port extension on the network analyzer.
- After port extension has been conducted then solder the semi-rigid cable 50 ohm connection point to the antenna

By performing either of these methods then the semi-rigid cable is also taken care of during the calibration. By just using network analyzer calibration kit, then the semi-rigid cable will be a part of the measurements

Antenna Match Example for 868MHz

- A compact PCB helical antenna at 868 MHz is matched to 50-ohm source.
- This antenna should be larger in size but it has been purposely designed to be as compact as possible. The PCB helical antenna is loaded in the match so the resonance will be at 868 MHz

FIG 2

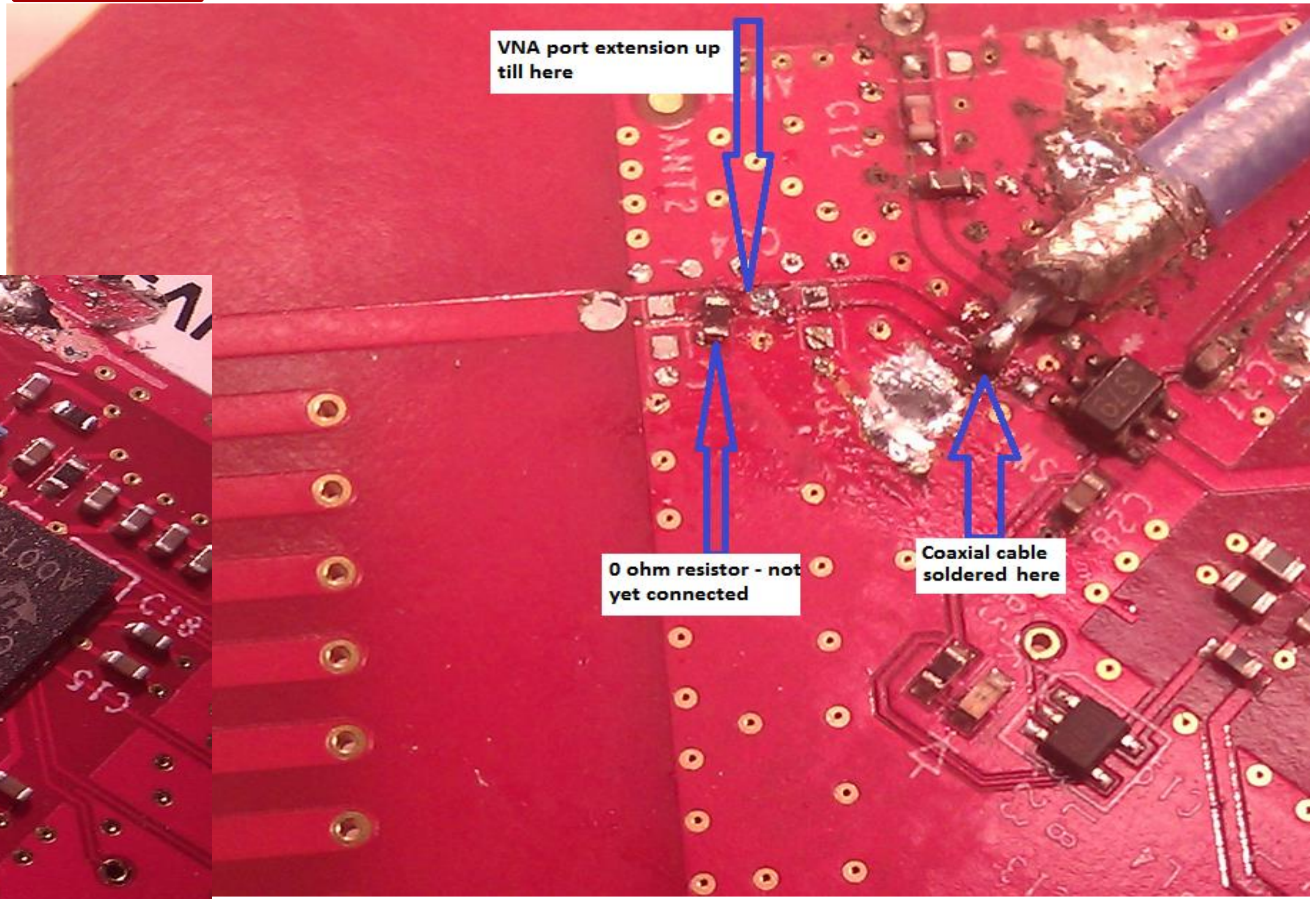
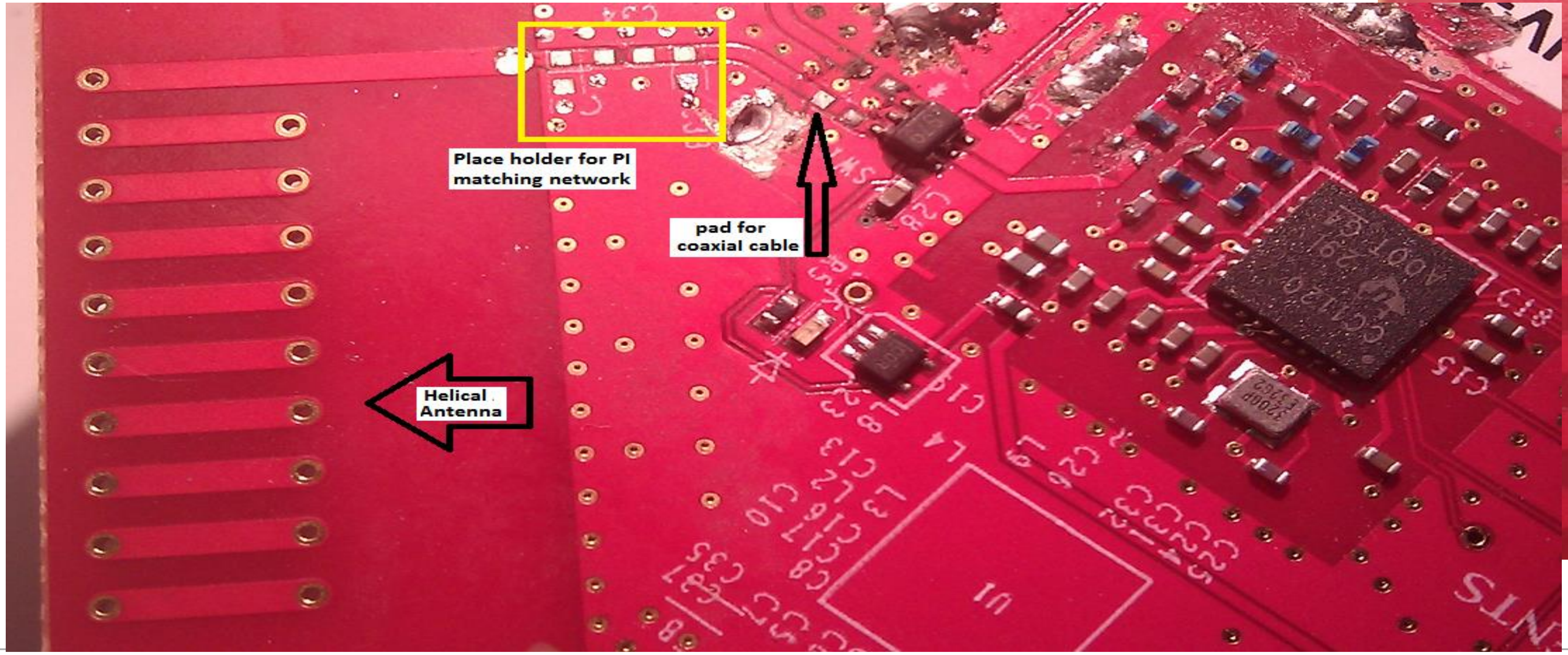
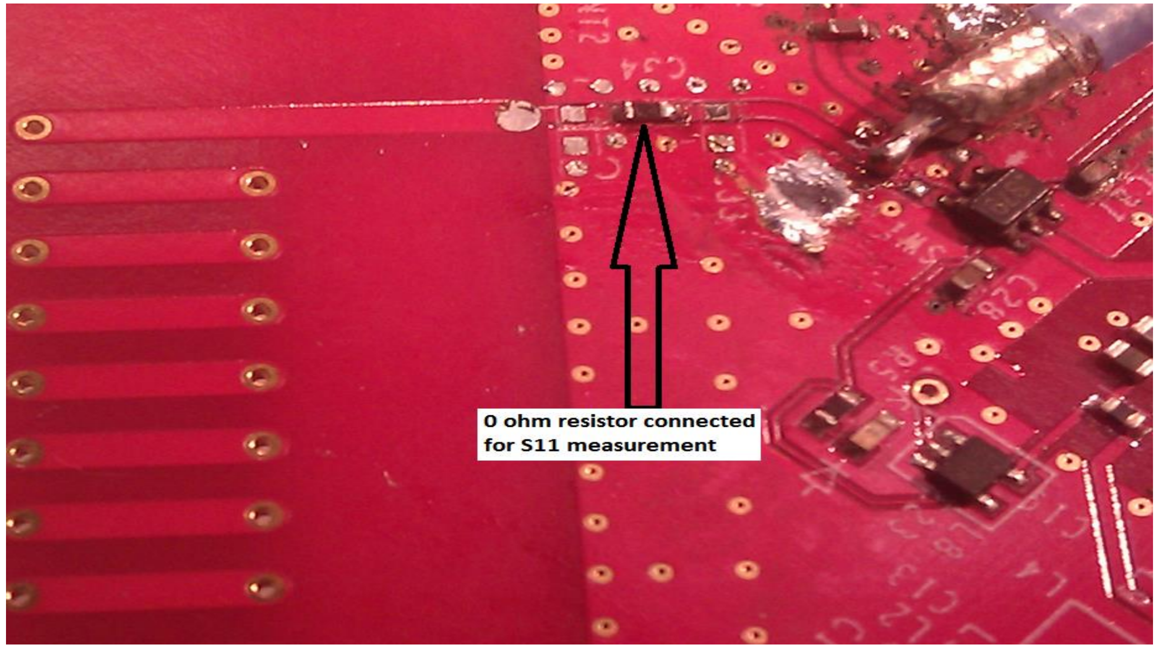


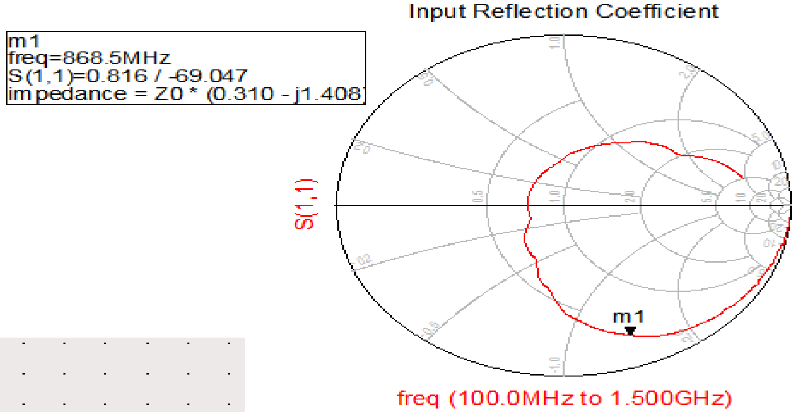
FIG 1

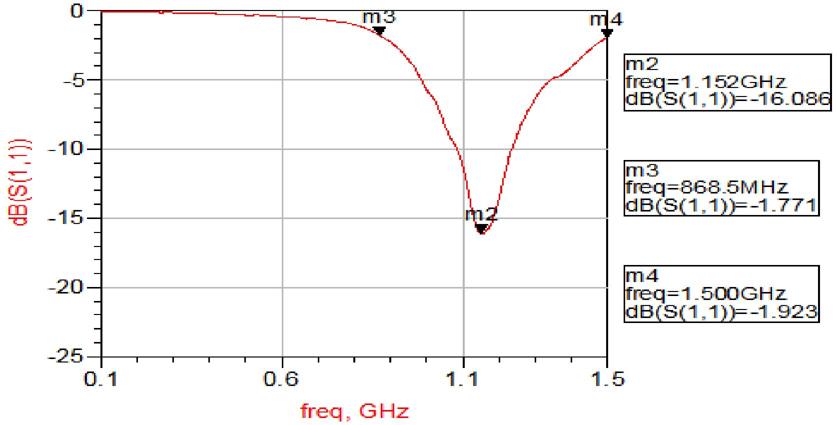


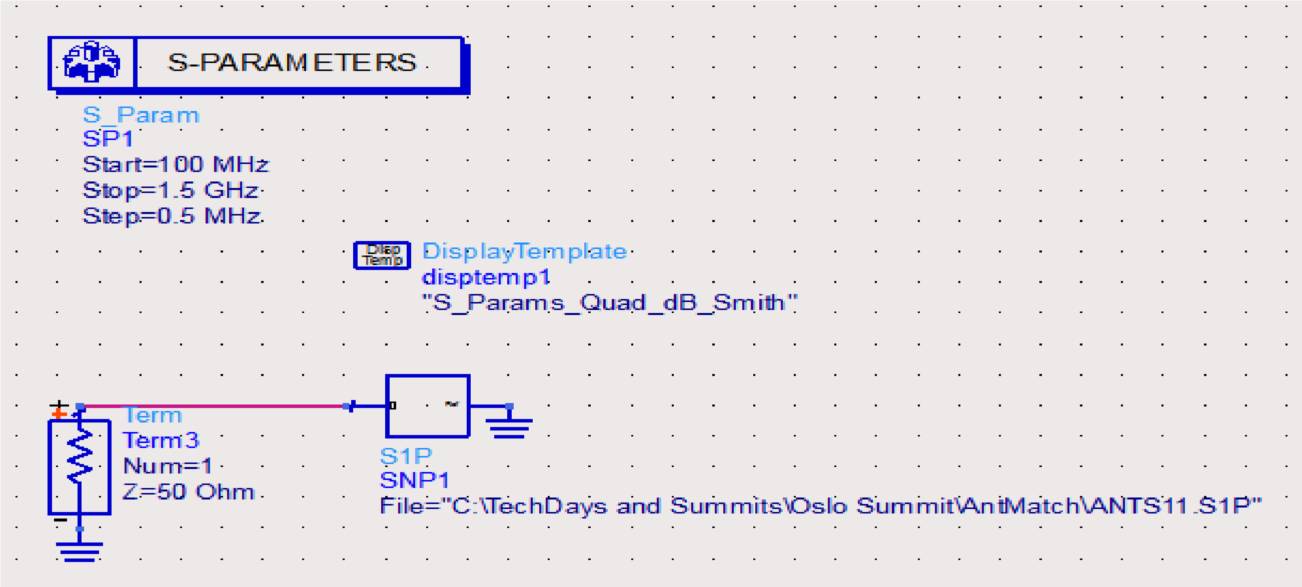
Antenna Measurement on VNA

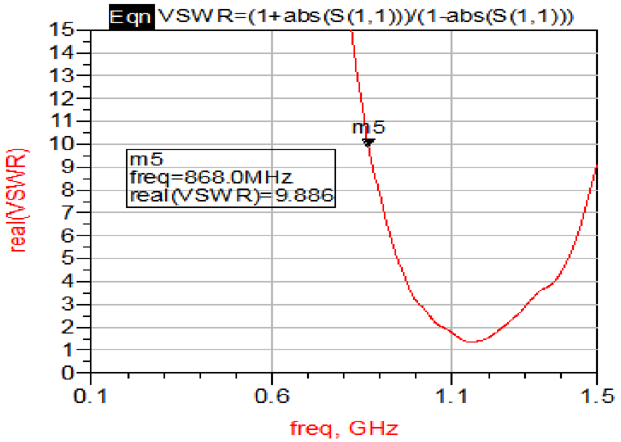


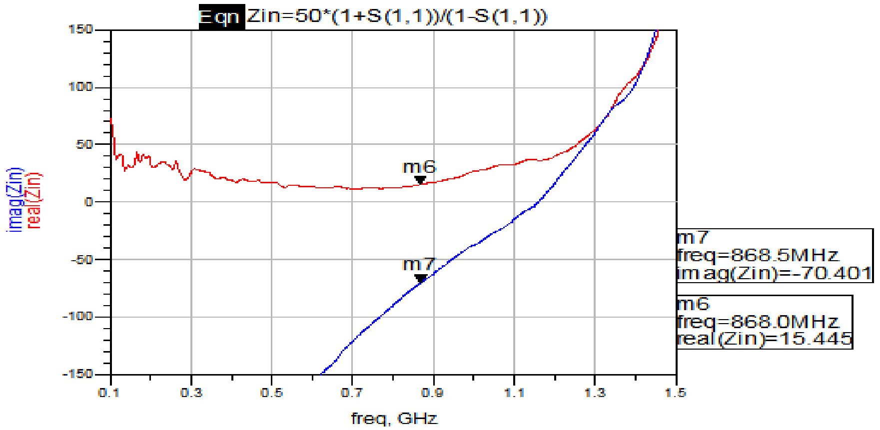
- S11 of unmatched antenna is measured and antenna impedance is calculated (or read directly from VNA) at 868MHz. The value turns out to be 15.4 – j70.4 @ 868MHz
- VSWR = 9.8





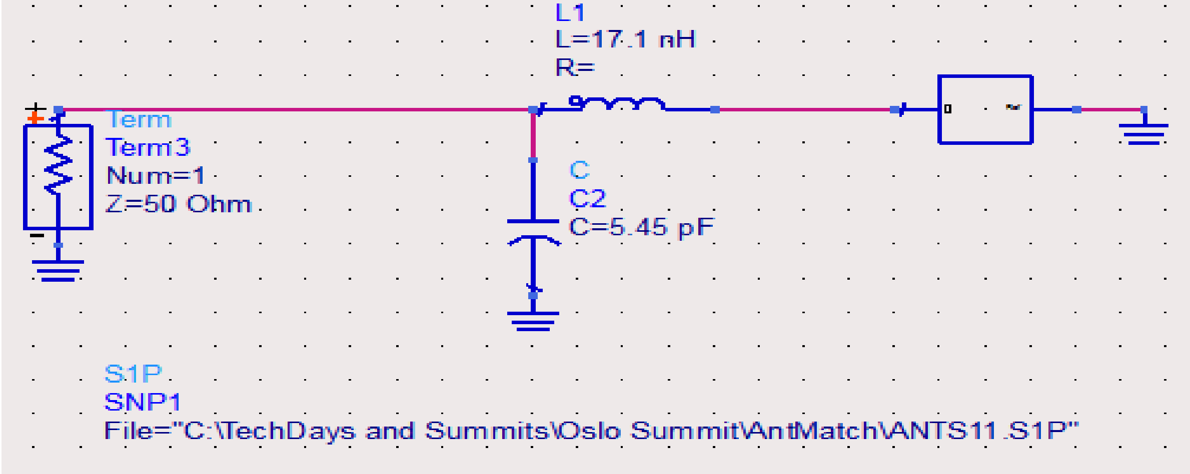


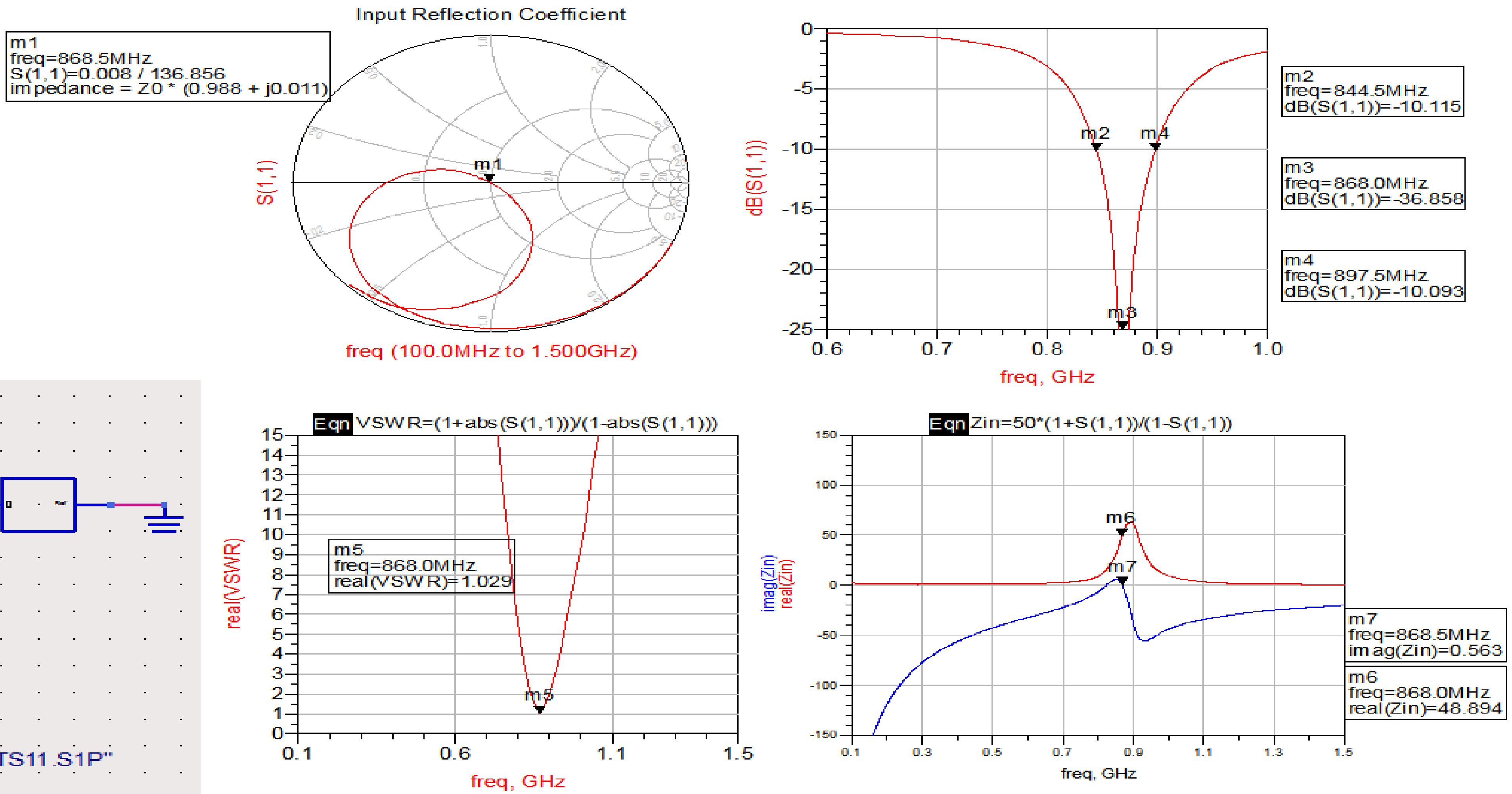




Analytic Solution at 868MHz -Theoretical Values

- Using the analytic solutions, equations (9) to (12), the **theoretical** values and result of the L-Match can be calculated as shown.
- The simulation is done again by choosing models of values available from vendors that are closest to the calculated ones.
- Once realistic models are chosen and simulated for desired performance, these values are put on the board and results are measured.



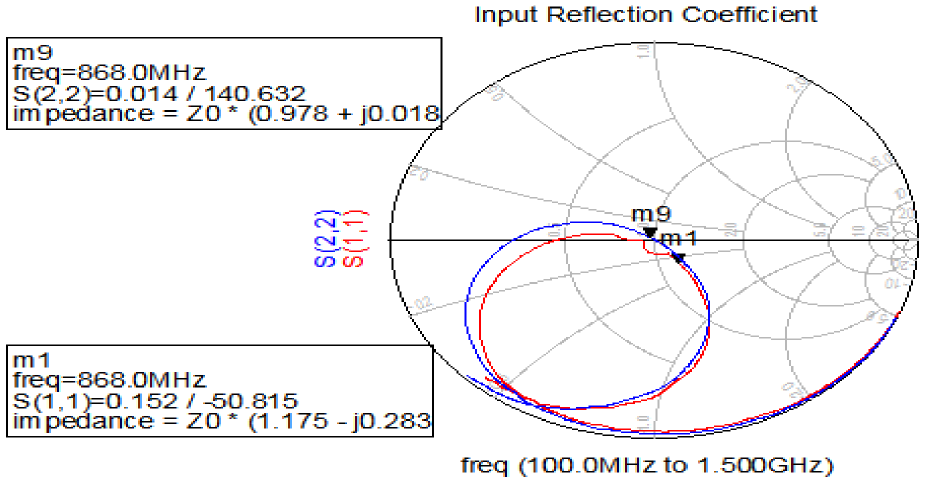


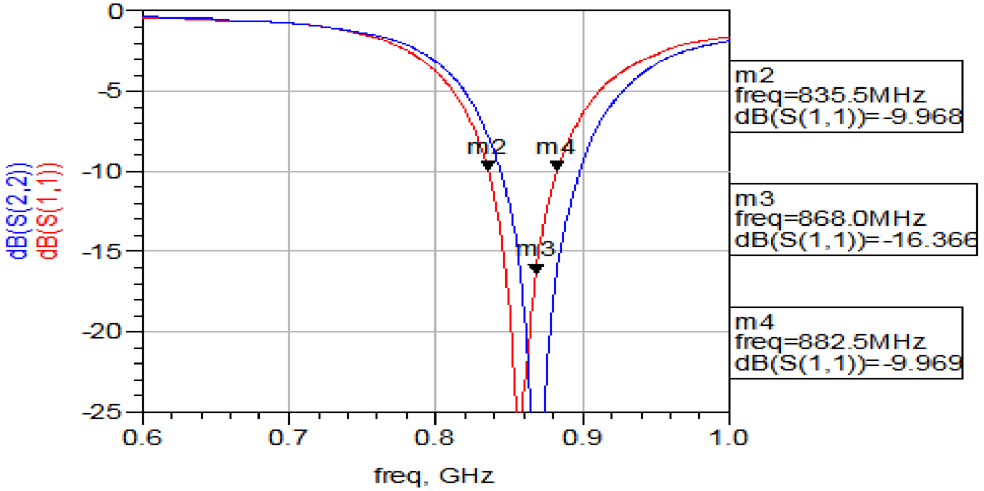
Solution With Real Values at 868MHz

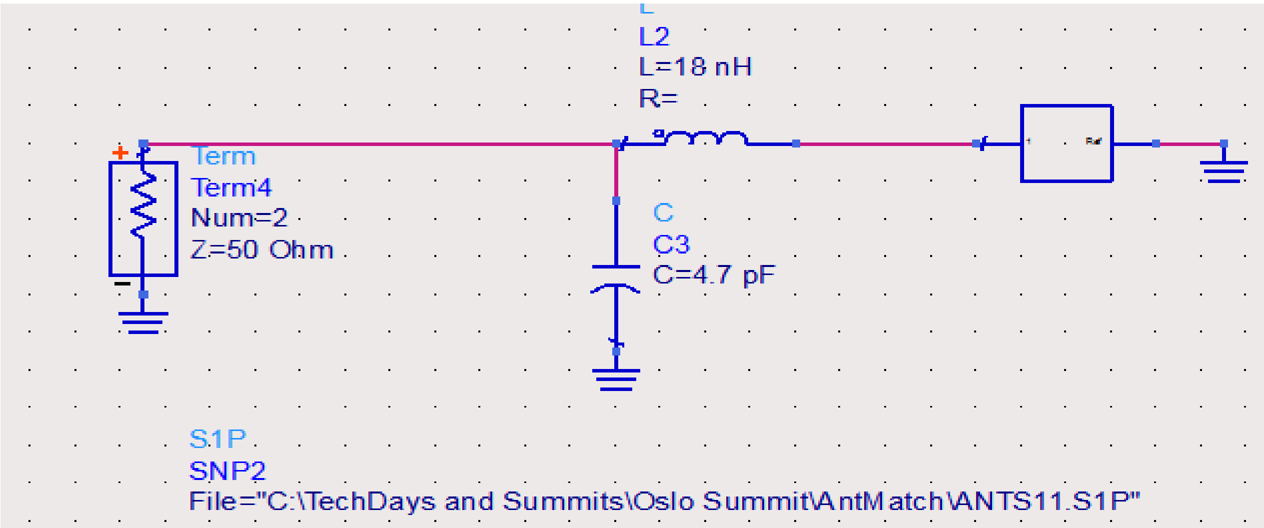
- Most likely the measurements will still be off and values are then tweaked on the board to give final acceptable antenna performance.
- Here we find that L=18nH and

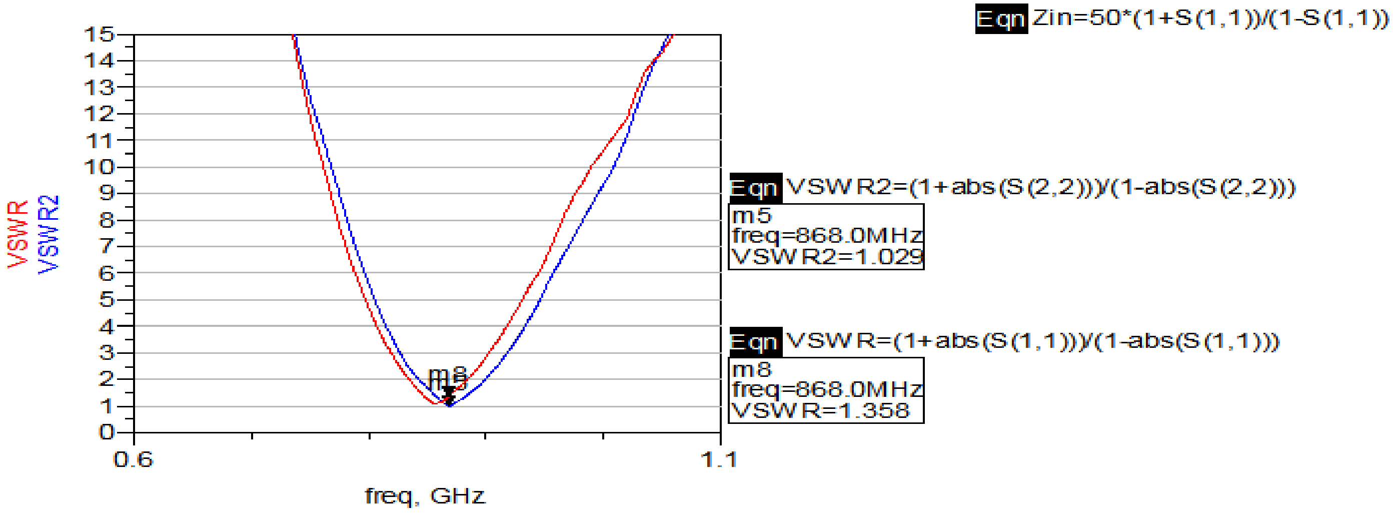
C = 4.7pF provide an acceptable

match (red curves)









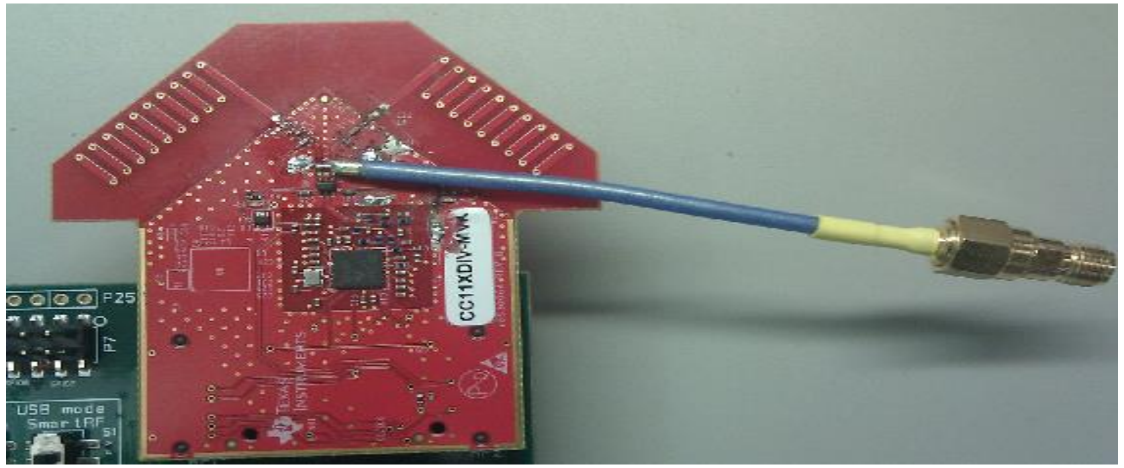
PCB Layout Practices for Antennas

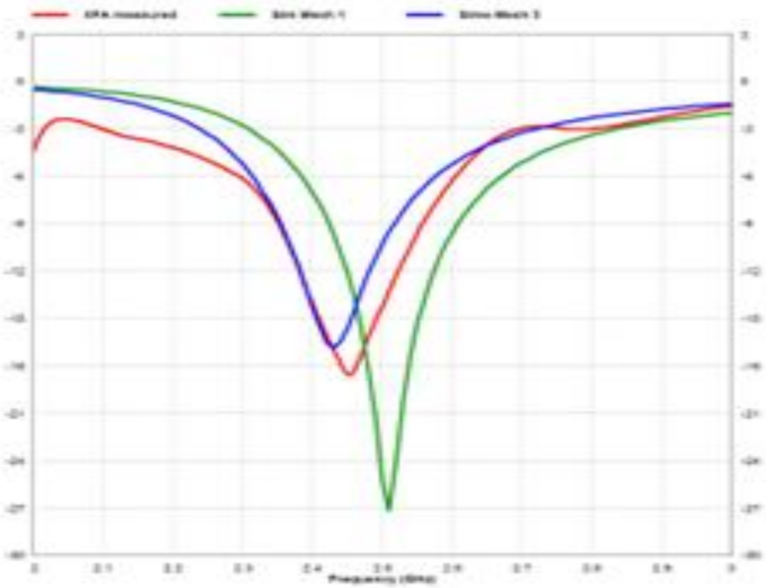
Important considerations for Antennas

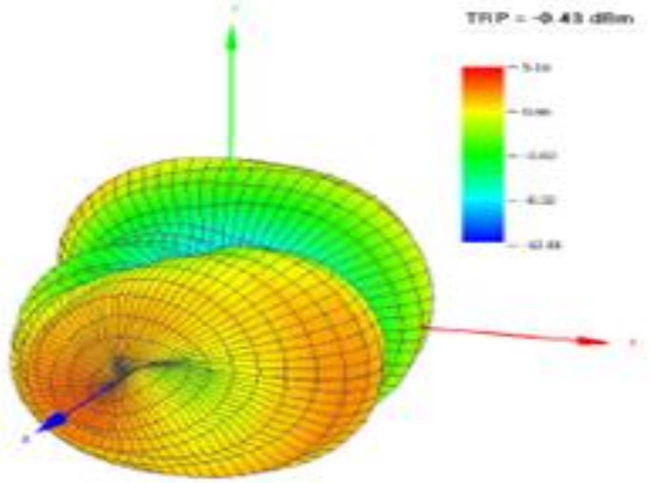
1. If using an antenna from a TI reference design, be sure to **copy the design exactly as drawn** and check if the stack-up in the reference design matches your stack-up.
2. Changes to feed line length of antenna will change input impedance match.
3. Any **metal** in close proximity, **plastic enclosure**, and **human body will change the antennas input impedance and resonance frequency**, which must be taken into account for matching.
4. For multiple antenna on same board, use antenna polarization and directivity to isolate.
5. For **chip antennas** verify that the spacing from and orientation with respect to the ground plane is correct **as specified in their datasheet**.

Antenna Radiation Pattern

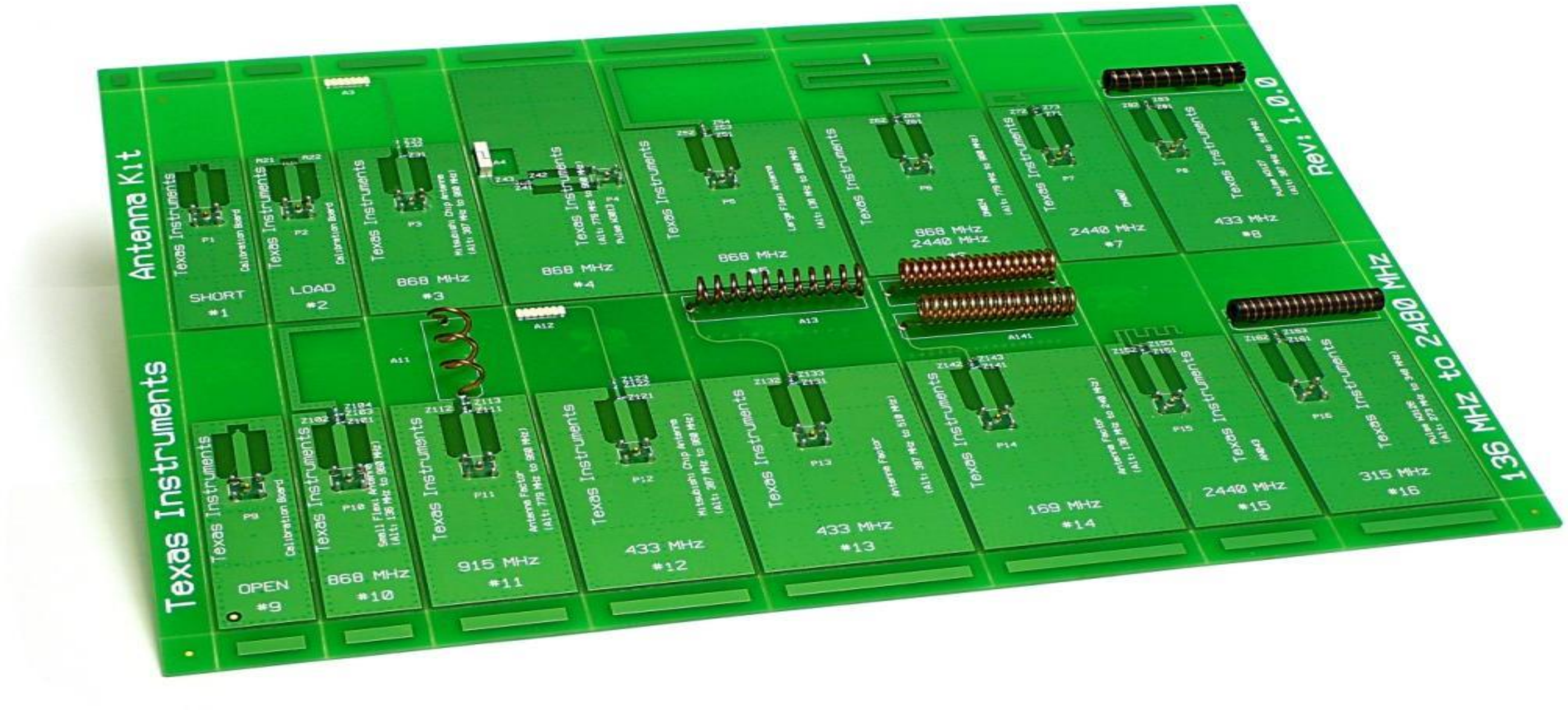
Measure the radiation pattern in an anechoic chamber with defined output power and signal generator.







Antenna Evaluation Kit



CC-ANTENNA-DK
Price $49

Antenna reference designs (PCB, Chip and Wire antennas)

13 low cost antennas and 3 calibration boards.

Frequency ranges from 136 MHz to 2.48 GHz.

See also DN031
www.ti.com/lit/swra328

References

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