Student Design Competition
IEEE IMS 2024 Washington, DC

Tunable Impedance Matching Network

TC4 - Microwave Components and Transmission Line Structures

Introduction:

The impedance of an antenna in a telecommunication system may undergo significant variation because of user interaction with the system or changing environmental conditions. Practical examples include the influence of user's hand and head on a cellular phone, influence of the surrounding onto an IoT node etc. Strong impedance mismatch between the antenna feed point and the RF front-end electronics interfacing the antenna results in substantial drop of power efficiency or sensitivity of the system.

When a power amplifier is directly coupled to an antenna, as shown in Fig. 1, the transducer power gain of the system is defined as:

$$G_T = \frac{P_L}{P_S} = 1 - |\Gamma_L|^2$$

where P_L is the power delivered to the load (antenna), P_S is the power available from the source (PA), Γ_L is the load reflection coefficient. It is assumed that Z_S is matched to the system characteristic impedance resulting in $\Gamma_S=0$. The VSWR of a practical antenna (e.g. in a cellular phone) may reach values of up to 20:1 (corresponding to the load reflection coefficient of $|\Gamma_L|=(20-1)/(20+1)\approx 0.9$), resulting in the power gain of $G_T=1-0.9^2=0.19$, meaning that almost 80% of the power can be lost due to the impedance mismatch between the RF front-end and the antenna.

A two-port impedance tuning network coupled between the source and load as shown in Fig. 2 may improve the transducer gain of the antenna system [1]:

$$G_T = \frac{P_L}{P_S} = \frac{1 - |\Gamma_L|^2}{|1 - S_{22}\Gamma_L|^2}|S_{21}|^2$$

where S_{21} and S_{22} are the s-parameters of the tuner.

The electrically-controlled tuner is expected to consume some power, $P_{tun.sup}$, which needs to be accounted for in the transducer gain:

$$G_T^* = \frac{P_L}{P_S + P_{tun.sup}} = \frac{P_S}{P_S + P_{tun.sup}}\frac{1 - |\Gamma_L|^2}{|1 - S_{22}\Gamma_L|^2}|S_{21}|^2$$

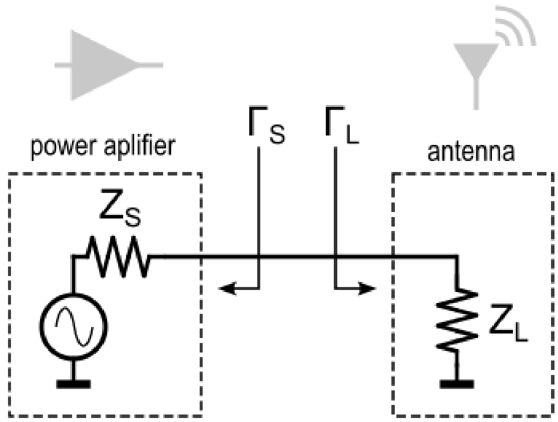


Figure 1. Unmatched antenna system

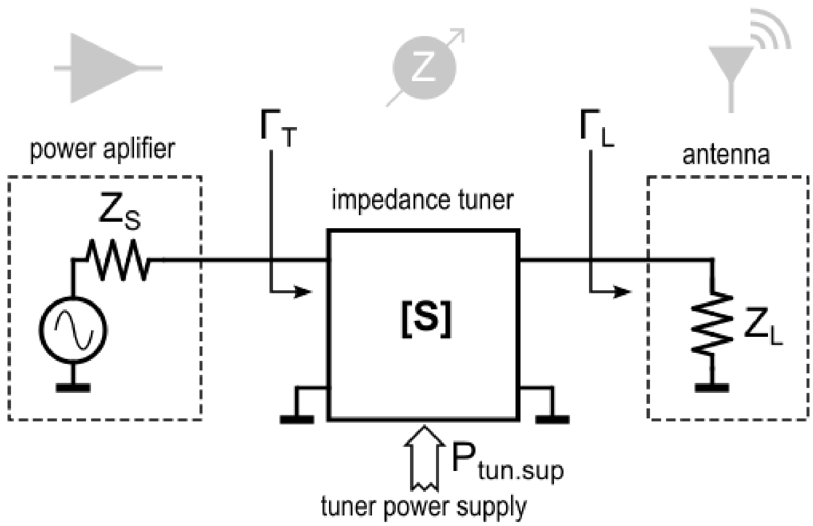


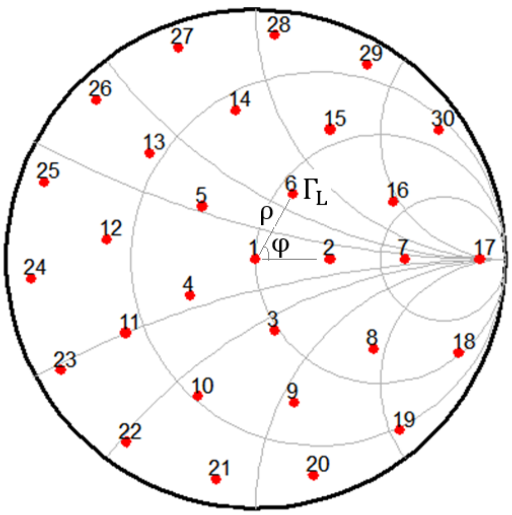
Figure 2. Antenna system with impedance matching

Design Specifications:

A two-port impedance tuning network optimized for the highest possible average transducer gain fulfilling the following specification shall be designed:

- Operating frequency: 1 GHz
- The list of antenna reflection coefficients Γ_L for which the tuner needs to be optimized is provided in the table below
- The reflection coefficients 1 to 6 with VSWR < 3:1 are weighted higher than the reflection coefficient with high VSWR, emphasizing the importance of low power loss in the impedance tuning network when the load is well matched to the source
- Source power: P_S = 0.5 W (note that for the sake of setup simplicity, the demonstrator will be measured at lower power typically available from VNA, but needs to be designed for 0.5W)

- The impedance tuning network may have no more than 16 states to cover all specified reflection coefficients Γ_L



The specified reflection coefficients can be generated using the following loop:

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for ρ = 0 : 0.3 : 0.9

  for φ = $0 : \frac{\pi}{8} \cdot \frac{1}{\rho} : 2\pi - \frac{\pi}{8}$

    $\Gamma_L = \rho \cdot e^{-j\varphi}$

  end

end

Point Nr (i)	Load Reflection Coefficient Γ_L (i)	Weight W (i)
1	0.000000+j·0.000000	2
2	0.300000+j·0.000000	2
3	0.077646-j·0.289778	2
4	-0.259808-j·0.150000	2
5	-0.212132+j·0.212132	2
6	0.150000+j·0.259808	2
7	0.600000+j·0.000000	1
8	0.476012-j·0.365257	1
9	0.155291-j·0.579555	1
10	-0.229610-j·0.554328	1
11	-0.519615-j·0.300000	1
12	-0.594867+j·0.078316	1
13	-0.424264+j·0.424264	1
14	-0.078316+j·0.594867	1
15	0.300000+j·0.519615	1
16	0.554328+j·0.229610	1
17	0.900000+j·0.000000	1
18	0.815677-j·0.380356	1
19	0.578509-j·0.689440	1
20	0.232937-j·0.869333	1
21	-0.156283-j·0.886327	1
22	-0.516219-j·0.737237	1
23	-0.779423-j·0.450000	1
24	-0.896575-j·0.078440	1
25	-0.845723+j·0.307818	1
26	-0.636396+j·0.636396	1
27	-0.307818+j·0.845723	1
28	0.078440+j·0.896575	1
29	0.450000+j·0.779423	1
30	0.737237+j·0.516219	1

Figure 3. Specification for the load reflection coefficients Γ_L

Competition Rules:

- A designed tuner PCB must comprise two SMA female connectors for the RF input and RF output. No restrictions on the PCB material, size, thickness, etc are applied.
- The tuner PCB must be custom-designed and assembled by the competition participant(s).
- The following solutions are not allowed:
  - Mechanical or electro-mechanical laboratory microwave tuners
  - Electronic laboratory tuners
  - Fully-assembled evaluation kits or other off-the-shelf assembled boards with tuners
  - Commercial tuner modules with all switchable or tunable parts as well as inductors and capacitors integrated in one package

- Male banana plugs shall be used for DC supply and control (if applicable).
- Supply voltage must not exceed 20 V.
- The supply current (for calculating supply power) must be accessible and measurable via male banana plugs.
- The circuit must be electrically controlled.
- If the circuit is controlled via a digital interface (e.g. SPI, MIPI RFFE), the controller must be organized by the competition participant(s) and will not be available as part of measurement equipment provided by the organizers.
- If the circuit is controlled via a digital interface the supply current in active mode of the designed tunable network must be accessible and measurable via male banana plugs. The current consumption of the digital controller is not considered to be part of the tunable network consumption.
- No on-board batteries are allowed.
- The design must comprise passive RF signal path, meaning, RF amplifiers are not allowed.
- Only catalog parts with datasheets freely available in internet are allowed for essential elements of the circuit (essential elements are switchable and tunable parts, capacitors, inductors). The list of used parts and the schematic of the design must be provided to the judges.
- The demonstrator must comply with the rules listed above.
- A hardware demonstrator needs to be presented for judging at IMS. S-parameter and DUT power consumption measurements as well as FOM calculation from the measured data will be conducted by the judges only. A team representative must be present at testing to set up and control the DUT.

Organizers can recommend RF switch parts suitable for the competition (please see contact information below). The choice of parts is not limited to the recommended devices and other **switches with datasheets freely available in the web** can be used.

Evaluation Process:

The performance of the designed tuner is evaluated using the following figure of merit (FOM):

$$FOM = \frac{1}{\sum_{i=1}^{30} w\,(i)} \sum_{i=1}^{30} w\,(i) \cdot \max_{state}\{G_T^*(i, state)\}$$

The meaning of FOM is: for each of the 30 specified load reflection coefficients Γ_{L} a maximum transducer gain over all possible tuner states is identified, the mean value of identified 30 maximum transducer gains is calculated considering the weight of each load reflection coefficient.

- The design is measured in small-signal mode in 50Ω environment:
  - The DUT is attached to 2-port VNA
  - The 2-port s-parameters for 16 states of the tuner are measured and saved as *.s2p files
  - The power consumption $P_{tun.sup}$ of the DUT for each state is recorded. If the digital controller (e.g SPI, MIPI, RFFE) is used to control the DUT, it must be disconnected from the DUT during power consumption measurements. The DUT must remain in active mode with disconnected controller.

- The 16 s-parameters files together with the power consumption values are used to calculate the FOM and G_T^* according to the equations above. The s-parameters at 1 GHz will be used for calculation.
- The FOM (0 < FOM < 1) shall be maximized for the best performing tuner.

How to Participate:

Competing teams will be required to register to the IMS Student Design Competition according to the rules posted on the IMS-2024 homepage.

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References:

[1] Guillermo Gonzalez, “Microwave Transistor Amplifiers: Analysis and Design”, Prentice Hall, second edition.