Investigation of Board-Mounted Omni-Directional Antennas for WLAN-Applications

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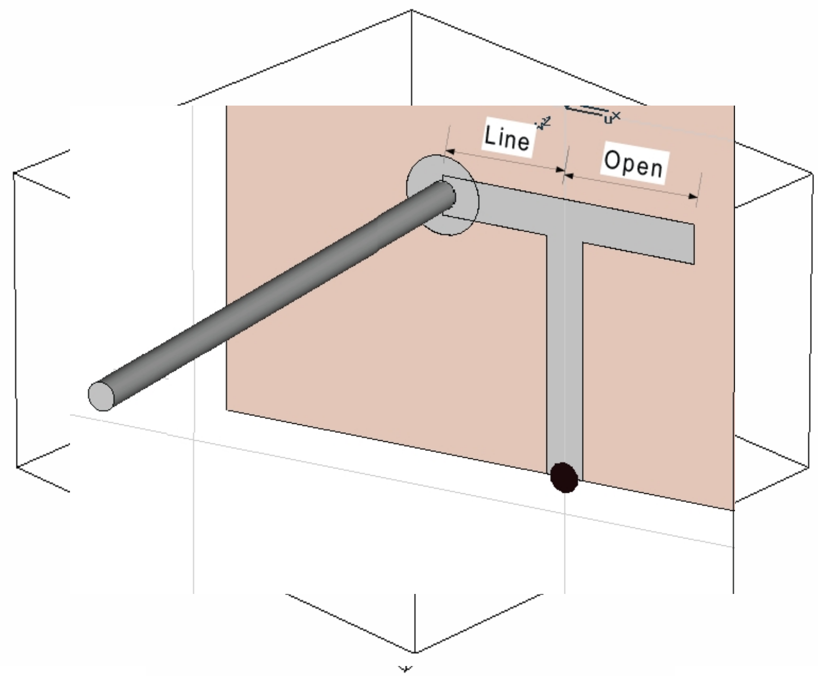
Description of the Problem

- Goal for W-LAN (i.e. 2.4 GHz) antennas: 360° coverage with one single antenna.
- We have two options:
  - Printed circuit board (PCB): horizontally oriented
  - Off-board unit: monopoles
- Recently investigations
  - Antenna arrays
  - An option is a set of board mounted monopole antennas.

Thesis Task

- Investigate of various types of monopole antennas:
  - Mounted on a circuit board
  - Fed by a microstrip line
- Four types of antennas:
  - Quarter-wave Monopole
  - Shorted monopole with top-loading
  - Folded shorted monopole with top loading
  - Half-wavelength Monopole of with microstrip matching circuit

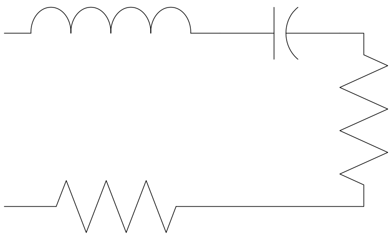


Thesis Task

- Design, simulation and fabrication of radiators.
- Test of the reflection coefficient, efficiency and radiation pattern
- Comparison of the radiator variants:
  - Volume
  - Height
  - Bandwidth
  - and Efficiency

Background Theory

- The model of an antenna



  - Radiation power factor (small antennas):

$$p_e = \frac{radiated\_power}{reactive\_power} = \frac{R_r}{X}$$

  - The quality factor:

$$Q = \frac{energy\_stored\_per\_unit\_time}{energy\_lost\_per\_unit\_time} = \frac{X}{R_e + R_{loss}} = \frac{f}{\Delta f}$$

  - Radiation bandwidth:

$$\Delta f = \frac{f}{Q}$$

    - only for Q>>1

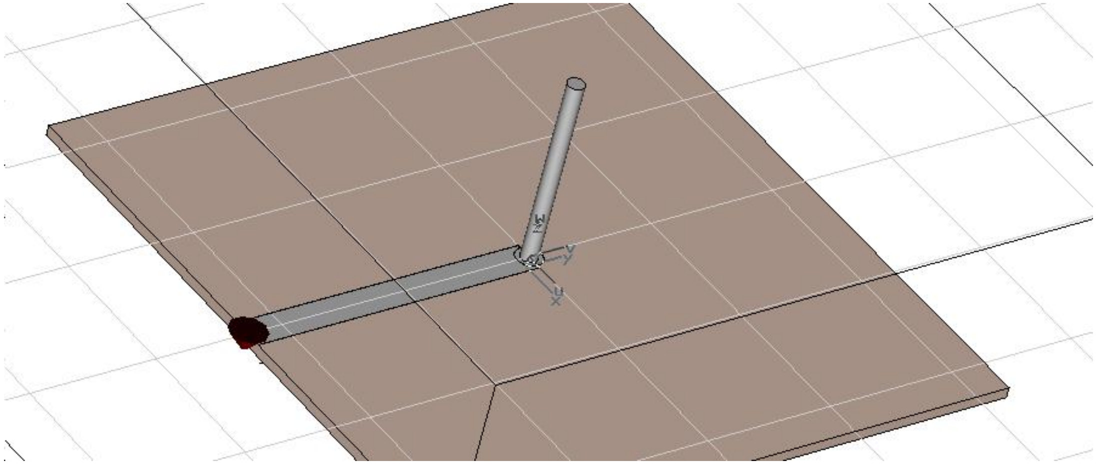
Background Theory

- Quarter-wave Monopole antenna (λ/4):
  - Mount the upper rod of a dipole on a ground plane
  - Typical value of resonance: 36 Ohm
  - Thickness improves the antenna BW
  - h effective:

$$h_e = h_p / 2$$

  - Radiation resistance

$$R_r \approx 400\left(\frac{h_p}{\lambda}\right)^2 = 1600\left(\frac{h_e}{\lambda}\right)^2$$



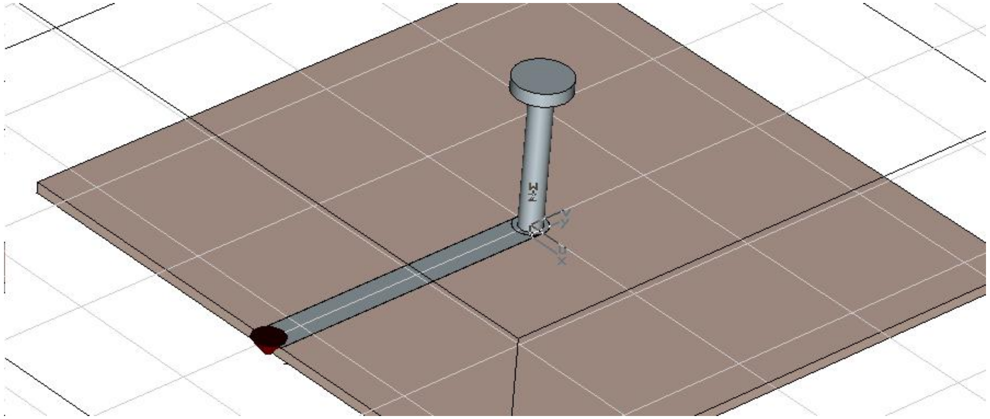
Top loaded monopole

- Formulas (Wheeler)

$$wC = Y_0 \frac{A_e}{h_e l} \qquad R_e = \frac{Z_o}{3\pi}\left(\frac{h_e}{l}\right)^2 \qquad l = \frac{\lambda}{2\pi}$$

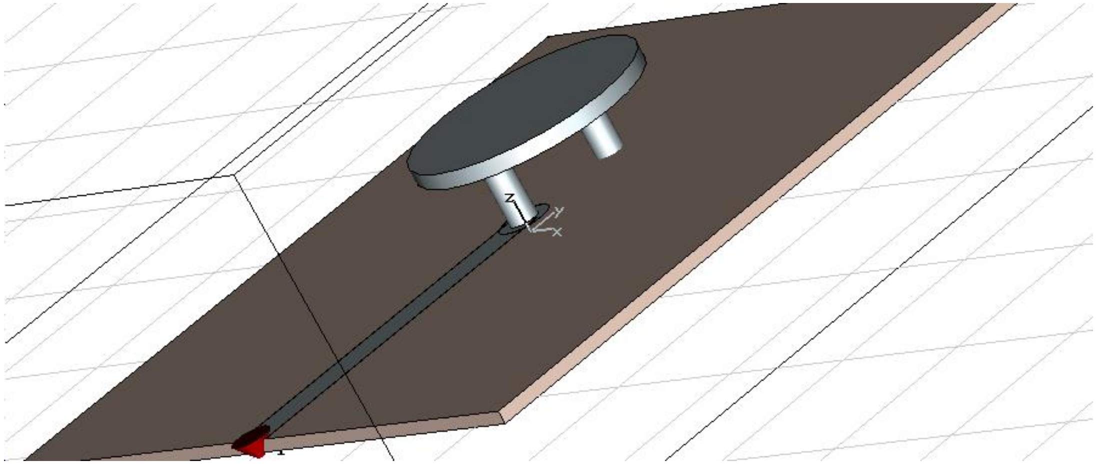
$$p_e = \frac{1}{3\pi}\frac{h_e A_e}{l^3}$$

- Radiation resistance is proportional to the square of the length of the rod
- Size of the load is directly related to the reactance and will reduce the bandwidth.



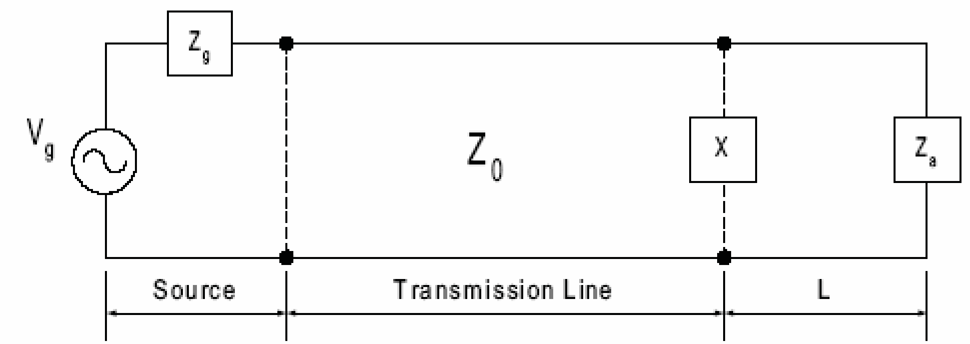
Background Theory

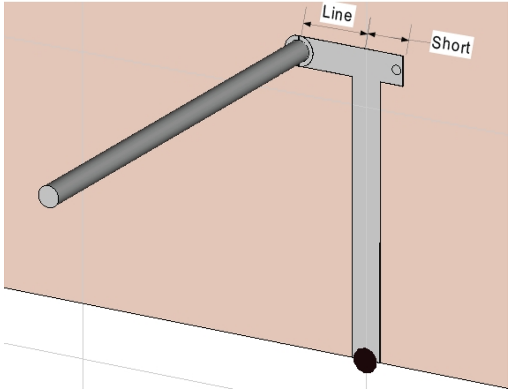
- Top Loaded Folded Monopole:
  - the radiation resistance is improved due the top loading disk
  - the resonant length are reduced by disk loading a monopole
  - the radiation resistance of a dipole can be increased considerably by folding the radiator
  - Better matching with less influence on radiation resistance

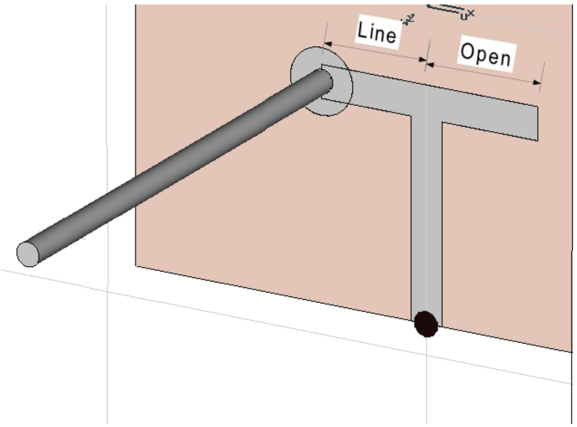


Background Theory

- Long Monopole Antenna λ/2:
  - Impedance transformation method

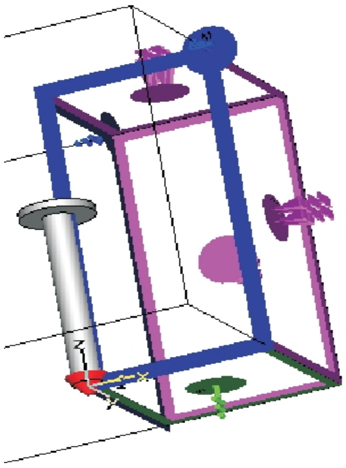




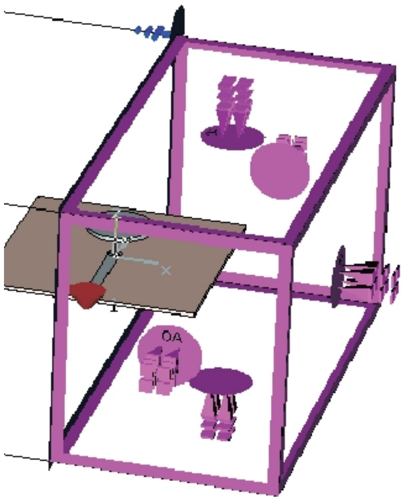


Simulation Scenario

- 2 different scenarios:
  - Ideal Scenario
    - Infinite ground plane
  - Real Scenario:
    - Finite ground plane
    - Dielectric material with an specific thickness
    - Microstrip feeding line



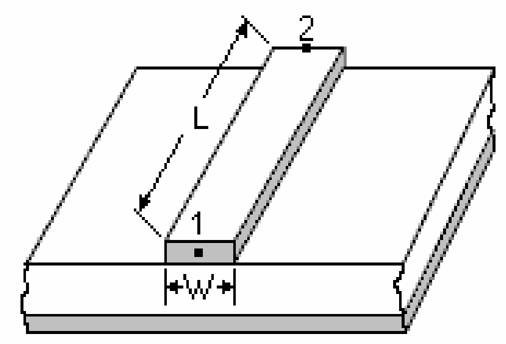
- Simulation Tool:
  - CST Microwave Studio
  - Transient Solver, with feeding line impedance of 50 ohm



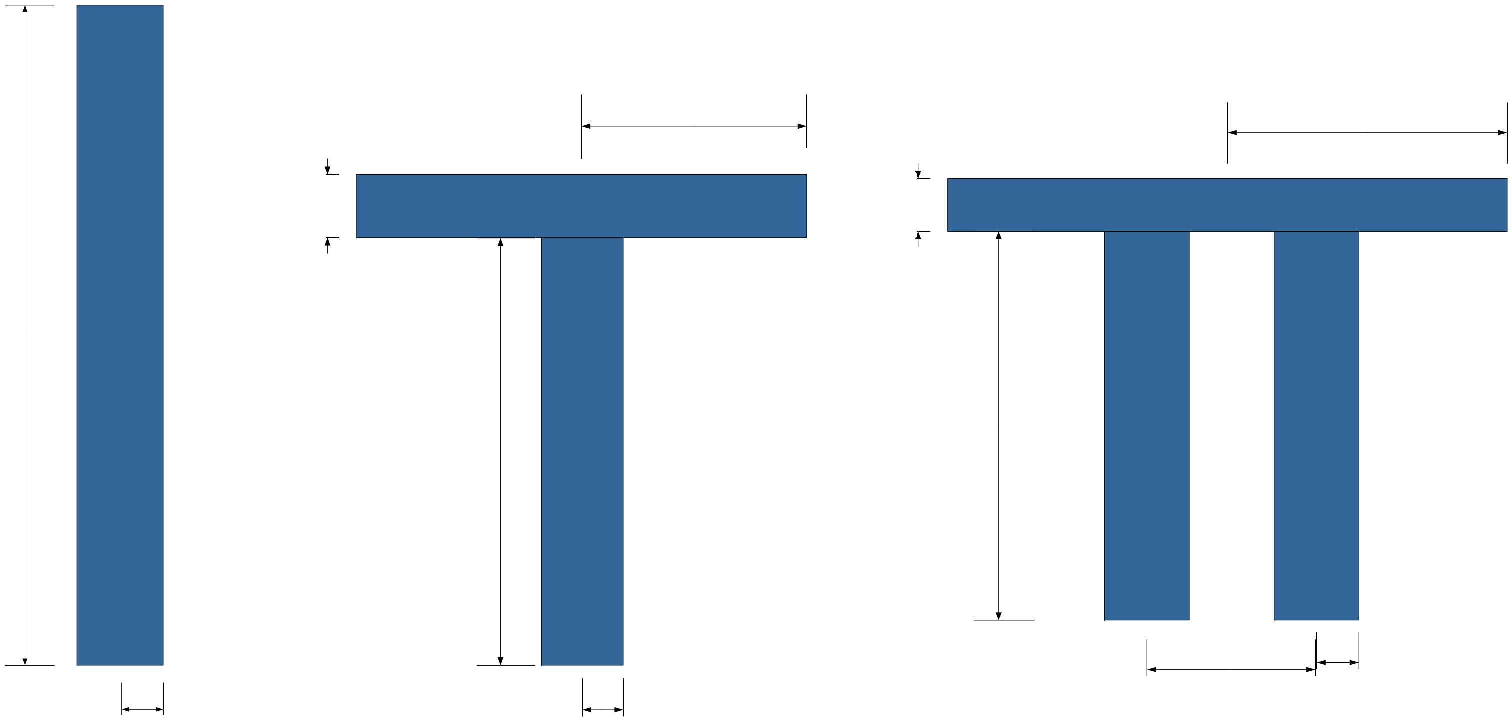
Simulation Scenario

- The Microstrip Line:
  - The size general dimensions of the microstrip line was design using the tool Line Calc of ADS
  - Materials: Duroid RT5870, Rogers RO4003, TMM4
  - Specifications:

Characteristic	RT5870	RO4003	TMM4
ξ_r	2.2	3.38	4.5
$\tan\delta$	0.009	0.0027	0.002
Thickness of the dielectric	1.6 mm	1.6 mm	1.6 mm
Thickness of the conductor	0.035 mm	0.035 mm	0.035 mm
Length (L)	4.70334 mm	3.659 mm	2.968 mm
Width (W)	88.8286 mm	76.17 mm	67.569 mm

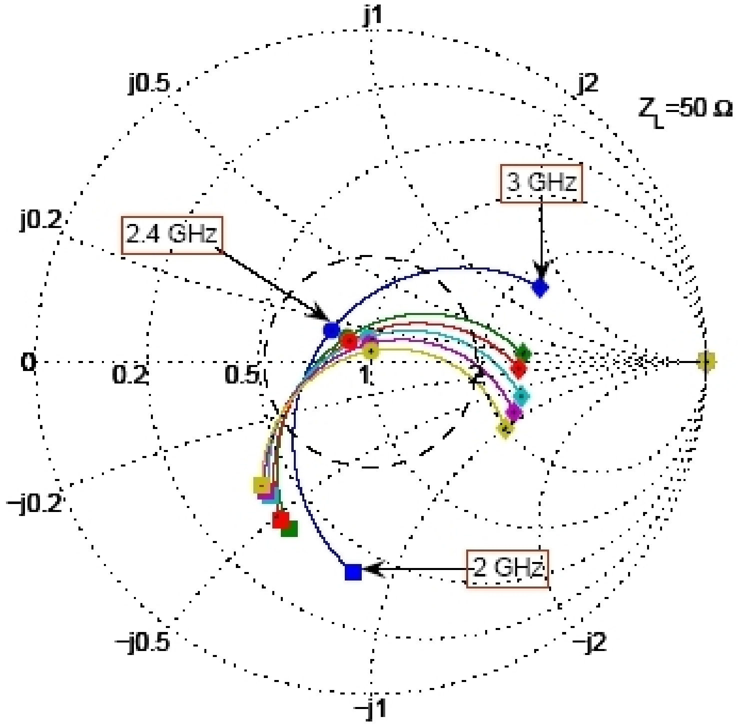


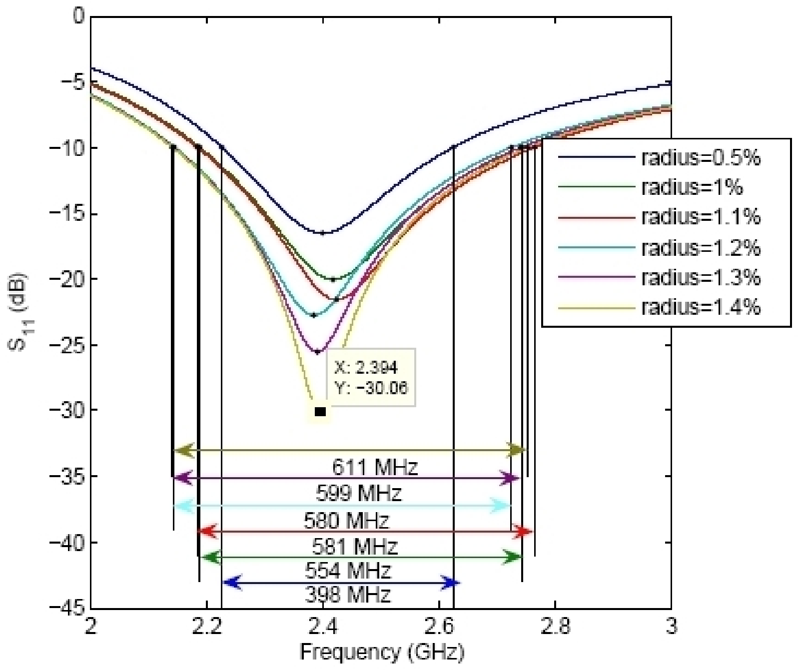
Simulation Scenario



Simulation Results:

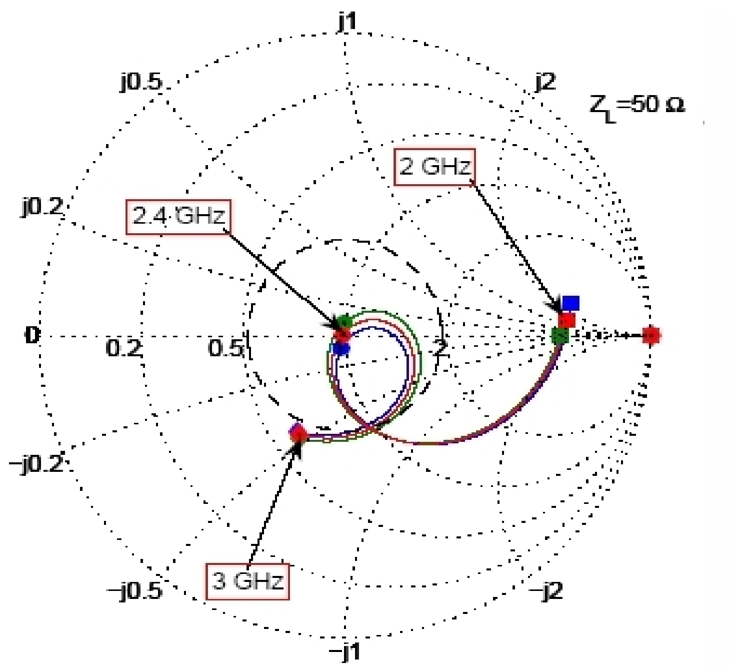
- Rod radius variation – Ideal Scenario:
  - Common parameter to the first three antennas.
  - A bigger radius leads to a bigger BW, and a better matching
  - Example: Quarter wave Monopole, a smaller radius leads to a value closer to 35 ohm

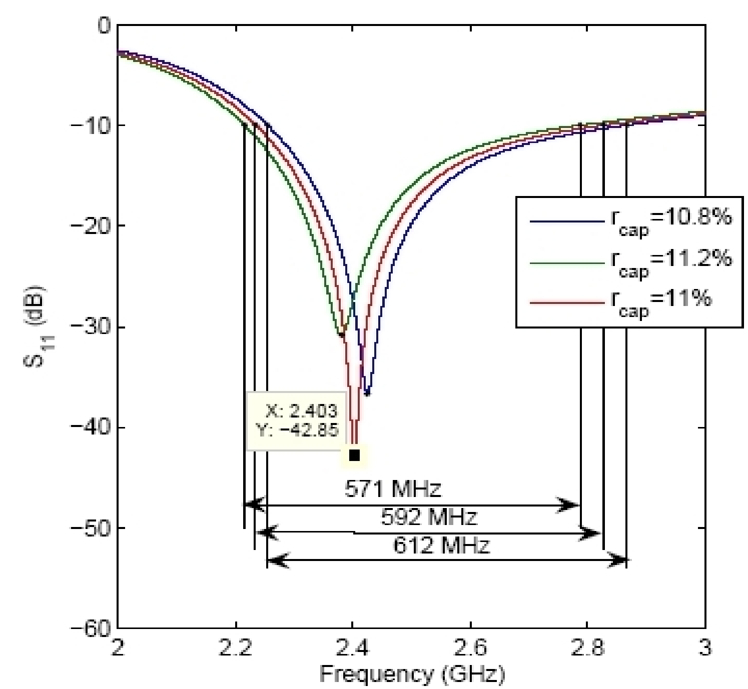




Simulation Results

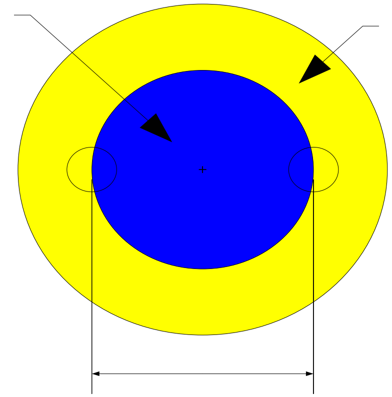
- Variation of the load radius:
  - Capacitive element
  - As the radius increases, the reactance of the antenna is increased.
  - Influence also on the active part of the antenna.
- Example on the ideal scenario: Top loaded monopole
- Example on the real scenario: Top loaded folded monopole
- A smaller load leads to a bigger BW

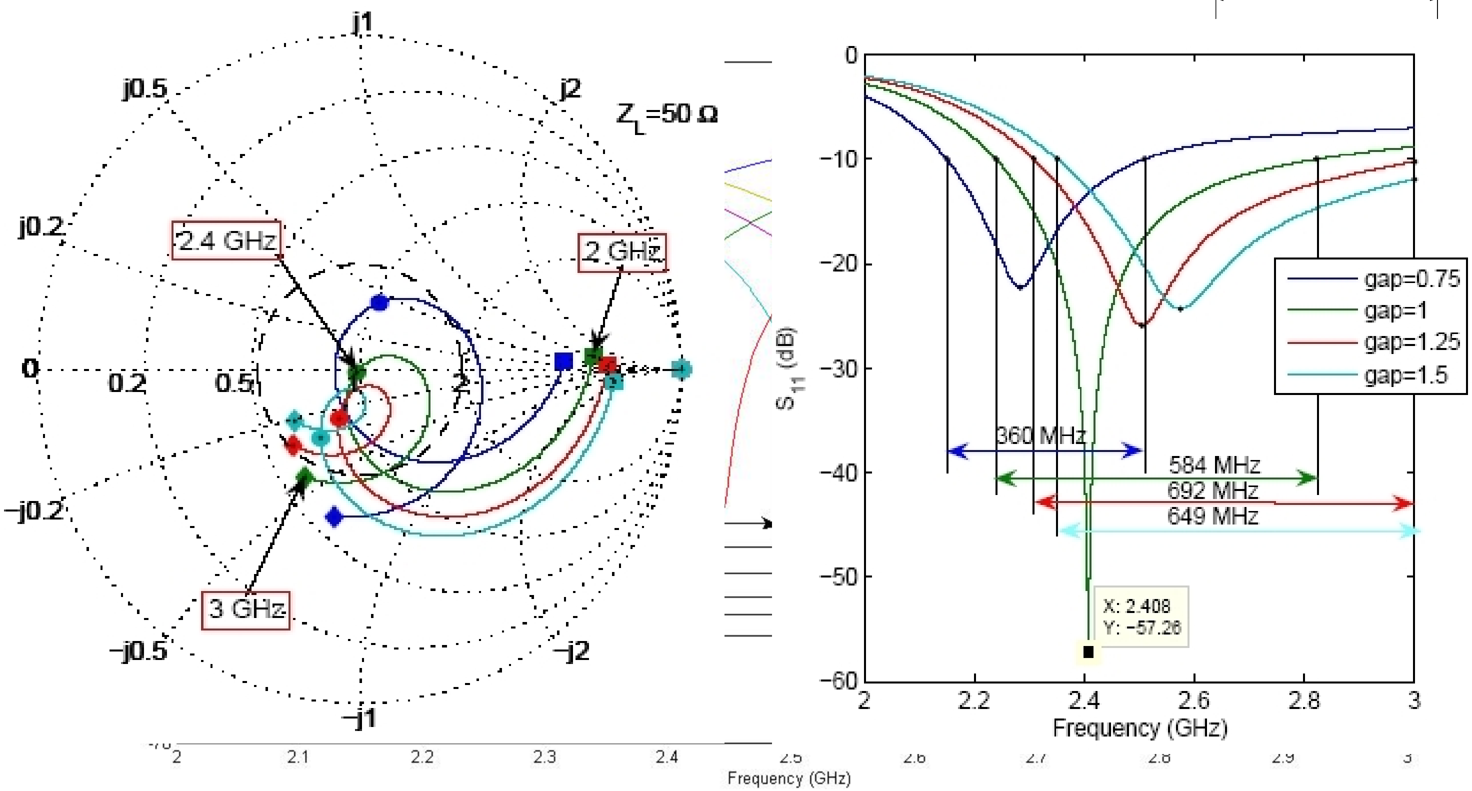




Simulation Results

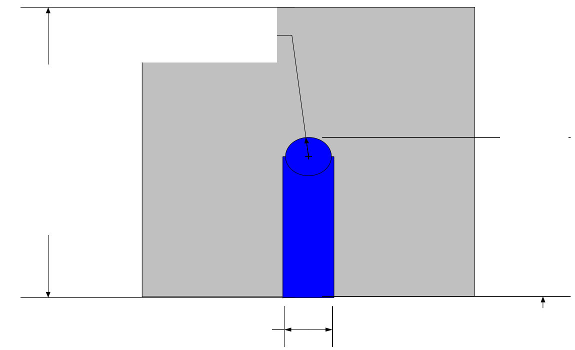
- **Variation of the gap between rods**: (only for the top loaded folded monopole)
  - Ideal scenario: no apparent clear tendency on the behavior of the parameter
  - Real Scenario:
    - Influence on the active and reactive part of the impedance
    - Internal load and external load, leading to an equivalent radius





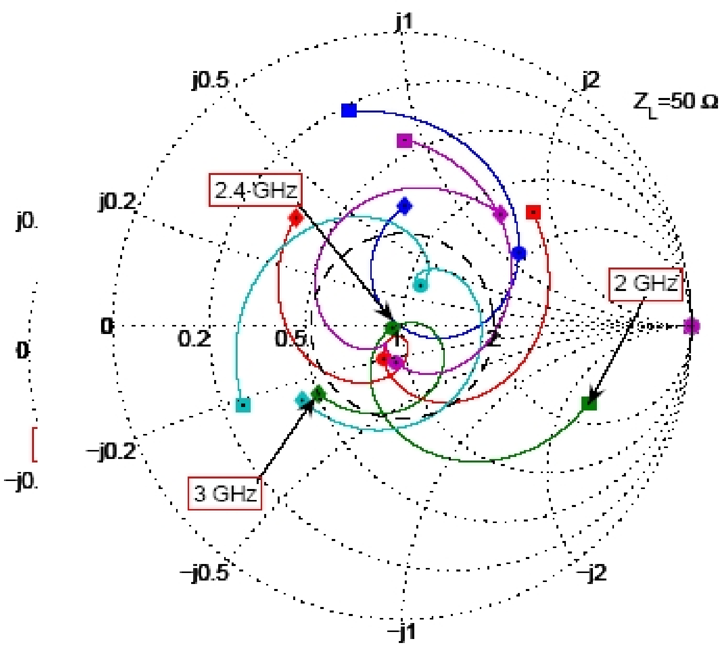
Simulation Results

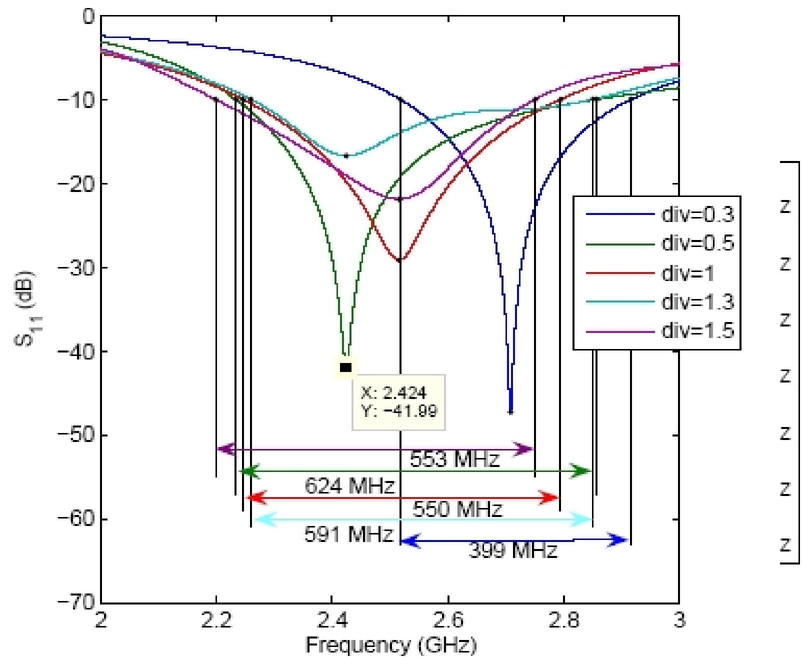
- Variation of the dielectric material size
  - The length of the line also presents influence on the reflection coeffcient
  - The chassis mode of once λ is more predominant on the top loaded monopole than on the top loaded folded monopole
  - Some other values like twice λ also show some relevance



Top loaded monopole

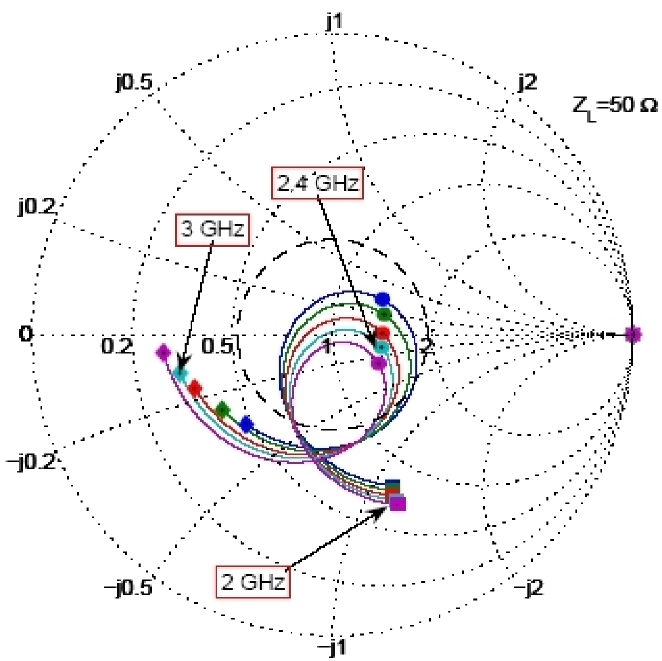
Top loaded folded monopole

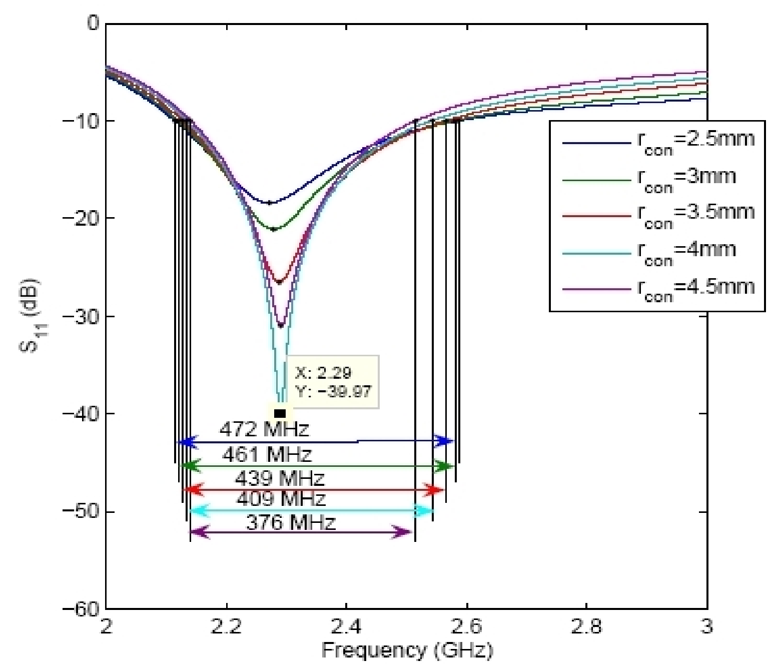




Simulation Results

- Variation of the connector on the feeding microstrip line
  - Test performed on the top loaded and top loaded folded monopole
  - The element is almost a pure reactive element
  - As the radius of the connector is increased, the reactance of the antenna is reduced.

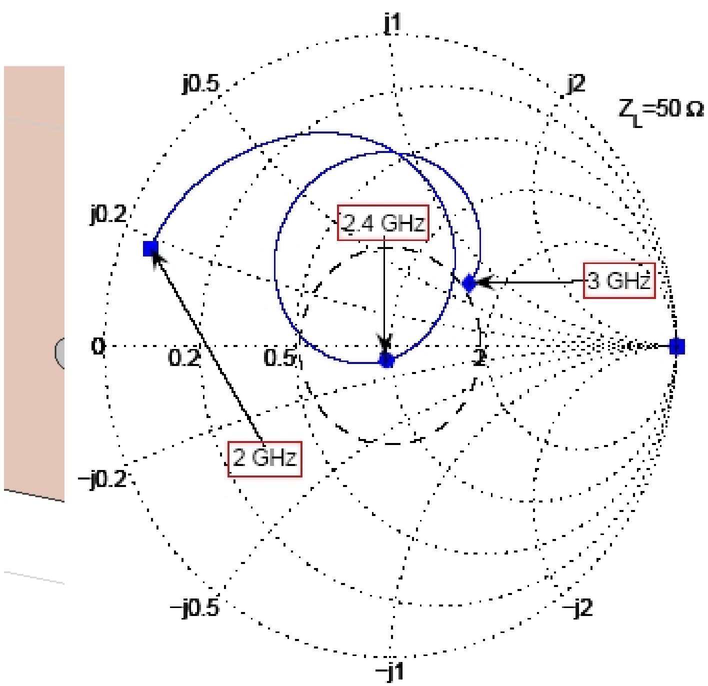


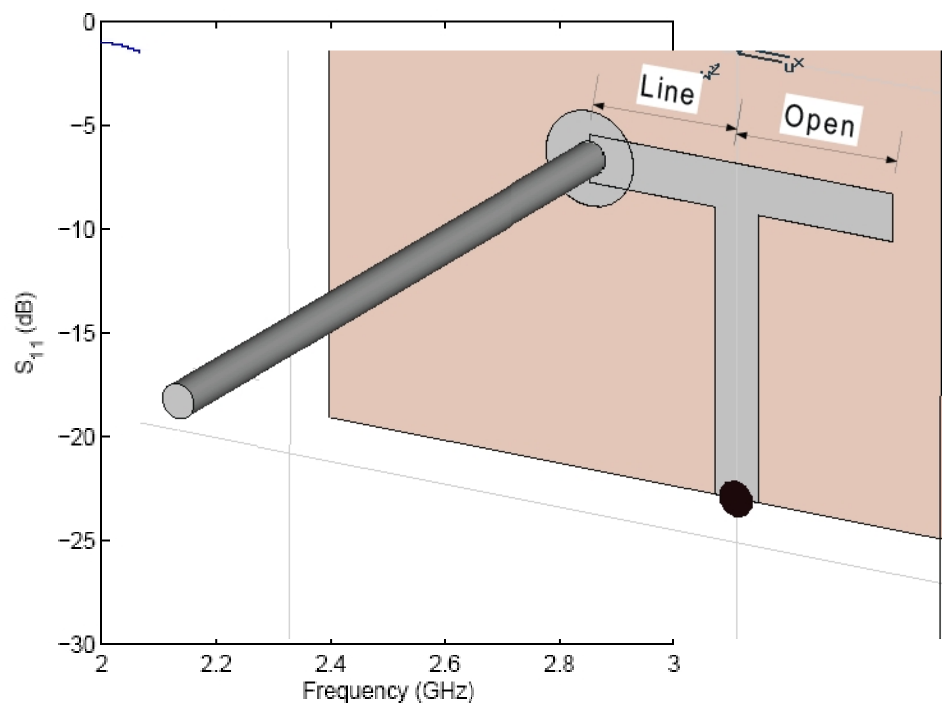


Top loaded Monopole

Simulation Results

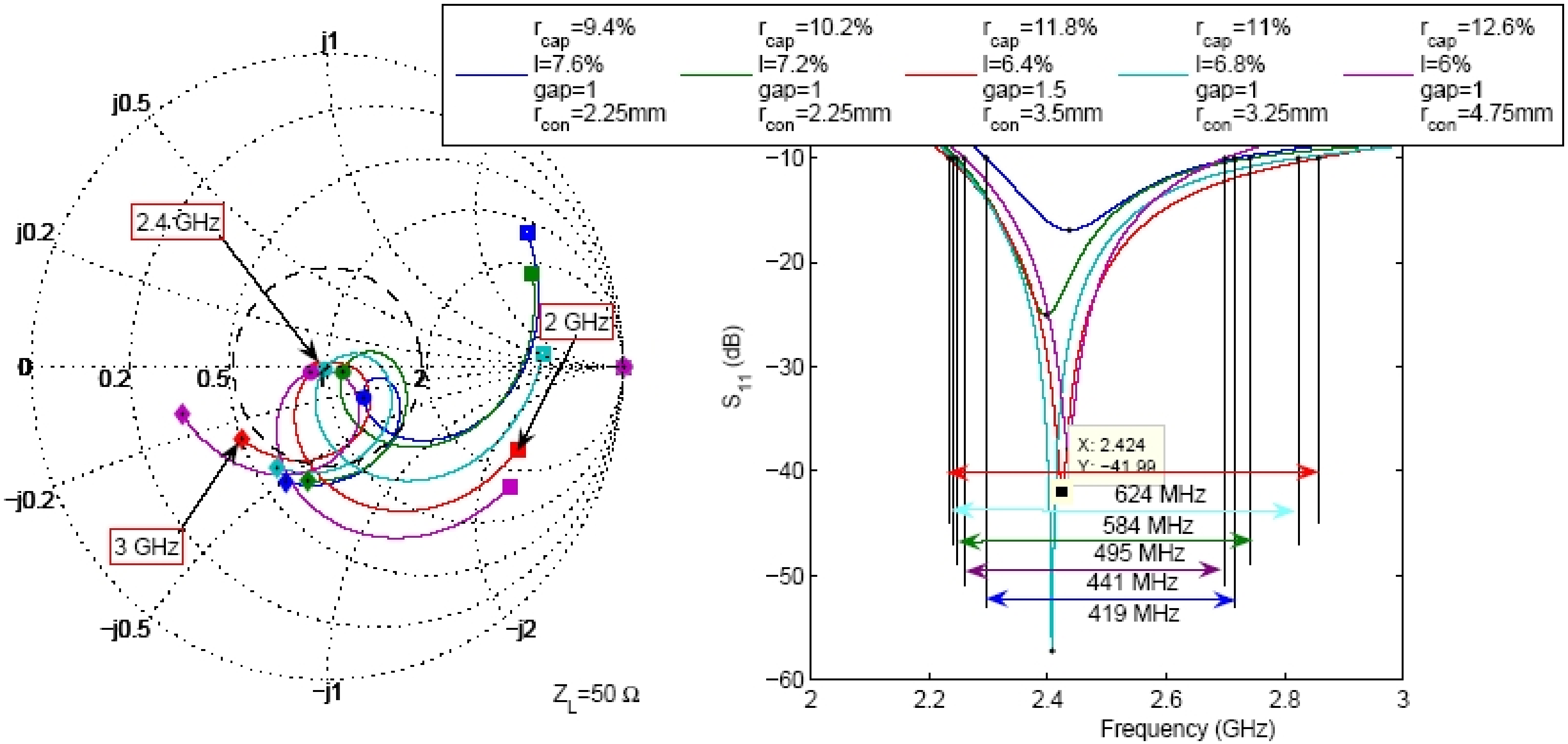
- **Half-wave monopole:**
  - 2 options of the compensation circuit: Short circuit and open circuit
  - Antenna without network: BW: 328 MHz = 26% @ 1.26 GHz
  - Open circuit network: BW: 82 MHz = 2.7% @ 2.93 GHz
    - Line length = 11.46%
    - Open length = 17.28%
  - Short circuit network: BW: 151 MHz = 5.1% @ 2.93 GHz
    - Line length= 6.876%
    - Short length = 17.28%





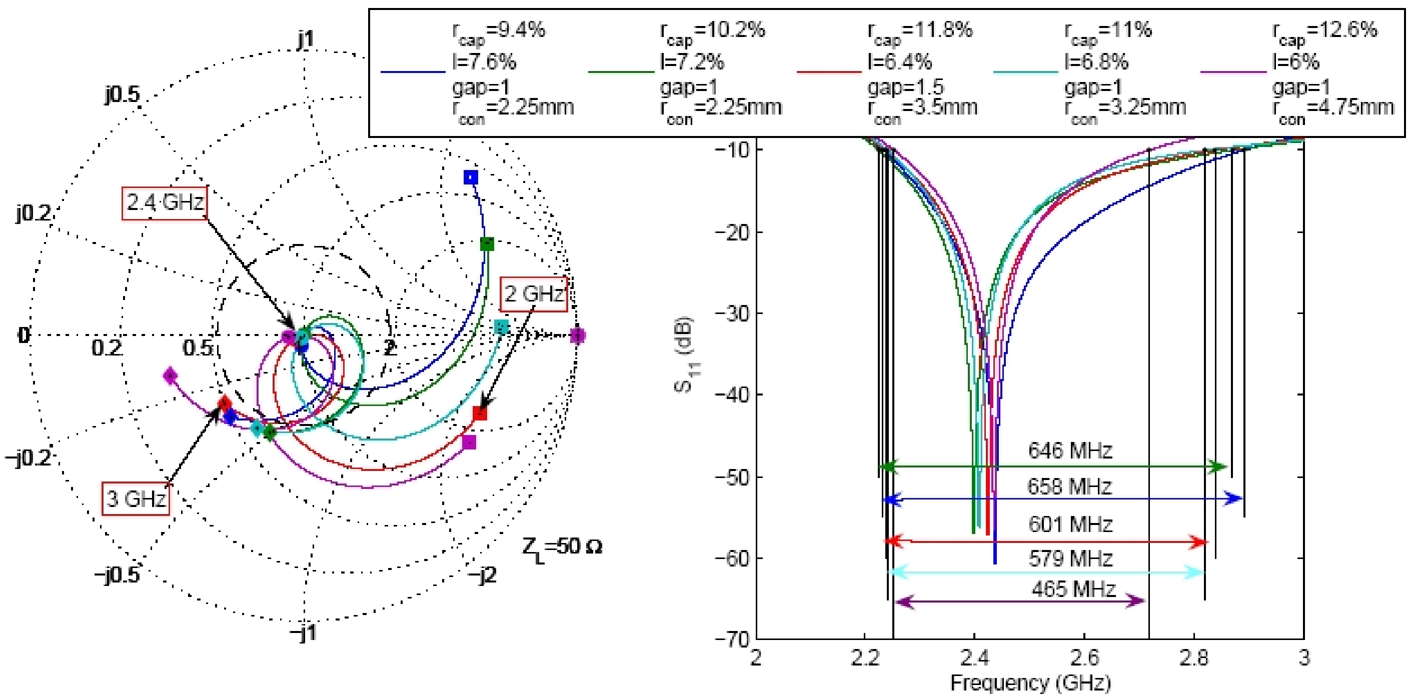
Simulation results

- Specific antenna impedance
  - The influence of microstrip on the antenna is removed
    - Shows if the matching was improved through loses
    - Shows some possible influence on the BW
  - All the materials used on the simulations have very small loses



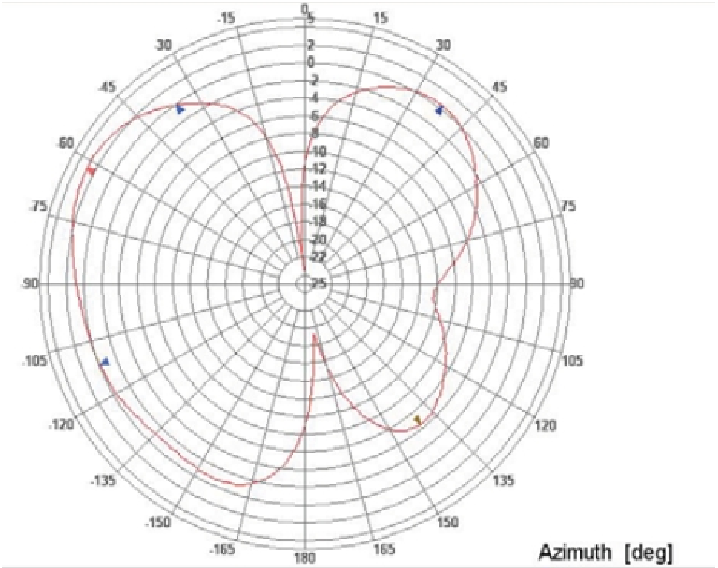
Simulation results

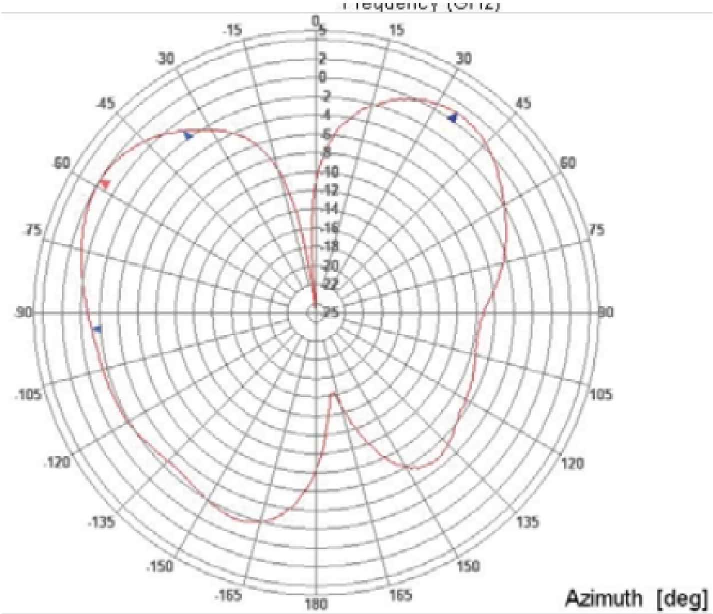
- Potential bandwidth:
  - It is defined for the case of a perfect matching on the antenna
  - The presence of the microstrip line changes the behavior of the antenna system
  - In some cases the BW is decreased



Built Antennas

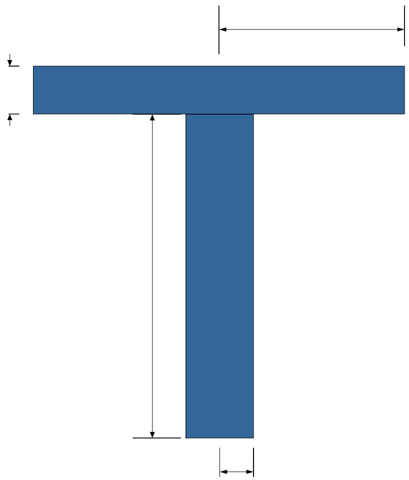
- 2 radiators were built for the verification of the results:
  - Top loaded monopole antenna:
    - radius=1.4%
    - rod length=16.8%
    - load radius=3.4%
    - thickness of the load = 2mm
  - Top loaded monopole antenna:
    - radius=1.4%
    - rod length=6.8%
    - load radius=11.6%
    - gap = load radius
    - thickness of the load = 2mm

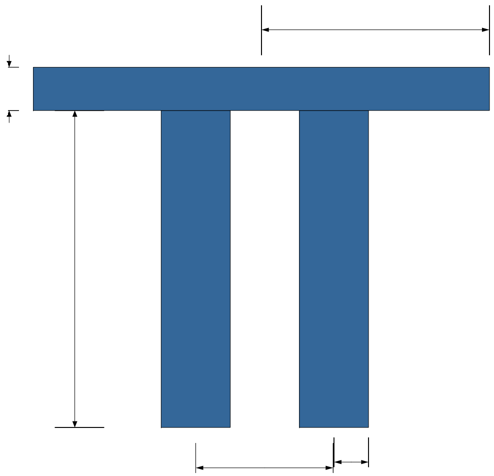




Design rule

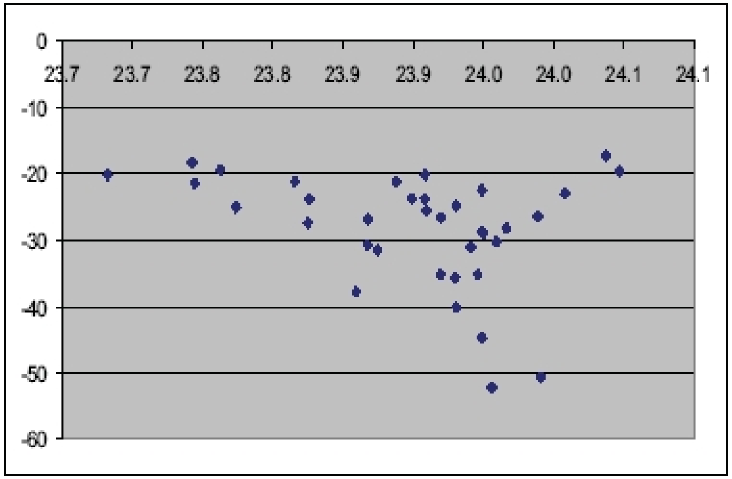
- The central frequency will be related through: $$central\_\lambda = \frac{c}{central\_freq}$$
- Central λ is presented
  - Some fundamental parameters will be referred to the normalized lambda:
    - rod length,
    - load radius,
    - gap between rods
    - thickness of the dielectric material: 1.6mm (1.28% of central λ in average)
- Top loaded folded monopole - Disc areas:
  - Internal area of the load, defined by the gap between rods
  - Difference of the areas leading to an equivalent radius, referred to the central λ.



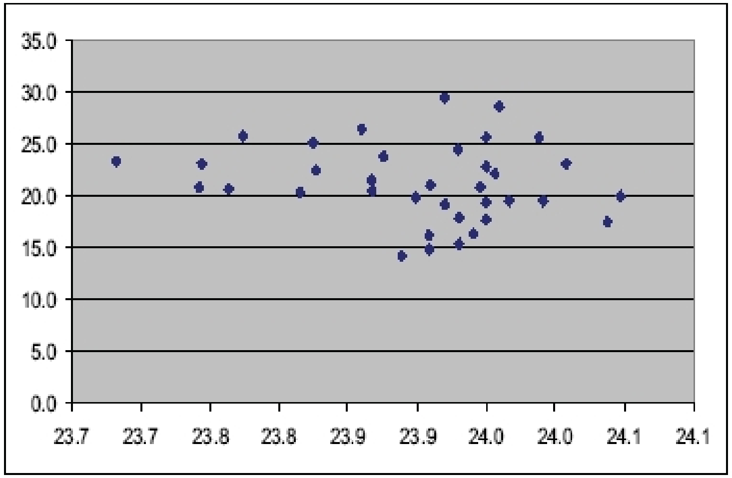


Design rule

- Top loaded monopole - design rule:
  rod length + 2 x radius load + dielectric material thickness
  - From 23.73 to 24.03: best values of S11
  - As the design rule goes down, bigger BW
  - A good compromise: 23.9
  - Important to remind: As the load presents a lower value, the bandwidth is improved



Reflection coefficient VS design rule



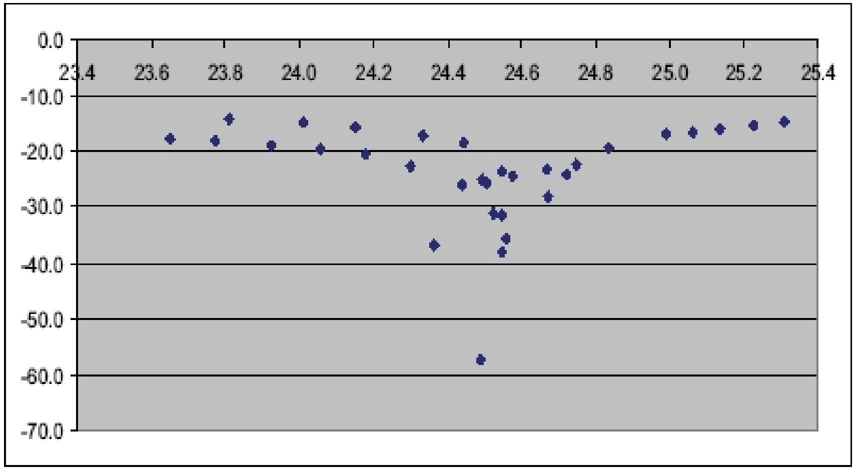
Relative BW VS design rule

Design rule

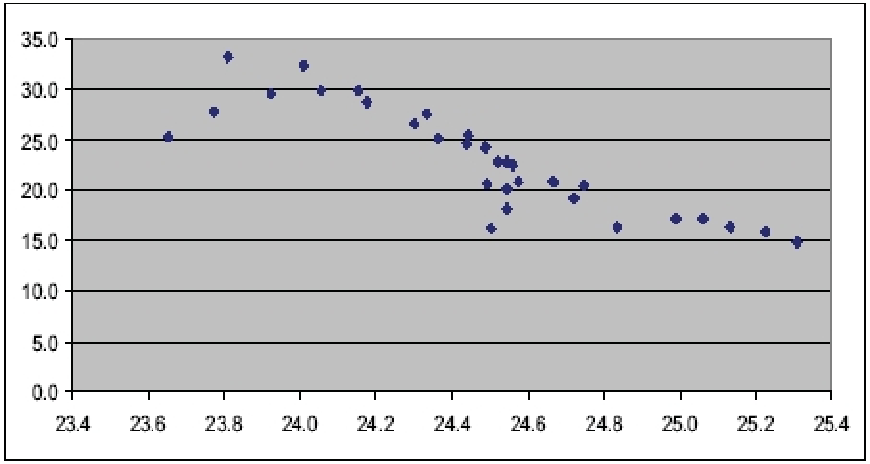
- Top loaded folded monopole - design rule:

  2 x rod length + radius load + dielectric material thickness

  - Peak of S11: 24.5
  - Peak of BW: 24
  - Important to remind: gap between rods is constant to once the radius load



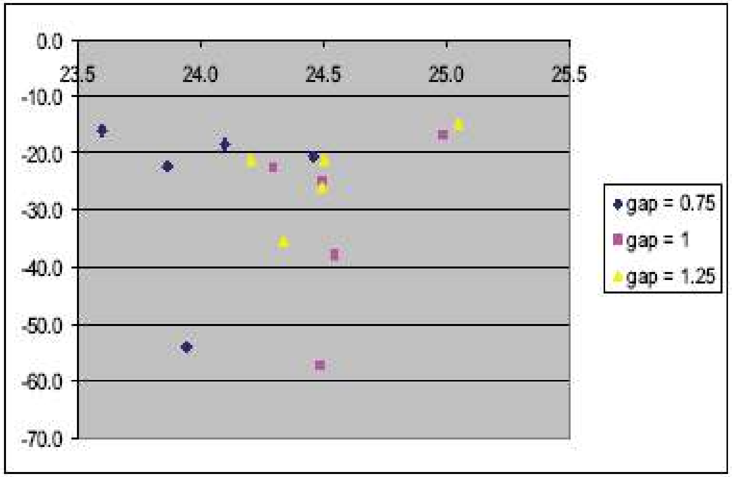
Reflection coefficient VS design rule



Relative BW VS design rule

Design rule

- Top loaded folded monopole - design rule:
  - Variation of the gap VS design rule:
    - The compromise of the values is no longer valid
    - For each value of the gap, the better matching belongs to a different value of the design rule
    - Influence on the electrical length in a higher degree than the lineal relation.



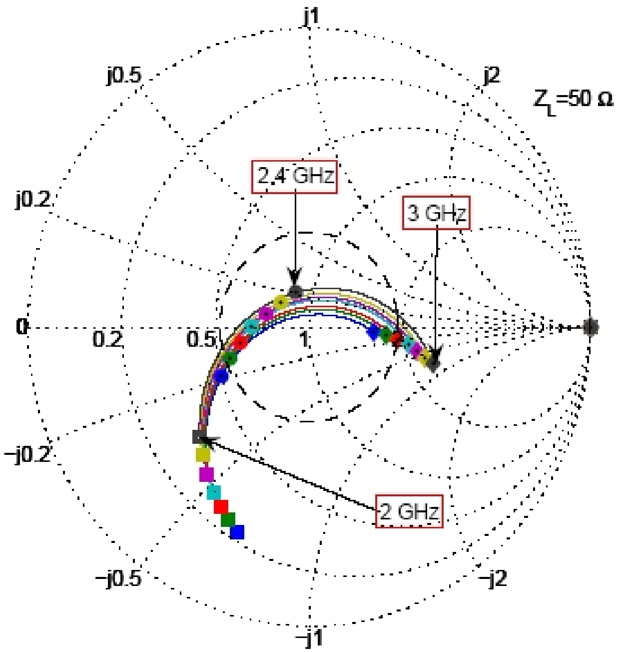
Reflection coefficient VS design rule

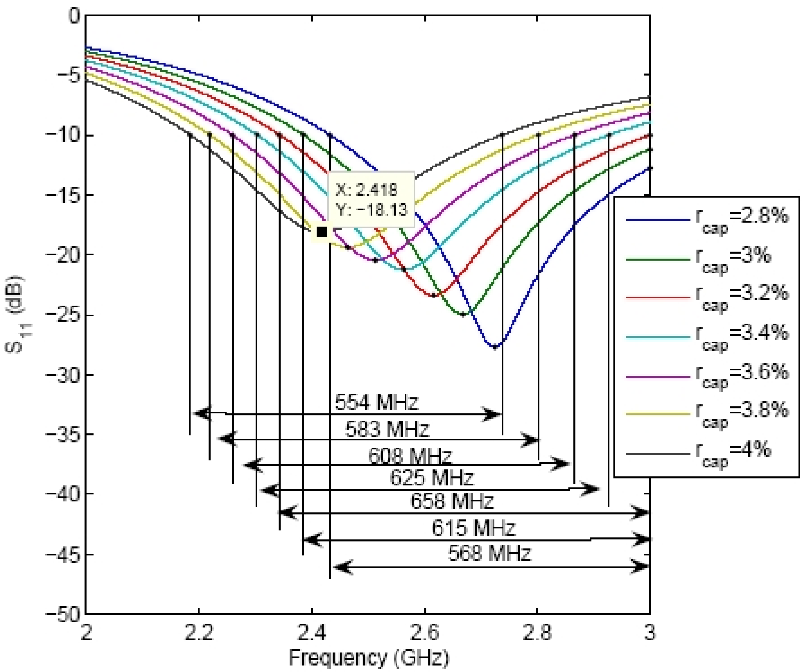
Observations

- The presence of a small top load improves the matching for the antenna
- The radius of the rods have influence on the BW
- The possibility of having another elements to have a better control of the BW and reflection coefficient is important
- It is possible to infer a rule for the electrical length of the antenna

Simulation Results

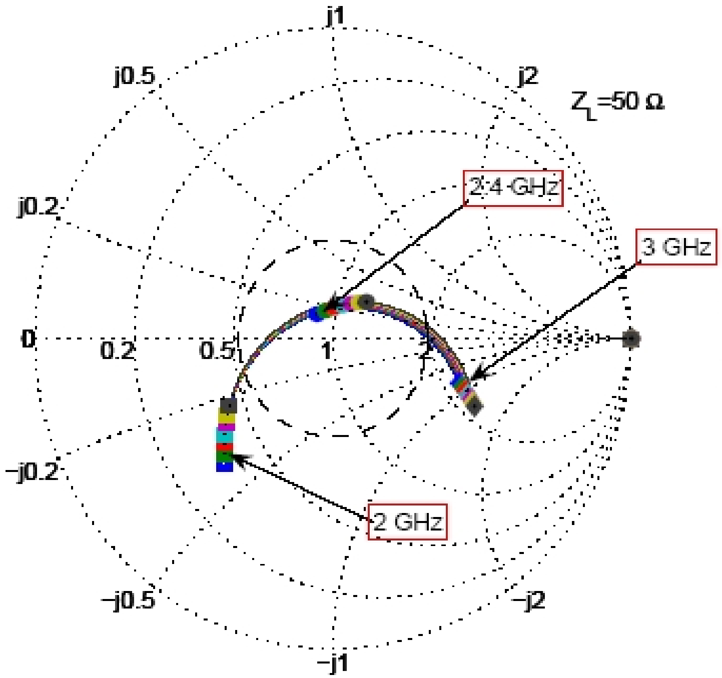
- Top loaded monopole – Ideal Scenario:
  - Top disc
    - Constant rod length (17.5%) and rod radius (1.4%)
    - The impedance is increased on the its reactive and active part as the load radius increases.
    - The bandwidth decreases

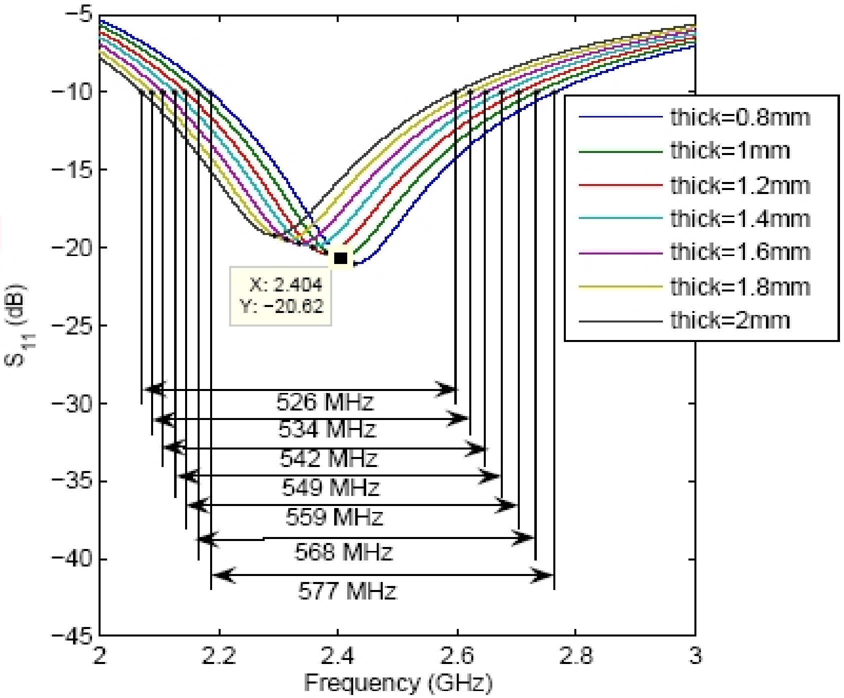




Simulation Results

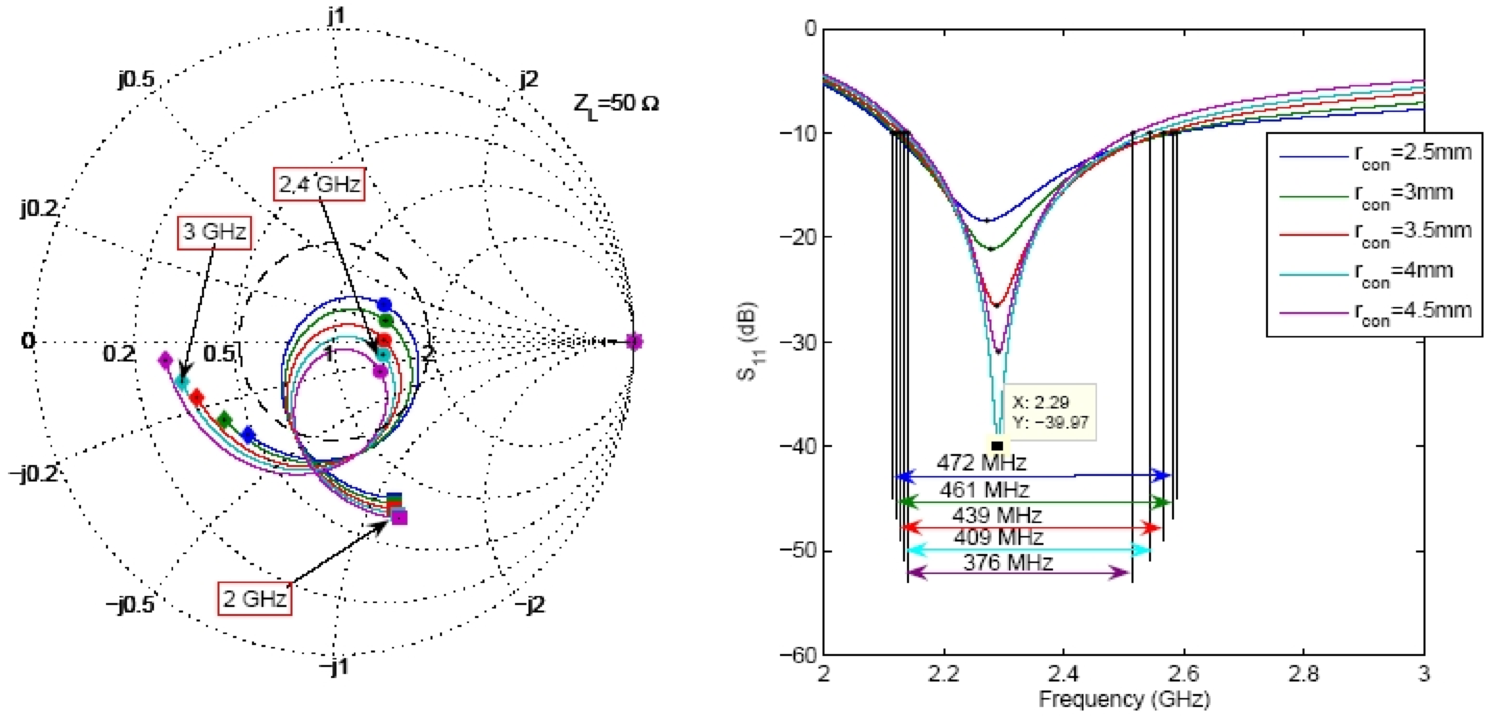
- Top loaded monopole – Ideal Scenario:
  - Variation of the thickness of the load
    - A thicker load, influences only on the central frequency (l=17.5% r_cap=3.4% r=1.4%)

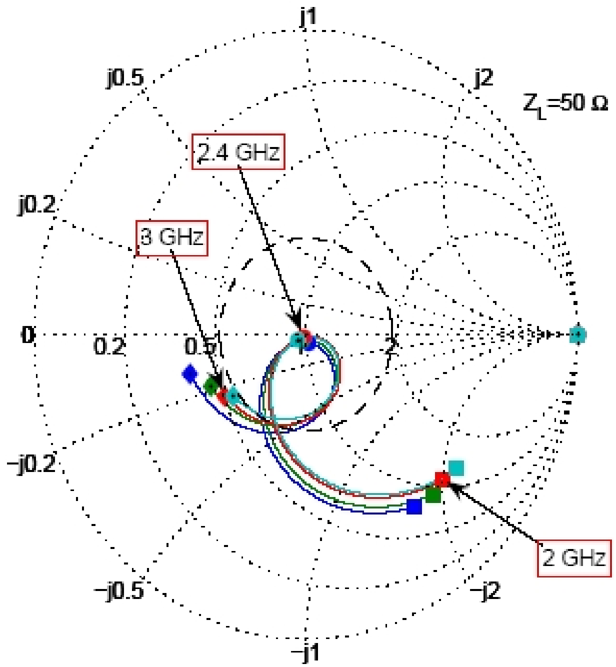




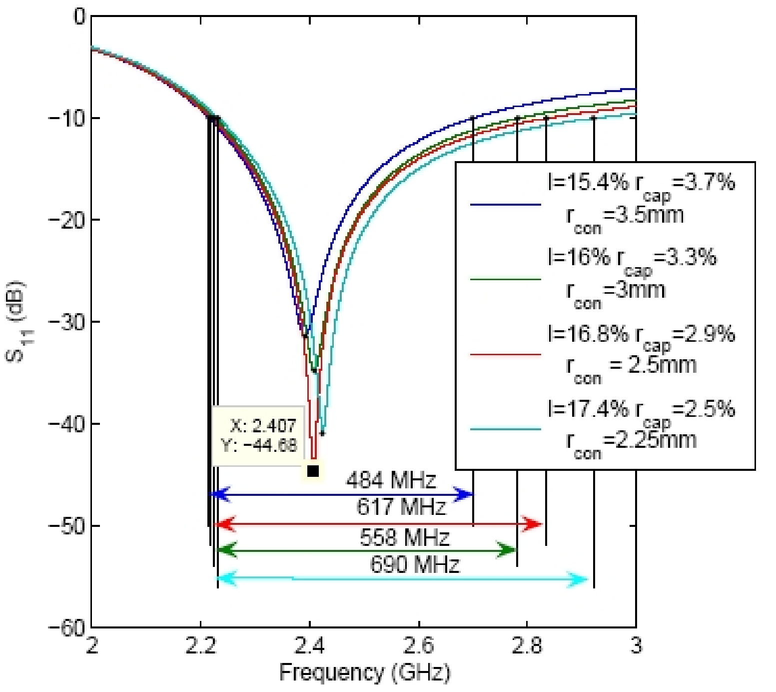
Simulation Results

- Top loaded monopole – Real Scenario:
  - Pure capacitive element.
  - l=15.6% r_cap=4.1 r=1.4%





j1
j0.5
j2
Z_L=50 Ω
2.4 GHz
j0.2
3 GHz
0
0.2
0.5
1
2
−j0.2
2 GHz
−j0.5
−j2
−j1



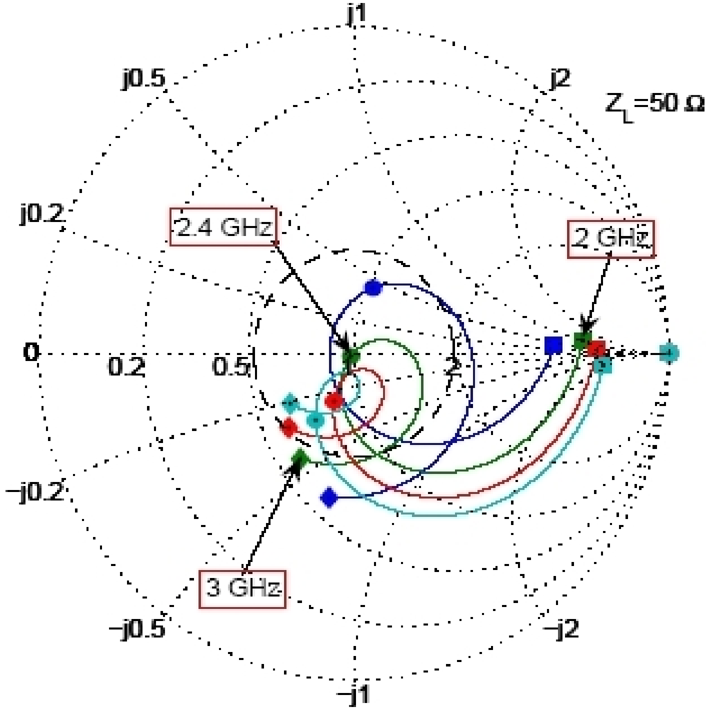
0
−10
−20
−30
−40
−50
−60
S_{11} (dB)
2
2.2
2.4
2.6
2.8
3
Frequency (GHz)
X: 2.407
Y: −44.68
484 MHz
617 MHz
558 MHz
690 MHz
l=15.4% r_{cap}=3.7% r_{con}=3.5mm
l=16% r_{cap}=3.3% r_{con}=3mm
l=16.8% r_{cap}=2.9% r_{con} = 2.5mm
l=17.4% r_{cap}=2.5% r_{con}=2.25mm

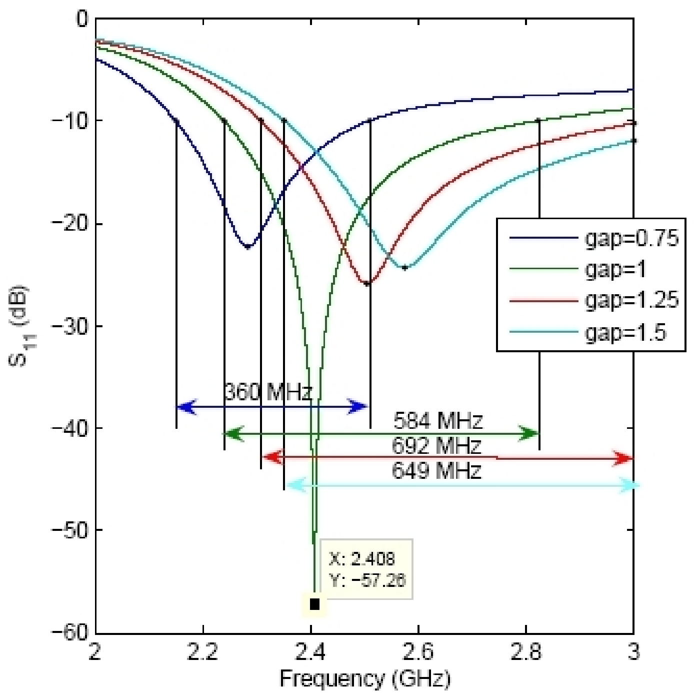
Tuning antennas

- In a more realistic simulation, the microstrip line has to be taken on account.
- The connector pad that it is present to increase mechanical stability, also can be used as a capacitance.
- It is also important to take on account the discretization

Design rule

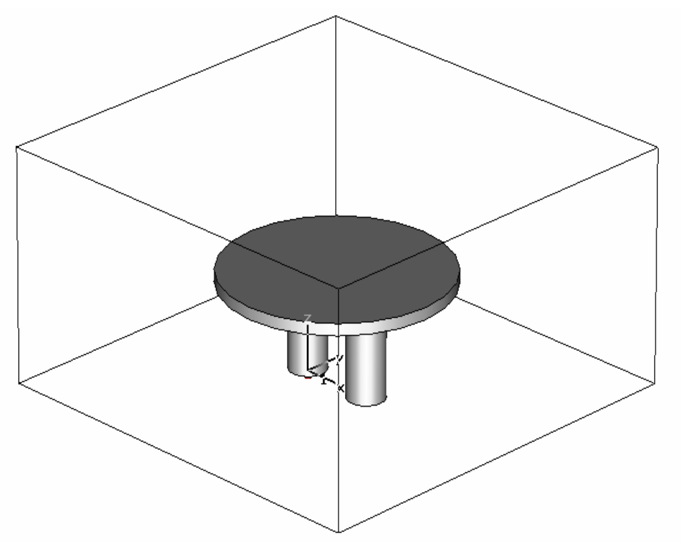
- Disc areas:
  - Top loaded monopole: remains the same
  - Top loaded folded monopole:
    - The gap between rods shows some influence, therefore we need to standardize the load disc area.

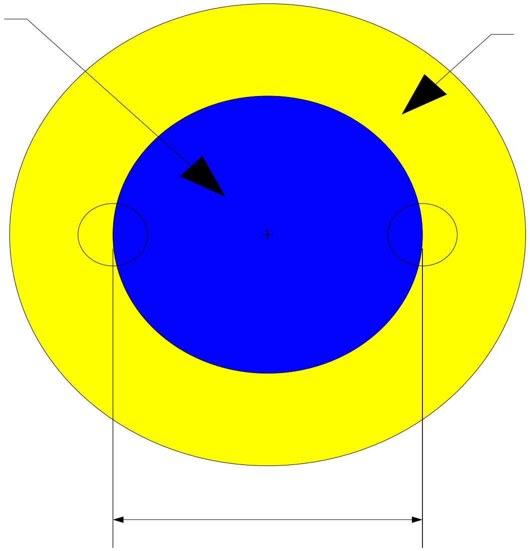




Design rule

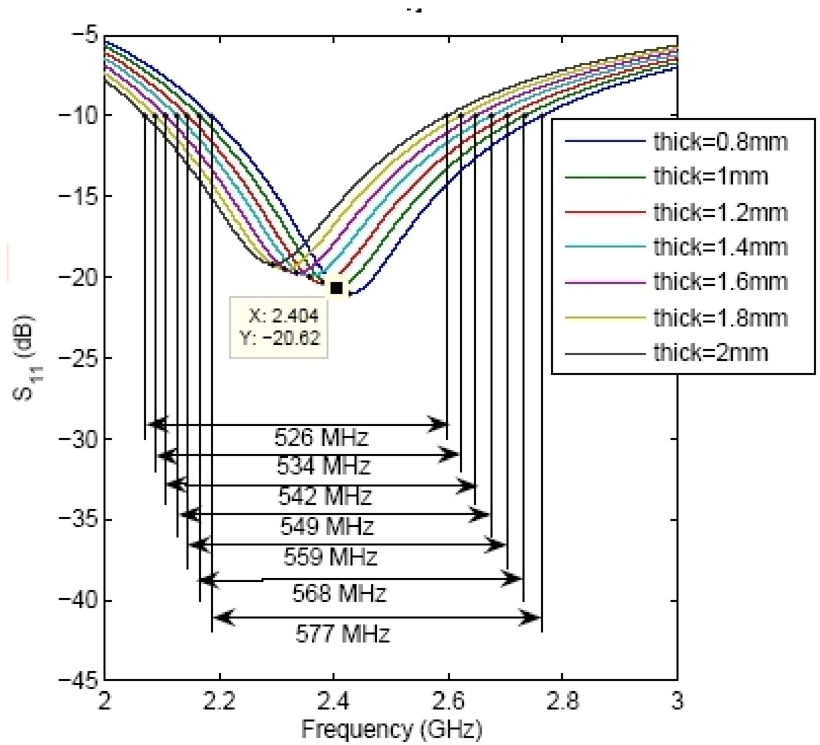
- Top loaded folded monopole - Disc areas:
  - Total area of the load
  - Internal area of the load, defined by the gap between rods
  - Difference of the areas
    - Equivalent radius, referred to the central λ



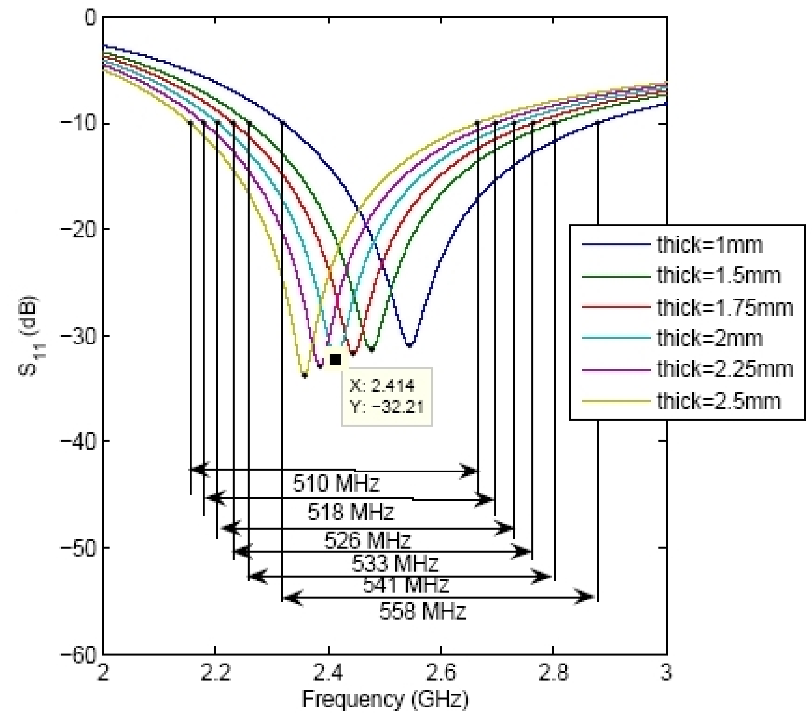


Simulation Results

- Variation of the thickness of the load disc:
  - There is no definitive influence on the bandwidth
  - Influence mainly on the reactive part of the impedance: a thicker load leads to a bigger reactance



Top loaded monopole



Top loaded folded monopole