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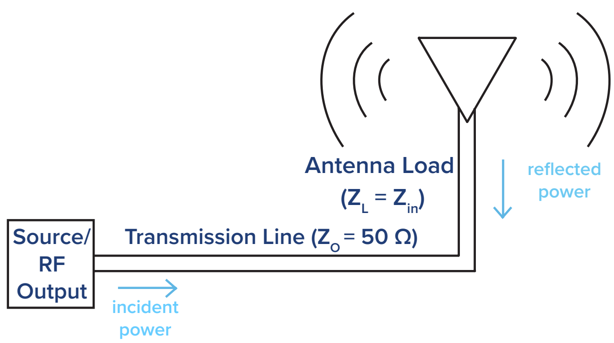
WHITE PAPER

Antenna Impedance Matching – Simplified

Why Antenna Matching is required

Antenna's have become an essential part of consumer electrionics, and without realizing, we carry multiple antennas on our person every day. 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 essential to realize 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 circuity 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 in terms of 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 significant amount of engineers' time; therefore it is worth understanding the basic techniques to match this impedance.

What is Impedance Matching?

Impedance matching is the process of designing the antenna's input impedance (Z_{in}) or matching it to the corresponding RF circuitry's output impedance, which would be 50 Ω in most cases. A perfect match is obtained when $Z_L = Z_O$ ($Z_{in} = Z_O$) 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 is crucial because antenna impedance can be altered depending on the electrical properties, size and proximity 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 location of the matching network. The impedance matching technique should consider any length of the transmission line if present between the calibration point and the matching network. A VNA can be used to measure S11 characteristics and to view the impedance on a Smith chart.

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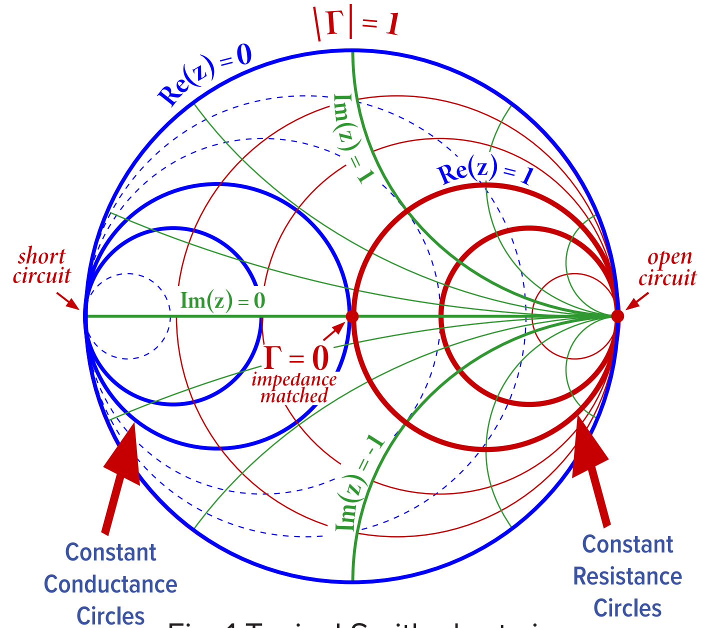

Fig. 1 Typical Smith chart view

A 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 50 Ω by adjusting the reactance values. This is achieved by designing a matching network, which is a circuit between the feed line and the antenna. A Smith chart can be used to determine matching network's 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 types to achieve optimal 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 around. If the arbitrary impedance is at Point O, then the result of adding lumped elements in the matching network would be as shown in Fig. 2.

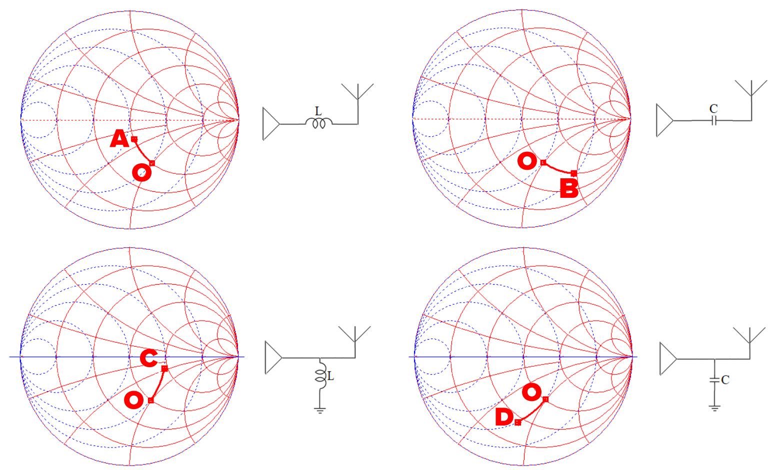

Fig. 2 Impedance transformations for lumped network elements

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 Direction A in a constant resistant circle. A series capacitor will move the impedance toward Direction B along a constant resistant circle. A shunt inductor will move the impedance toward Direction C and a shunt capacitor will move the impedance toward Direction 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 series circle, and the left/constant conductance circle is the shunt 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, the 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 $|\Gamma| = 1$ 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 50 Ω circle; then appropriate series reactance is added to get the resulting impedance to the 50 Ω point. (See Fig. 4.)

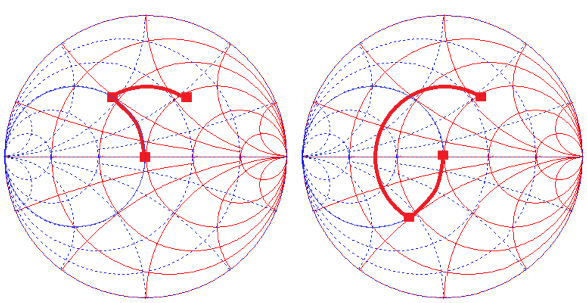

Fig. 3

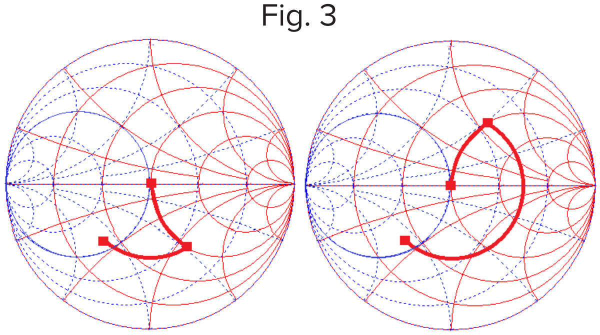

Fig. 4

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 50 Ω 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 50 Ω 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.

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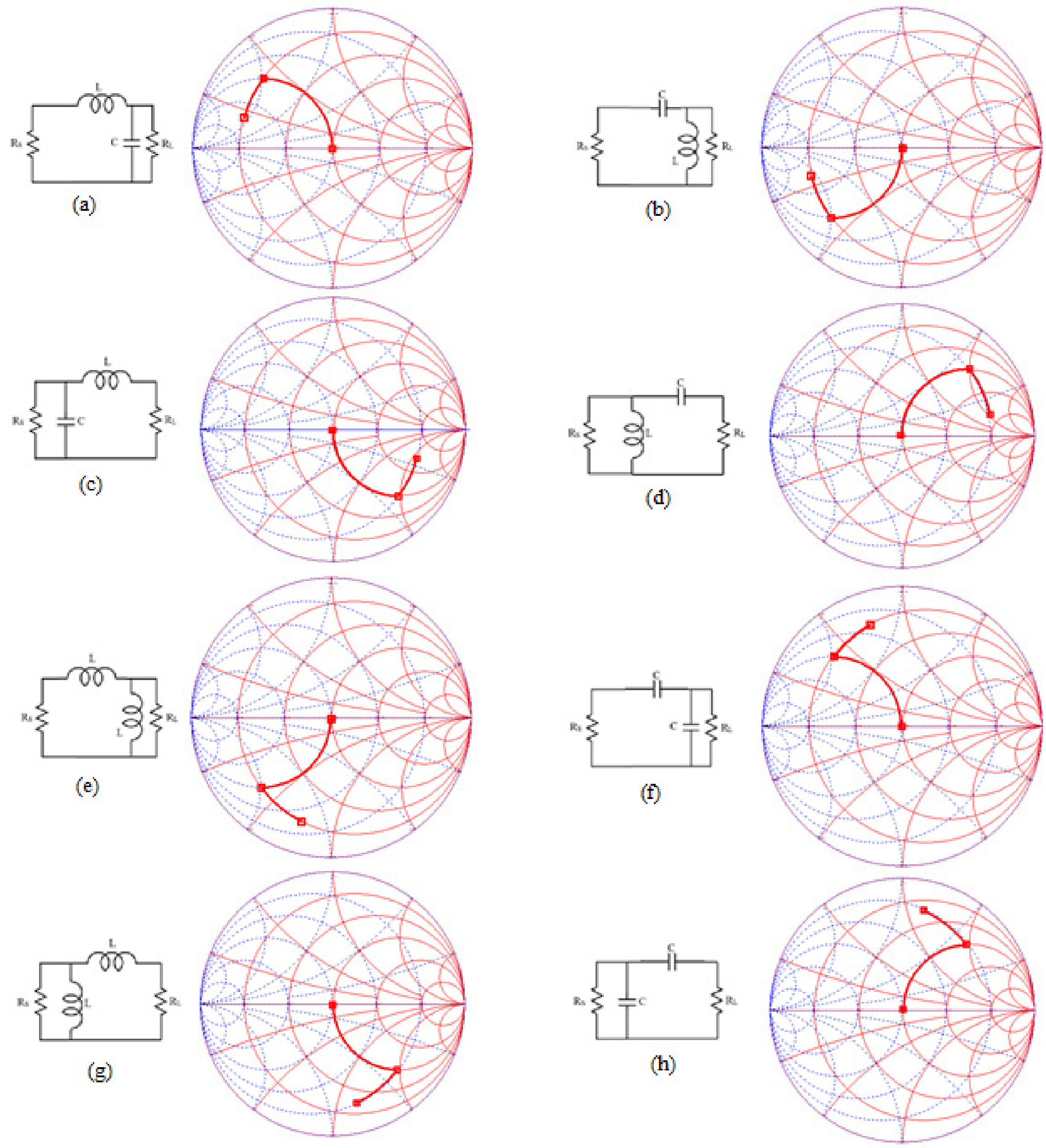

Fig. 5 Impedance transformations for L-network matching topologies

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 from Fig. 5 are shown in Fig. 6 (I) and (II) respectively.

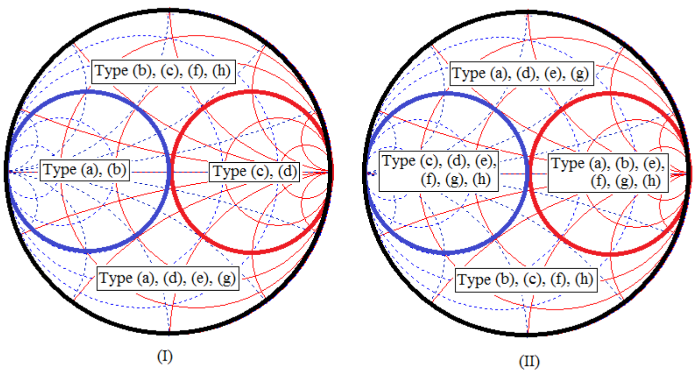

Fig. 6 Permissible (I) and Forbidden (II) areas for L network matching

The matching circuit bandwidth depends on Q factor and frequency, where the Q factor of the circuit is based on source and load impedances, 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 a network where there is more than one section of L-network, the termination ratios can be reduced, decreasing the Q of each section and thus enhancing 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 the built-in Smith chart function in a VNA for accuracy. Please take note that inaccurate calibration or port extension can give wrong results, which would need to be rectified and recalibrated for accuracy.

Conclusion

Despite being a complicated procedure requiring testing and validation, antenna matching is essential in all RF designs. Impedance matching ensures maximum efficiency. Without proper matching, the antenna becomes a choke point of performance due to reduced range, increased power consumption and poor transmission quality. Recent advancements in Internet of Things and smart applications demand highly efficient and reliable antenna systems. Abracon offers an Antenna Optimization service for customers seeking to maximize the performance of the antenna in their application. Please contact the Abracon sales team for further information.

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APAKN1804 -C2G-T	APAKN2504 -C2G-T	AMCA52-2R510G-S1F-T	AMCA52-2R540G-S1F-T
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AMCA72-2R860G-02F-T	AMCA81-3R010G-S1F-T	AMCA92-2R660G-S1F-T	ACAG1204-915-T
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