

Back to Basics: Impedance Matching (Part 3)

[Electronic Design](#)

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The L-network is a real workhorse impedance-matching circuit (see “[Back to Basics: Impedance Matching \(Part 2\)](#)”). While it fits many applications, a more complex circuit will provide better performance or better meet desired specifications in some instances. The T-networks and π -networks described here will often provide the needed improvement while still matching the load to the source.

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[Welcome To Antennas 101](#)

[Resistor L-network Matches Impedances](#)

Rationale For Use

The main reason to employ a T-network or π -network is to get control of the circuit Q. In designing an L-network, the Q is a function of the input and output impedances. You end up with a fixed Q that may or may not meet your design specs. In most cases the Q is very low (<10). This may be too low for applications where you need to limit the bandwidth to reduce harmonics or help filter out adjacent signals without the use of additional filters. Remember the relationship for determining Q:

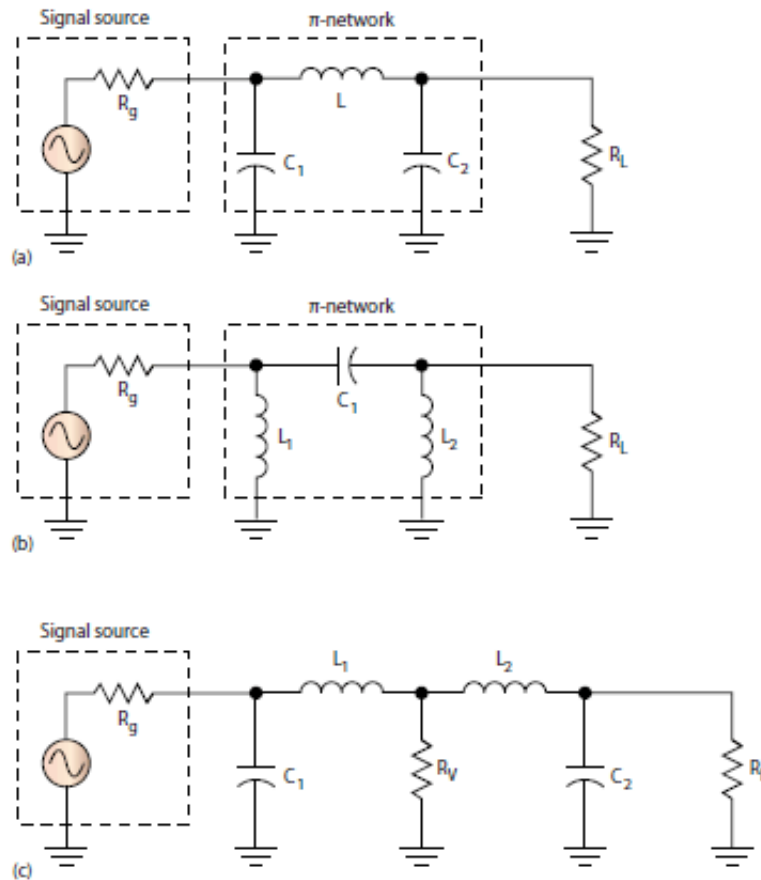
$$Q = f/BW$$

where f is the operating frequency and BW is the bandwidth.

The T-networks and π -networks provide enough variety to fit almost any situation.

π -Networks

The basic π -network's primary application is to match a high impedance source to lower value to load impedance. It can also be used in reverse to match a low impedance to a higher impedance. The low pass version in [Figure 1a](#) is the most common configuration, though the high pass version in [Figure 1b](#) also can be used.



1. The π -network matching circuit is used mostly in high- to low-impedance transformations. The basic circuit (a) is a low pass circuit. A high pass version (b) can also be used. The π -network also can be considered two back-to-back L-networks with a virtual impedance between them (c).

You may design a π -network using L-network procedures. The π -network can be considered as two L-networks back to back. To use the L-network procedures, you need to assume an intermediate virtual load/source resistance R_V as shown in [Figure 1c](#). You can estimate R_V from:

$$R_V = R_H / (Q^2 + 1)$$

R_H is the higher of the two design impedances R_g and R_L . The resulting R_V will be lower than either R_g or R_L depending on the desired Q . Typical Q values are usually in the 5 to 20 range. An example will illustrate the process.

π -Network Design Example

Assume you want to match a 1000- Ω source to a 100- Ω load at frequency (f) of 50 MHz. You desire a bandwidth (BW) of 6 MHz. The Q must be:

$$Q = f/BW = 50/6 = 8.33$$

$$R_V = R_H/(Q^2 + 1) = 1000/[(8.33)^2 + 1] = 1000/70.4 = 14.2 \Omega$$

The design procedure for the first L-section uses the formulas from [“Back to Basics: Impedance Matching \(Part 2\).”](#) Use the desired Q of 8.33 with an R_L value equal to R_V .

The inductor L_1 value is:

$$X_L = QR_L = 8.333(14.2) = 118.3 \Omega$$

$$L = X_L/2\pi f$$

$$L_1 = 118.3/2(3.14)(50 \times 10^6)$$

$$L_1 = 376.7 \text{ nH}$$

The capacitor C_1 value is:

$$X_{C1} = R_g/Q$$

$$X_{C1} = 1000/8.33 = 120 \Omega$$

$$C_1 = 1/2\pi f X_C$$

$$C_1 = 1/2(3.14)(50 \times 10^6)(120)$$

$$C_1 = 26.54 \text{ pF}$$

Now calculate the second section with L_2 and C_2 using an R_g value of R_V or 14.2Ω with the load R_L of 100Ω .

The Q is now defined by the L-network relationship:

$$Q = \sqrt{(R_L/R_g) - 1}$$

R_g in this case is R_V or 14.2Ω .

$$Q = \sqrt{[(100/14.2) - 1]} = \sqrt{[(7) - 1]} = \sqrt{6} = 2.46$$

The inductance L_2 , then, is:

$$X_{L2} = QR_g = 2.46(14.2) = 35 \Omega$$

$$L_2 = X_L/2\pi f$$

$$L_2 = 35/[2(3.14)(50 \times 10^6)]$$

$$L_2 = 111.25 \text{ nH}$$

The capacitance C_2 is:

$$X_{C2} = R_L/Q$$

$$X_C = 100/2.46 = 40.65 \, \Omega$$

$$C_2 = 1/2\pi f X_C$$

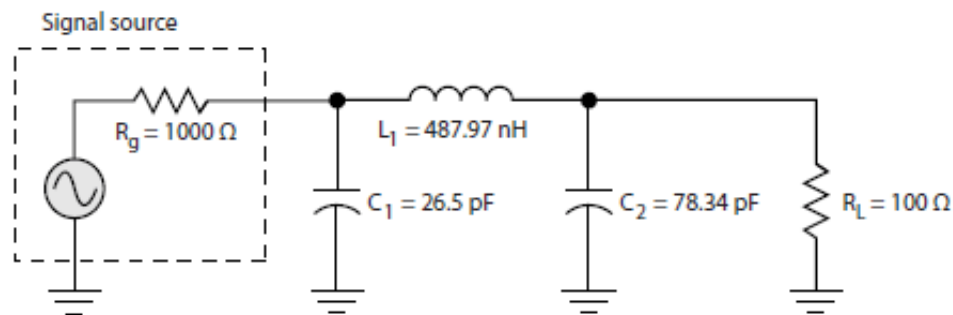
$$C_2 = 1/[2(3.14)(50 \times 10^6)(40.65)]$$

$$C_2 = 78.34 \, \text{pF}$$

Note that the two inductances are in series so the total is just the sum of the two or:

$$L_1 + L_2 = 376.7 + 111.25 = 487.97 \, \text{nH}$$

Figure 2 shows the final circuit.



2. The π -network resulting from the example problem matches a 1000- Ω generator to a 100- Ω load at a frequency of 50 MHz with a bandwidth of 6 MHz and a Q of 8.33.

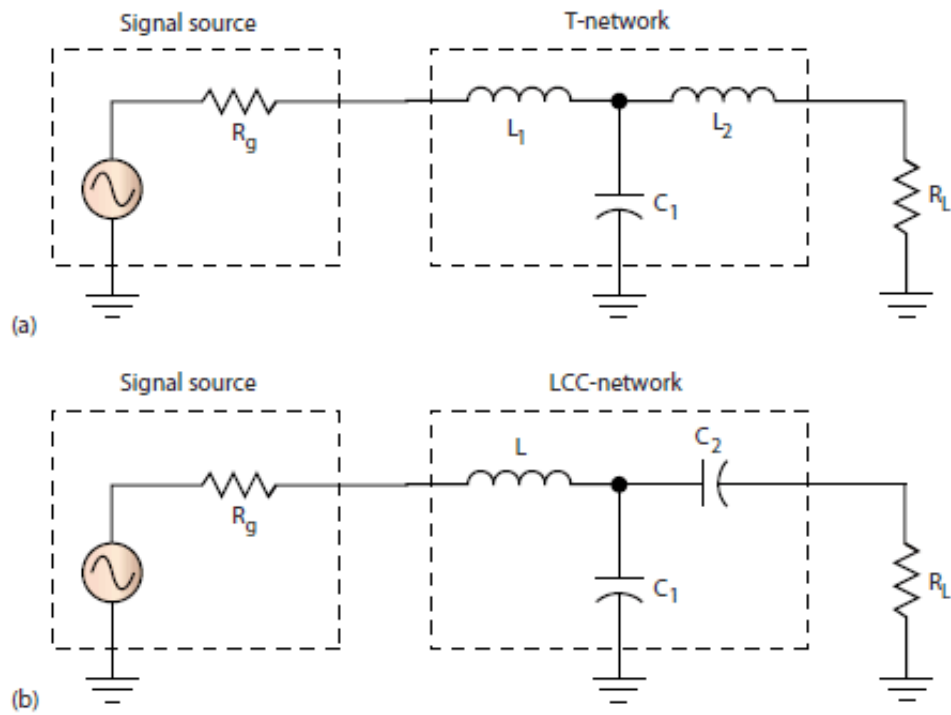
Two Web tools provide the same results:

<http://bwrc.eecs.berkeley.edu/research/rf/projects/60ghz/matching/impmatch.html%20>

http://www.raltron.com/cust/tools/network_impedance_matching.asp%20

T-Networks And LCC Design Example

Figure 3 illustrates the basic T-networks. The basic T shown in Figure 3a is not widely used, but its variation in Figure 3b is. The second network is called an LCC network.



3. There are two versions of the T-network, an alternate matching network: the low pass version (a) and the more popular LCC network (b).

To design these networks, you can also consider them as two cascaded L-networks. However, since the version in [Figure 3b](#) is so common, you can also use some shortcut formulas. Here is the procedure:

1. Select the desired bandwidth and calculate Q.
2. Calculate $X_L = QR_g$
3. Calculate $X_{C2} = R_L \sqrt{[R_g (Q^2 + 1)/R_L - 1]}$
4. Calculate $X_{C1} = R_g (Q^2 + 1)/Q[QR_L/(QR_L - X_{C2})]$
5. Calculate the inductance $L = X_L/2\pi f$
6. Calculate the capacitances $C = 1/2\pi f X_C$

Assume a source or generator resistance of 10Ω and a load resistance of 50Ω . Let Q be 10 and the operating frequency be 315 MHz.

$$X_L = QR_g = 10(10) = 100 \Omega$$

$$L = X_L/2\pi f = 100/2(3.14)(315 \times 10^6) = 50 \text{ nH}$$

$$X_{C2} = R_L \sqrt{[R_g (Q^2 + 1)/R_L - 1]} = 50 \sqrt{\{[10(101)/50] - 1\}} = 219 \Omega$$

$$X_{C1} = R_g (Q^2 + 1)/Q [QR_L/(QR_L - X_{C2})] = 10(101)/10 [500/(500 - 219)] = 179 \Omega$$

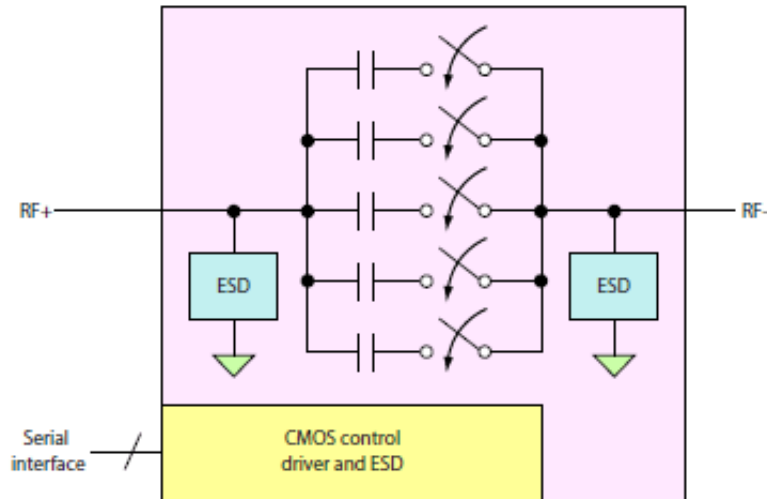
$$C_2 = 1/2\pi fX_C = 1/2(3.14)(315 \times 10^6)(219) = 2.31 \text{ pF}$$

$$C_1 = 1/2\pi fX_C = 1/2(3.14)(315 \times 10^6)(179) = 2.82 \text{ pF}$$

Applications With Tunable Networks

Impedance-matching networks must be tunable before they can be used over a wider frequency range or match a wider range of impedances for lower standing wave ratio (SWR) values. One or more of the components must be variable to make such networks. While manually variable capacitors and inductors are available, they are too large for practical modern circuits and their variability cannot be controlled electronically. Electronic control permits automatic tuning and matching circuits to be built.

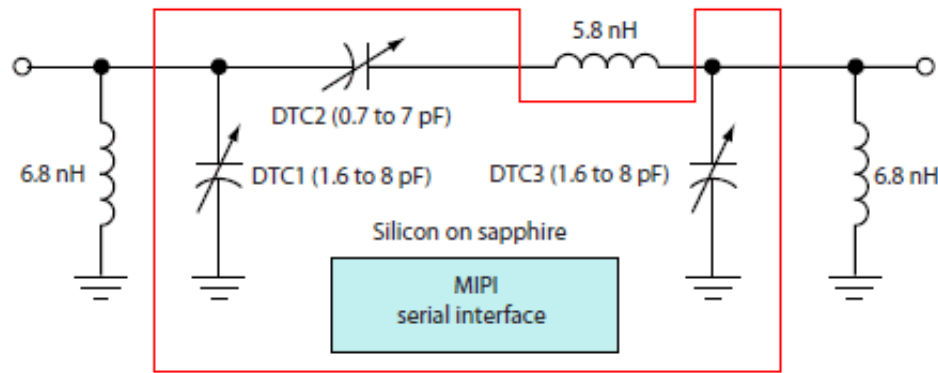
Different types of electronically variable capacitors are now available to implement such automatic tuners and matching circuits. The varactor diode or voltage variable capacitor has been available for years, and its continuously variable nature over a wide capacitance range is desirable. However, it is nonlinear and requires a significantly high bias voltage for control. Two other available options are the digitally tunable capacitor and the microelectromechanical-systems (MEMS) switched capacitor. Both are available in IC form and are ideal for making high-frequency variable matching networks.



4. Peregrine Semiconductor's solid-state UltraCMOS DTC for wireless applications uses five MOSFET switched capacitors.

Peregrine Semiconductor's PE64904 and PE64905 Digitally Tunable Capacitors (DTCs) consist of five fixed capacitors switched by an array of MOSFET switches ([Fig. 4](#)). These devices are made using a unique silicon-on-sapphire process. The capacitance is changed by a serial 5-bit code word using either a serial peripheral interface (SPI) or an I²C interface. The capacitor may be used in a series or parallel format. Maximum shunt capacitance is 5.1 pF with a minimum of 1.1 pF. Maximum series capacitance is 4.6 pF with a minimum of 0.6 pF. The capacitors can be put in series or parallel for larger or smaller values.

[Figure 5](#) shows a circuit using several of these capacitors. It's both a tunable filter and impedance-matching circuit. It's also a reconfigurable coupled resonator topology that's widely used in band-pass filters and impedance-matching networks. Using external inductors, this network provides wide impedance coverage over the cellular phone bands of 698 to 960 MHz and 1710 to 2170 MHz. Such tunable networks can provide automatic adjustment when cell sites are changed or can correct for the antenna detuning when the phone is held.



5. Tunable matching networks can use UltraCMOS DTCs to target multi-band LTE/WCDMA/GSM applications on UMTS-FDD Bands I, II, III, IV, V, VIII, and XII.

Wispry's MEMS devices also are commercially available tunable capacitors. The basic element is a MEMS capacitor that can be switched to produce an incremental change of 0.125 pF per bit. Each capacitor comprises a fixed plate with a dielectric on its surface. Above it is a mechanical flap forming the other plate. When an electrostatic charge is applied to the plates, they're attracted to one another. The upper plate is pulled downward, significantly decreasing plate spacing and increasing capacitance. By forming an array of these tiny capacitors, larger values can be created.

The company makes several versions of this device including custom circuits. Capacitance values to a maximum of 10, 20, or 30 pF can be formed with a tuning range of 10:1. The capacitance is controlled digitally with a serial word using either an SPI or the MIPI radio-frequency front-end (RFFE) interface. Capacitive devices use external inductors.

Also, Wispry's WS2017 standard impedance matching network is a variable π -network matching device featuring on-chip inductors. Again, the primary application is automatic tuning and impedance matching in cell phones and other small RF equipment. It operates over the 824- to 2170-MHz frequency range. An on-chip dc-dc converter provides the high voltage to operate the switchable capacitors. The device uses an SPI for control. A similar product, the WS2018, has similar specifications as well as the MIPI RFFE interface.

References

1. Bostic, Chris, *RF Circuit Design*, Howard W. Sams, 1982.
2. Frenzel, Louis E., *Principles of Electronic Communication Systems*, McGraw Hill, 2008.

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