

Antenna Impedance Matching – Simplified

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Why Antenna Matching is required

Antennas are now so commoditized that we all carry multiple along with us in our day-to-day life. When discussing antennas, the term “impedance matching” commonly appears during the design and final application phases. What is so important about impedance matching? The antenna must be impedance matched when assembled for the end-user environment so that it operates in the desired frequency band with maximum efficiency. Optimal efficiency results in maximum range, minimum power consumption, reduced heating and reliable data throughput. It is good to understand that an antenna itself can be considered an impedance transformer. The antenna transitions power received from the RF circuitry through the Tx line (matched to an impedance of 50 Ω in most cases) to free space (impedance of 377 Ω).

Matching the input impedance of the antenna to 50 Ω is a requisite to ensure that the maximum power is transferred from the RF circuitry to the antenna with negligible amount being reflected back. Standing wave ratio (SWR) is a measure that defines how well the antenna impedance is matched to the connected Tx line impedance. A value less than 1.5 is desirable. A low flat SWR enables maximum power transfer from the transmission line. SWR can be expressed as the reflection coefficient Γ , which refers to the power reflected from the antenna. Γ is a function of load impedance, Z_L , and characteristic impedance, Z_o .

$$SWR = \frac{1 + |\Gamma|}{1 - |\Gamma|}$$

(Equation 1)

$$\Gamma = \frac{Z_L - Z_o}{Z_L + Z_o}$$

(Equation 2)

Efficient impedance matching consumes a large amount of engineers’ time; hence it is worth understanding the basic techniques to match the impedance.

What is Impedance Matching?

Impedance matching is the process of designing the antenna’s input impedance (Z_L) or matching it to the corresponding RF circuitry’s output impedance (Z_o), which would be 50 Ω in most cases. A perfect match is obtained when $Z_L = Z_o$ in Equation 2, which gives Γ a value of zero, and the SWR becomes unity in Equation 1. If the impedance of the line feeding the antenna and the antenna impedance do not match, then the source experiences complex impedance, which would be a function of the line length. Even if the antenna specifications say 50 Ω impedance or matching is achieved using a matching network, the length of the line feeding the antenna is of significance, specifically if it is greater than approximately 1/10th the wavelength of the highest frequency of operation. Matching on the final board will be crucial because antenna impedance can be altered depending on the electrical properties, size and nearness of the adjacent objects mounted on the end product, any enclosures, etc.

A Vector Network Analyzer (VNA) can be used to measure the input impedance of the antenna in the end-user environment, as this helps to optimize the antenna for the actual operating conditions. The VNA should be calibrated as close to the measurement plane as possible or at the matching network location. The impedance matching technique should consider any length of the transmission line if present between the calibration point and the matching network. The VNA can be used to measure S11, representing the reflection coefficient. S11 is typically displayed on a Smith chart.

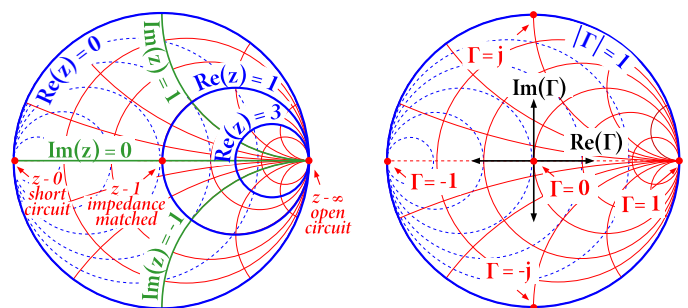


Fig. 1 Typical Smith chart view

The Smith chart is an excellent graphical aid for visualizing the impedance at any point of the transmission line or at the input of the antenna system across the different frequencies. A Smith chart consists of constant resistant circles and constant conductance circles as shown in Fig 1. A Smith chart can be used to perform an impedance match by bringing impedance to the center of the chart, which corresponds to a pure resistance of 50Ω by adjusting the reactance values. This is achieved by designing a matching network, or circuit between the feed line and the antenna. A Smith chart can be used to determine matching network lumped element values.

Impedance Matching Methods

Antenna impedance is complex, consisting of both resistive and reactive parts, so the matching network must include components of both to achieve matching. If the source impedance is purely resistive and the load impedance is of complex type, then a complex conjugate of the load impedance would be required for the matching network. In other words, for a load impedance of $R+j*X$, the impedance of the matching network would be $R-j*X$ or the other way round. If the arbitrary impedance is at Point O in the graphs below, then the result of adding lumped elements in the matching network would be as shown in Fig. 2.

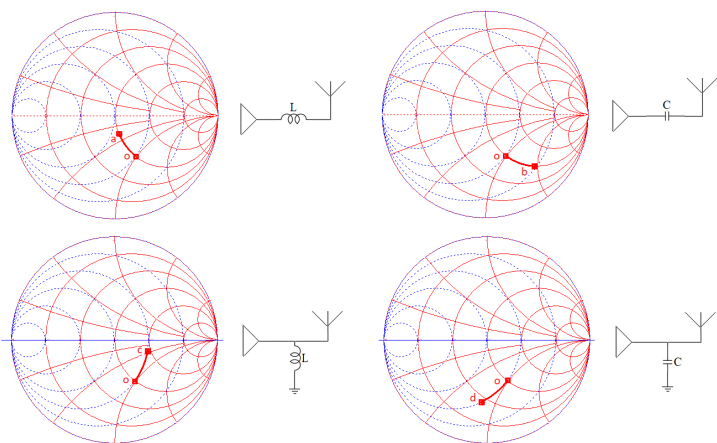


Figure 2 Impedance transformations for lumped network elements

When a series inductor is connected to the antenna, the combined impedance of the antenna and the series inductor at the output will move toward Point A in a constant resistant circle. A series capacitor will move the impedance toward Point B along a constant resistant circle. A shunt inductor will move the impedance toward Point C and a shunt capacitor will move the impedance toward Point D along a constant conductance circle.

A few golden rules that simplify impedance matching are provided below.

1. A Smith chart can be divided into two halves: The upper half is inductive, and the lower half is capacitive.
2. Whenever impedance is to be moved up, an inductor (L) is required; use a capacitor (C) if the impedance is to be moved down.
3. The right/constant resistance circle is the shunt circle, and the left/constant conductance circle is the series circle. So, a shunt element is required if the impedance needs to be moved along the left circle. Otherwise, use a series element.

The addition of a series L or C will only match the impedances lying on the constant resistance circle, and a shunt L or C will match the impedances lying on the constant conductance circle. Multiple matching network element combinations can achieve the desired matching impedance. Other requirements such as filter type, Q-factor, and specific components can also be considered.

By combining any of the series inductor, series capacitor, shunt inductor, and the shunt capacitor, any value of the load impedance in the Smith chart can be matched, except those spots located on the $|Γ| = 1$ circle, where the impedance is purely resistive. Transmission lines are most commonly used to match the real impedances. Impedance matching at a frequency can be achieved by extending the length of the

transmission line to bring the impedance on the Smith chart to reach the unit conductance circle that contains the $\Gamma=0$ point; then suitable shunt reactance is added to move the combined impedance to the $\Gamma=0$ point. (See Fig. 3.) The arbitrary impedance can also be rotated until it reaches the 50Ω circle; then appropriate series reactance is added to get the resulting impedance to the 50Ω point. (See Fig. 4.)

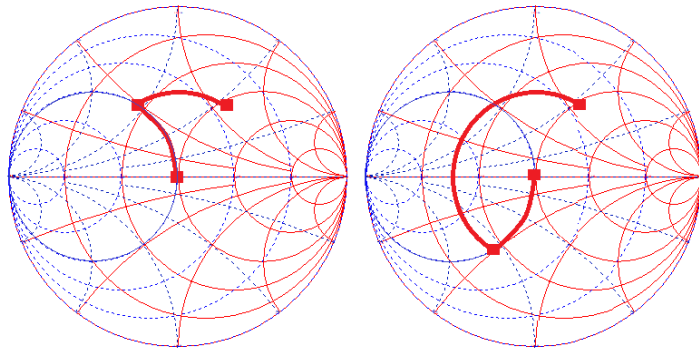


Figure 3

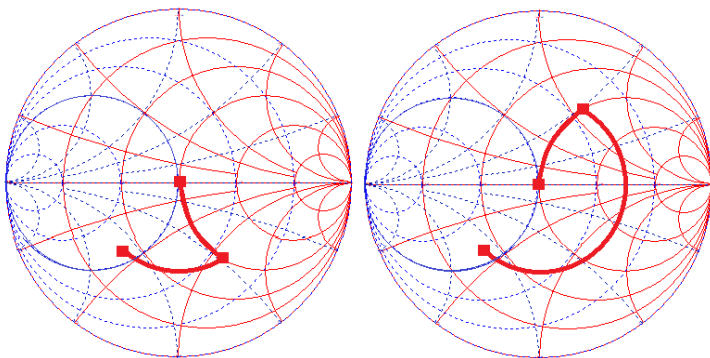


Figure 4

Any matching network can only move a limited portion of the impedance curve to the target matching circle on the Smith chart, which means there is a bandwidth limit for any matching network. The matching circuit can be used to achieve both impedance matching and bandwidth enhancement, and this is achieved by appropriately using the above principles while arranging the lumped elements in the form of L-networks, Pi-networks, and T-networks.

A simple L matching network consists of two lumped components, L and C, arranged in any of the eight different configurations shown in Fig. 5.

Not every L-network configuration can guarantee the required matching between the given arbitrary load and source impedances. Each of these configurations has certain forbidden areas where matching cannot be achieved. Select the appropriate L-section topology based on where R_L lies.

The series reactance L in Fig. 5(a) makes the impedance move along the constant resistance circle until it intersects with the unit conductance circle; then shunt C moves along the unit conductance circle to the 50Ω matching point. This configuration will only match capacitive impedances that fall outside the resistance circle passing through the origin or inductive impedances that fall inside the conductance circle passing through the origin. Similarly, the series reactance C in Fig. 5(b) makes the impedance move along the constant resistance circle until it intersects with the unit conductance circle. Then shunt L moves along the unit conductance circle to the 50Ω matching point. This configuration will only match inductive impedances that fall outside the resistance circle passing through the origin or capacitive impedances that fall inside the conductance circle passing through the origin.

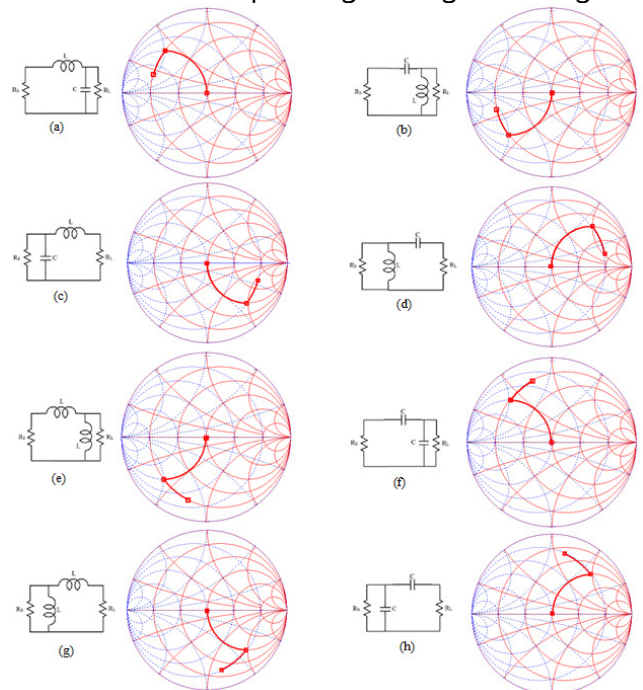


Fig. 5 Impedance transformations for L-network matching topologies

The shunt reactance C shown in Fig. 5(c) makes the impedance move along the constant conductance circle until it intersects with the unit resistant circle. Then the series L moves along the unit resistant circle to the 50 Ω matching point. This configuration will only match inductive impedances that fall outside the resistant circle passing through the origin or capacitive impedances that fall inside the resistant circle passing through the origin. Similarly, the shunt reactance L in Fig. 5 (d) makes the impedance move along the constant conductance circle until it intersects with the unit resistant circle; then series C moves along the unit resistant circle to the 50 Ω matching point. This configuration will only match capacitive impedances that fall outside the conductance circle passing through the origin or inductive impedances that fall inside the resistant circle passing through the origin.

An L-network with only inductive reactances can only match capacitive impedances that fall outside the resistant and conductance circles passing through the origin. An L-network with only capacitive reactances can only match inductive impedances that fall outside the resistant and conductance circles passing through the origin. The permissible and forbidden areas for the different types of L-networks are shown in Fig. 6 (I) and (II) respectively.

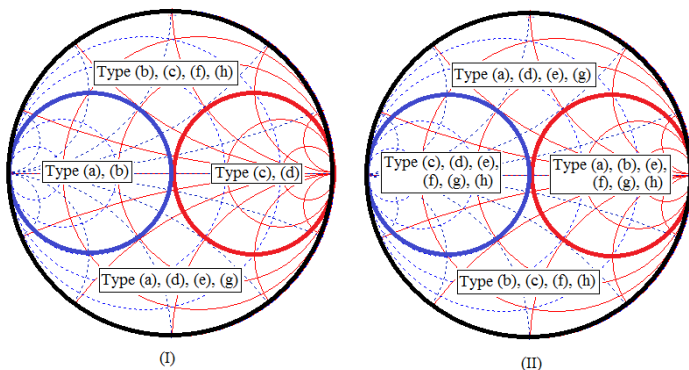


Fig. 6 Permissible and Forbidden areas for L network matching

The matching circuit bandwidth depends on Q factor and frequency, where the Q factor of the circuit is based on source and load impedances,

circuit is based on source and load impedances, and the L-network does not provide considerable control over Q.

$$BW = F / Q$$

To enhance the bandwidth over which impedance is matched, an additional L-network can be included to the single section. In such scenarios, the impedance transforms to intermediate impedance using the first section. Then, the second L-network section matches the impedance to the desired value. If the bandwidth requirements are still not met, additional sections can be included to guarantee impedance matching over a wider bandwidth. In such networks where there is more than one section of L-network, the termination ratios can be reduced, which decreases the Q of each section and thus enhances the matched bandwidth of the circuit. Three-element networks, like Pi or T, provide greater flexibility to control the circuit Q, thereby controlling bandwidth while providing impedance matching. Once the matching circuit is decided, the impedance can be measured using a Smith chart in VNA for accuracy. Inaccurate calibration or port extension can give wrong results, which would need to be rectified and recalibrated for accuracy.

Conclusion

Although a complicated process that requires testing and validation, antenna matching is essential in all RF designs. Impedance matching ensures maximum efficiency. Without proper matching, the antenna becomes a chokepoint of performance due to reduced range, increased power consumption and impaired data transfer. Today’s advanced IoT and wearable applications cannot afford inefficient operation. Abracon offers an Antenna Optimization service for customers wishing to maximize the performance of the antenna in their application.

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