NetworkSmith

Interactive Smith Chart Design and Analysis Tool for RF Impedance Matching

User Guide

Version 1.0

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1 Introduction

1.1 Purpose of NetworkSmith

NetworkSmith is an interactive RF and microwave network design tool centered around the Smith chart and reflection-coefficient-based workflow. The software is developed primarily for practicing RF engineers who routinely work on RF circuit matching problems (for example, matching an RF amplifier output, characterized by S22, to 50 Ω). Specifically, the software helps engineers answer the following questions in an intuitive graphical manner.

- what is the appropriate circuit topology for the matching network;
- how to incorporate other design considerations, when required, such as DC requirements, frequency characteristics, and bandwidth specifications, etc. in the matching network;
- what are the component values as a starting point for bench tuning if necessary.

The software, along with the User Guide, is also intended to support the development of engineering intuition through direct graphical interaction with matching networks as well as to serve as an educational and training environment.

Unlike many modern RF tools that primarily emphasize numerical optimization or automated synthesis, NetworkSmith is designed to maintain the Smith chart as the central engineering environment. The software encourages users to visualize how impedances, admittances, and reflection coefficients move through a network as components are added, modified, or tuned. This graphical approach helps users understand not only which matching solution works, but also why the solution behaves as it does.

The software supports interactive construction and analysis of passive matching networks using lumped elements and transmission lines in shunt or series topologies commonly encountered in RF and microwave engineering. Dynamic update features allow users to observe matching behavior in real time as network parameters are adjusted, reinforcing the physical interpretation of impedance transformation and network behavior.

The software also provides several tools for users' convenience in network setup and result reporting.

This guide is written to support users with varying levels of RF experience while maintaining standard RF and microwave engineering terminology and methodology throughout.

1.2 Why the Smith Chart Still Matters

The Smith chart is one of the most enduring graphical tools in electrical engineering. Originally developed by Phillip H. Smith in the 1930s for transmission-line analysis and impedance calculations, the Smith chart remains widely used in modern RF and microwave engineering despite the enormous advances that have occurred in numerical simulation and computer-aided design.

Modern circuit simulators can rapidly compute highly accurate matching solutions and optimize complex RF networks automatically. However, numerical results alone often do not provide strong physical intuition regarding how a network behaves, why a particular topology works, or how impedance transforms through a matching structure. The Smith chart is unusual because it continues to provide value that extends well beyond numerical calculation alone. Its continued relevance comes primarily from its ability to provide immediate visual interpretation of impedance behavior and matching-network operation.

The graphical nature of the Smith chart makes it particularly effective for understanding concepts such as:

- impedance and admittance transformation,
- reactive cancellation,
- movement caused by series and shunt elements,
- transmission-line behavior,
- matching topology selection,
- bandwidth and network Q behavior,
- tradeoffs among different matching approaches.

This visual interpretation is often difficult to obtain from equations or simulation data alone. As a result, the Smith chart continues to play an important role not only in education but also in practical RF engineering workflow.

For many engineers, the Smith chart serves as a bridge between mathematical analysis and physical understanding. It allows matching networks to be viewed as continuous geometric transformations rather than isolated numerical solutions. This perspective is especially valuable during the early stages of RF design, where engineering intuition and topology exploration are often more important than final numerical optimization.

NetworkSmith is built around this philosophy. Rather than treating the Smith chart as a secondary visualization attached to a simulator, the software places the Smith chart at the center of the design workflow. Users are encouraged to interact directly with impedance trajectories, observe how networks evolve as components are added or modified, and develop intuition regarding matching behavior through graphical exploration.

The goal is not merely to produce correct matching solutions, but also to help users understand the engineering reasoning behind those solutions. In this sense, the Smith chart remains not only a computational tool, but also a powerful environment for visualization, learning, and RF design intuition.

1.3 Passive-Network Assumptions

NetworkSmith is primarily intended for the analysis and design of passive impedance-matching networks used in RF and microwave systems. Typical matching structures consist of passive elements such as capacitors, inductors, resistors, and transmission lines arranged to transform impedances and control reflection behavior over a specified frequency.

Although practical RF systems often include active devices such as amplifiers, mixers, or oscillators, the matching structures connected to these devices are generally treated as passive networks. NetworkSmith therefore focuses on the passive behavior of the surrounding matching environment rather than on active-device operation itself.

The software assumes operation within the passive region of the Smith chart, where reflection coefficients satisfy:

$$|\Gamma| \leq 1$$

This assumption is consistent with the behavior of physically realizable passive networks and allows the Smith chart to maintain its standard geometric interpretation. Under these conditions, impedance transformations, transmission-line behavior, impedance/admittance conversion, and matching trajectories can be visualized directly and intuitively on the chart.

NetworkSmith is therefore best viewed as a passive-network synthesis and visualization environment intended for practical RF matching applications.

1.4 Reflection-Coefficient-Based Workflow

NetworkSmith is fundamentally organized around reflection coefficient (Γ) rather than impedance alone. This reflects both the mathematical foundation of the Smith chart and the workflow commonly used in practical RF engineering.

In RF and microwave systems, measured and simulated network behavior is frequently represented using scattering parameters (S-parameters). For a one-port system, the S parameter is the reflection coefficient, making reflection-coefficient-based workflows highly practical during measurement, tuning, and design optimization.

Because the Smith chart is itself a graphical representation of reflection coefficient, impedance, and admittance are treated within NetworkSmith as derived representations rather than primary quantities. Operations such as adding series or shunt components, adjusting transmission-line length, or transforming between impedance and admittance are therefore visualized as geometric movement on the Smith chart.

This approach provides several important advantages:

- direct compatibility with measured RF data,
- intuitive visualization of impedance transformations,
- rapid matching-network experimentation,
- efficient bench-tuning workflow,
- immediate graphical interpretation of network behavior.

In many practical situations, engineers begin with measured or simulated reflection coefficients and then iteratively construct matching networks by observing how each component moves the impedance trajectory on the Smith chart. NetworkSmith is specifically designed to support this style of RF engineering workflow.

2 Smith Chart Fundamentals

2.1 Reflection Coefficient, Normalized Impedance and Admittance

The original Smith chart is essentially an overlay of three coordinate systems, namely reflection coefficient, normalized impedance and normalized admittance. They are briefly discussed in this subsection. For more detailed coverage on the subject refer to the references listed in the References section.

Reflection coefficient

The reflection coefficient, commonly denoted by Γ, is one of the central quantities used in RF and microwave engineering. It is the ratio of the amplitude of a reflected wave to that of an incident wave at a reference plane within a transmission system.

For a transmission line with characteristic impedance Z_0 terminated by a load impedance Z_L, the reflection coefficient is given by

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} \qquad (2.1)$$

The reflection coefficient is generally a complex quantity and can be expressed in either magnitude and phase (MA) format or real and imaginary (RI) format.

Normalized impedance

Γ in (2.1) is a function of both Z_L and Z_0, hence is not uniquely determined by Z_L. The inverse function of (2.1) is

$$Z_L = Z_0 \frac{1 + \Gamma}{1 - \Gamma} \qquad (2.2)$$

If the normalized impedance z is defined as:

$$z = \frac{Z_L}{Z_0}$$

(2.2) becomes

$$z = \frac{1+\Gamma}{1-\Gamma} \qquad (2.3)$$

Thus the normalized impedance z has a one-to-one relationship with Γ. The unique relationship between z and Γ implies that if all impedances in a network are normalized using the same Z_0, then impedance transformations can be mapped into transformations in Γ domain. Conversely, the result in the Γ domain can be converted back to impedance using the same Z_0. Similarly the normalized admittance is defined as

$$y = \frac{Y_L}{Y_0}$$

where:

$$Y_L = \frac{1}{Z_L}$$

$$Y_0 = \frac{1}{Z_0}$$

y is related to Γ by:

$$y = \frac{1}{z} = \frac{1-\Gamma}{1+\Gamma} \qquad (2.4)$$

Therefore the reflection coefficient Γ, the normalized impedance z and admittance y are uniquely related once a common parameter Z_0 is chosen. This is the key to the construction of the Smith chart. For this reason Z_0 is often referred to as the normalization or reference impedance, in spite of its original physical significance as the characteristic impedance of a transmission-line. In SnP file format, which is the RF industry standard for S parameter data, this impedance is denoted by Rn. NetworkSmith follows this convention by using Rn for the reference impedance.

2.2 Structure of the Smith Chart

Conceptually a complete Smith chart comprises three sets of coordinates (a specific version of the chart may not show all three coordinates). The basic system is the reflection coefficient Γ in polar format. For passive networks where $|\Gamma| \leq 1$, the Smith chart is a unit circle. As explained in Sec. 2.1, any Γ point on the chart is uniquely related to z and y according to (2.3) and (2.4) respectively. Thus in the same Γ

coordinate system, z and y coordinates can be constructed using constant variable curves. The three coordinate systems are:

- reflection coefficient (Γ),

  $\Gamma = |\Gamma|\angle\theta$, constant-magnitude ($|\Gamma|$) circles concentric at $\Gamma = 0$ and constant-angle (θ) radial lines;

- normalized impedance (z),

  $z = r + jx$, constant-resistance (r) circles with centers on Γ real axis ranging from 0 to 1 and constant-reactance (x) arcs,

- normalized admittance (y),

  $y = g + jb$, constant-conductance (g) circles with centers on Γ real axis ranging from 0 to -1 and constant-suseptance (b) arcs.

The z and y coordinates are in fact reflection in the center.

Important points and regions of the chart include:

- The chart center corresponds to:
  $|\Gamma| = 0$, $z = 1 + j0$, $y = 1 + j0$ which represents $Z = Z_0$.
- the rightmost boundary: $|\Gamma| = 1, \theta = 0$, total reflection, open circuit,
- the leftmost boundary: $|\Gamma| = 1, \theta = 180$, total reflection, short circuit,
- upper half: $x > 0, y < 0$, inductive region,
- lower half: $x < 0$, $y > 0$, capacitive region.

The structure of the Smith chart allows it to perform two major graphical functions.

First, any point on the chart simultaneously represents all three coordinate systems. A user may therefore determine reflection coefficient, normalized impedance, and normalized admittance graphically without explicitly performing mathematical conversions using the associated equations.

In traditional printed Smith charts, extensive coordinate labels and auxiliary scales were required to allow users to perform graphical conversion and network construction manually.

In computerized Smith-chart environments such as NetworkSmith, these conversions are performed internally by software. As a result, many coordinate labels and auxiliary markings are no longer required for routine operation.

To maintain a consistent and simplified workflow, NetworkSmith only uses reflection coefficient in magnitude-angle (MA) format for user input and result display. Internally, the software continuously performs conversions among reflection coefficient, impedance, and admittance representations during network manipulation and visualization. When conversion between coordinate systems is required explicitly, the Conversion Chart utility may be used. This approach preserves the geometric intuition of the Smith chart while reducing the complexity associated with traditional manual graphical procedures.

The second function of Smith chart as a powerful tool in network design lies in the fact that many RF network operations correspond to predictable geometric movement on the chart. Adding a series or shunt component, or changing transmission-line length, causes the network point to move along specific trajectories of the corresponding coordinate (e.g. adding a series inductance moves the network point along a constant resistance coordinate). The resulting network condition may therefore be determined graphically without direct calculation. This feature is at the core of NetworkSmith: it not only maintains the graphic representation of network transformation but also enhances it by adding an interactive capability to the entire network transformation chain.

2.3 Q Curves and Network Bandwidth

The network Q factor is an important concept in RF matching design because it strongly influences the network bandwidth . It is defined by the network's impedance, $Z = R + jX$ or admittance, $Y = G + jB$ as

$$Q = \frac{|X|}{R} = \frac{|x|}{r}$$

Or

$$Q = \frac{|B|}{G} = \frac{|b|}{g}$$

This definition indicates that any point on the Smith chart has a unique Q value. Using the same concept discussed in Sec. 2.2, a group of constant-Q curves can be used to visualize the movement of Q factor on the Smith chart in network transformations.

The significance of the network Q in network design and analysis is its effect on the bandwidth. The exact bandwidth of a network consisting of multiple transformations is a complex function of characteristics of all transformations involved. However, the transformation with the highest network Q in a sequence of transformations is generally the dominant factor in determining the overall network bandwidth. Therefore the network Q provides useful information in estimating the network bandwidth, particularly for comparison of different matching network configurations.

In general:

- low-Q networks tend to provide broader bandwidth,
- high-Q networks tend to provide narrower bandwidth and greater sensitivity to component variations.

Visual awareness of Q behavior can significantly improve matching-network design intuition. NetworkSmith optionally provides Q-curve overlays to assist users in understanding how impedance trajectories relate to network Q and matching behavior. These overlays are intended primarily as engineering visualization aids rather than exact bandwidth predictors.

3 NetworkSmith Concepts and Conventions

3.1 Introduction

Section 2 introduced the Smith chart and the relationships among reflection coefficient, normalized impedance, and normalized admittance. These concepts form the theoretical foundation of NetworkSmith.

This section explains the conventions, quantities, and component representations used throughout the software. Although these conventions are closely related to Smith chart theory, they are specific to how NetworkSmith represents matching problems and presents results to the user.

Understanding these concepts is important because the workflow used by NetworkSmith is based entirely on reflection coefficient. Once the meaning of the reflection coefficients and component representations used by the software is understood, the matching process becomes straightforward and intuitive.

3.2 Reflection Coefficients Used in NetworkSmith

Why NetworkSmith Uses Reflection Coefficient

The Smith chart is fundamentally a graphical representation of reflection coefficient. Unlike impedance and admittance, reflection coefficient can be visualized directly on the chart without the need for coordinate labels. The magnitude of the reflection coefficient corresponds to the distance from the chart center, while the phase corresponds to the angular position around the chart.

For this reason, reflection coefficient provides the most natural representation of network behavior on a Smith chart.

A second practical reason is that modern RF measurements and simulations are commonly performed using scattering parameters (S-parameters). Reflection coefficient data are therefore often available directly from measurement equipment such as vector network analyzers (VNAs) or from circuit and electromagnetic simulation software.

Reflection coefficient is commonly represented in magnitude-angle form:

$$\Gamma = |\Gamma| \angle \theta$$

where |Γ| is the magnitude of the reflection coefficient and θ is the phase angle.
NetworkSmith uses this magnitude-angle (MA) representation exclusively for user input and result display. This format directly corresponds to the graphical representation on the Smith chart and is also the format most frequently encountered in practical RF measurements.

When the original data are in a different format, the Conversion Chart in the Toolbox can be used to convert them to reflection coefficient format and vice versa.

Although the Smith chart itself is based on normalized impedance and admittance, NetworkSmith accepts and displays practical engineering quantities whenever possible. Internal normalization and coordinate conversion are performed automatically by the software.

Reflection Coefficients Used in NetworkSmith

Figure 3.1 illustrates the reflection coefficients used throughout NetworkSmith.

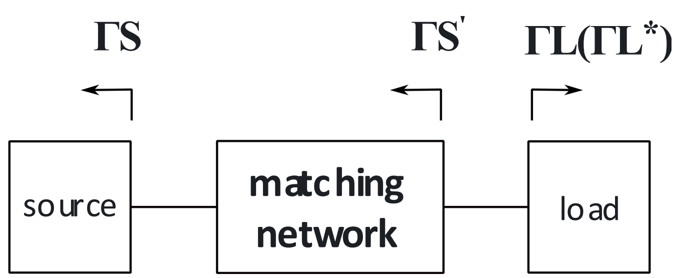

Figure 3.1 Reflection Coefficients Used in NetworkSmith

Four reflection coefficients may be encountered during a matching design.

ΓS — Source Reflection Coefficient

ΓS is the reflection coefficient of the source connected to the input side of the matching network. It represents the starting point of every NetworkSmith design and is therefore a required input.

ΓL — Load Reflection Coefficient

ΓL is the reflection coefficient of the load connected to the output side of the matching network. This quantity is typically obtained from measurement, simulation, or device specifications.

ΓL*— Conjugate Load Reflection Coefficient

ΓL* is the complex conjugate of the load reflection coefficient

ΓS'— Transformed Reflection Coefficient

ΓS' is the reflection coefficient looking into the network at its output side. As components are added, removed, or modified, ΓS' changes accordingly. The movement of ΓS' on the Smith chart provides a convenient graphical representation of the matching process. In network synthesis, ΓS' is known and is placed on the chart as a target for transformation, hence ΓS' is also referred to as target Γ in this document.

3.3 Perfect Matching Condition

Using the terminology defined above, a perfect match (no power reflection at the interface) is achieved when

$$\Gamma S' = \Gamma L^*$$

rather than

$$\Gamma S' = \Gamma L$$

For this reason, whenever a load reflection coefficient is provided, NetworkSmith displays both ΓL and ΓL* on the Smith chart. The objective of the matching process is then to transform ΓS through the matching network until ΓS' reaches ΓL*

In the Desktop version, a BOM option is available. Upon its activation, NetworkSmith recalculates the existing network using only components available from a specific part-number series (selected by the user). In this case, due to the discrete nature of component values, in general, a perfect matching between ΓS' and ΓL* (if ΓL is provided) is no longer possible. The program uses an optimization routine to minimize the mismatch in selecting the component values. For applications where the purpose of the network is to transform a known ΓS to a target value ΓS', the user should enter the complex conjugate of ΓS' as load at Step 2, then the correct target value will be used in BOM optimization.

3.4 Shunt Z Component

At a fundamental level, the Smith chart represents the transformation of a network when a single component, such as a resistor, capacitor, inductor, or transmission-line section, is attached to the network in either series or shunt configuration.

For more complex circuit branches containing multiple components, the situation becomes more complicated. If all components within the branch are connected in series and the entire branch is attached in series to the network, or if all components within the branch are connected in shunt and the entire branch is attached in parallel to the network, the transformation can usually be represented as a sequence of individual Smith chart operations.

In more general cases, however, a complex branch cannot be represented by a simple Smith chart trajectory.

Fortunately, at a single frequency any linear circuit branch can be represented by an equivalent impedance or admittance. This equivalent representation allows complex branches to be incorporated into Smith chart analysis.

For this reason, NetworkSmith includes the Shunt Z component, which is a configuration often encountered in RF circuits.

The Shunt Z component in Figure 3.2 represents a general impedance connected in parallel with the network and is specified by:

$Z = R + jX$

where: R is the resistance and X is the reactance.

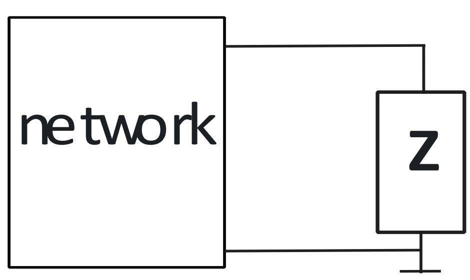

Figure 3.2 Shunt Z in NetworkSmith

The R and X values for a Shunt Z component can be determined from circuit analysis, simulation, measurement, or another design tool. Example 5 in Section 7 shows how to obtain R and X for a three-component branch using the Smith chart.

Because two independent quantities (R and X) define a Shunt Z component, there is generally no unique Smith chart trajectory associated with the transformation. For this reason, NetworkSmith displays a simple connection between the start and end points rather than attempting to display a physical transformation path.

3.5 Electrical Length of Transmission Lines

In NetworkSmith transmission lines are assumed to be lossless. Under this condition, the behavior of a transmission-line section in impedance transformation is completely determined by two component parameters: characteristic impedance and phase delay.

The phase delay, denoted as θ, is referred to as electrical length in the RF industry despite being a quantity of angle. This is because θ is related to the physical length of the transmission line ℓ by

$$\theta = \beta\ell \quad (3.1)$$

where $\beta = 2\pi/\lambda$ is the propagation constant (or wave number) and λ is the wavelength. The relationship expressed in (3.1) implies that once β is given the phase delay is completely determined by the physical length. For this reason, θ is usually referred to as electrical length in the RF industry despite being an angular quantity. When θ is expressed in degrees, (3.1) is

$$\theta = 360^{\circ}\frac{\ell}{\lambda}$$

Hence a transmission line having an electrical length of 360° corresponds to one complete wavelength at the operating frequency.

The impedance transformation produced by a transmission line depends only on its characteristic impedance and electrical length. For this reason, transmission-line components within NetworkSmith are specified using electrical length rather than physical length.

In practical applications, however, transmission lines are usually specified by physical length. Converting physical length into electrical length requires information about the propagation constant β within the transmission medium. At a fundamental level of physics, the difference in β among different transmission media is caused by the difference in the propagation velocity, $v_p = \omega/\beta$ (ω is the angular frequency).

For printed-circuit transmission lines, propagation velocity is often described using the effective dielectric constant ε_{eff}:

$$v_p = \frac{c}{\sqrt{\varepsilon_{eff}}}$$

Where c is the speed of light in free space.

For cables and many commercial transmission lines, propagation velocity is commonly specified using velocity factor VF:

$$VF = \frac{v_p}{c}$$

Another practical data format for the electrical length of a transmission-line section is electrical length@reference frequency. In this case, the electrical length at a different operating frequency can be simply calculated, because the ratio of the electrical length to the frequency is constant. For example:

100 MHz → 45°

200 MHz → 90°

400 MHz → 180°

Because Smith chart transformations depend directly on electrical length, NetworkSmith uses electrical length in degrees as the user input parameter for all transmission-line components.

To assist users working with physical transmission-line dimensions, NetworkSmith provides an Electrical Length Calculator in the Toolbox. The calculator can determine electrical length from physical length, and vice versa, for a given propagation parameter (effective dielectric constant or velocity factor), or convert electrical lengths between different operating frequencies.

This approach allows transmission-line behavior to be represented directly in the form required for Smith chart analysis while still supporting the practical quantities commonly encountered in RF design.

4 User Interface and Basic Operation

4.1 Main Window Layout

The NetworkSmith user interface is shown in Figure 4.1. It consists of three primary areas:

- **User Inputs Panel** on the left,
- **Smith Chart Display Area** in the center,
- **Toolbox Panel** on the right.

The User Inputs panel contains the controls used to define network parameters and the component library for creation of matching networks. The Smith Chart Display Area provides a graphical representation of the network and its transformations. The Toolbox panel contains auxiliary functions that assist the design process.

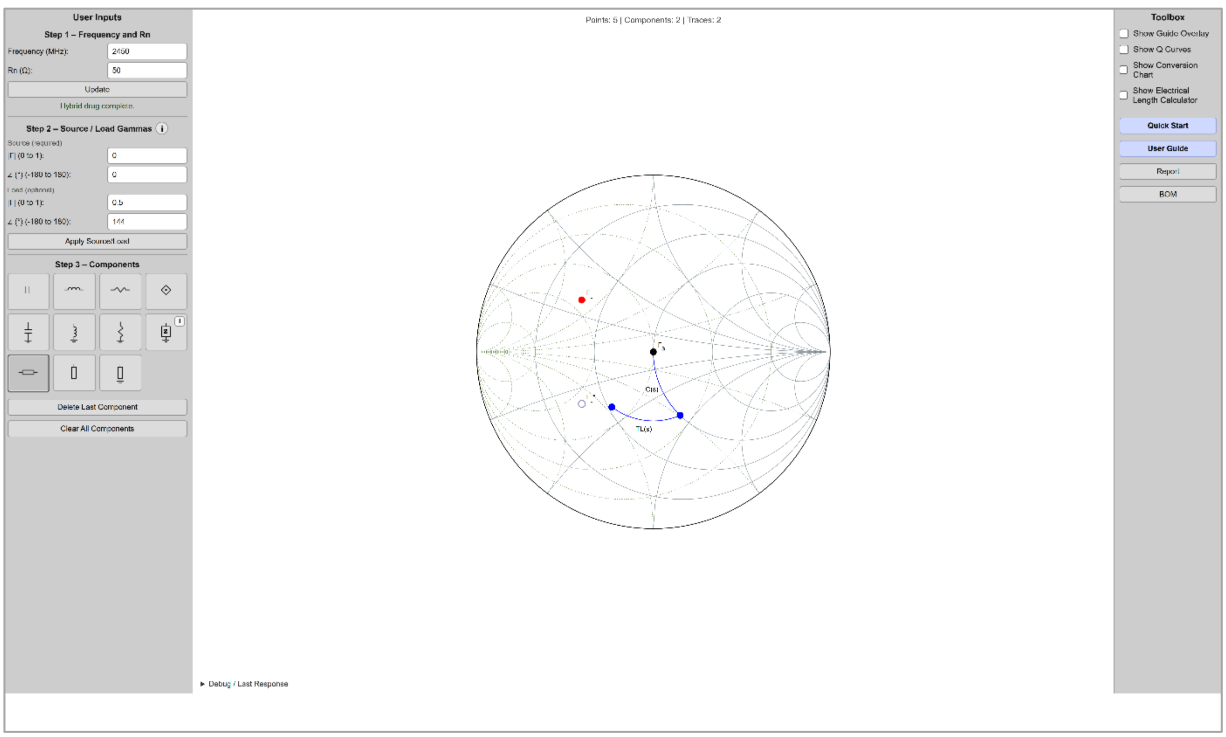

Figure 4.1 NetworkSmith User Interface

NetworkSmith is designed around a three-step workflow. To ensure that all calculations are performed using consistent operating conditions, the three steps must be completed in order:

1. Define frequency and normalization resistance.
2. Define source and optional load reflection coefficients.
3. Place and edit matching-network components.

Step 2 is enabled only after Step 1 has been completed, and Step 3 is enabled only after the source reflection coefficient has been applied in Step 2.

The workflow generally proceeds from top to bottom within the User Inputs panel.

4.2 Step 1 — Frequency and Normalization Resistance

The controls in Step 1 define the operating conditions for the matching network.

Frequency

The frequency field specifies the operating frequency of the network. Component values and transmission-line behavior are calculated at this frequency.

Because reactive components and transmission lines are frequency dependent, changing the operating frequency generally changes the behavior of the entire network.

Normalization Resistance Rn

The normalization resistance defines the reference impedance used by the Smith chart.

Common values include:

- 50 Ω for most RF systems (the default value in NetworkSmith),
- 75 Ω for certain communication and video systems,
- other values as required by specific applications.

Changing Rn affects the relationship between reflection coefficient, impedance, and admittance displayed by the software.

Update

The Update button applies the frequency and normalization settings to the current design.

Frequency and normalization updates may affect existing networks. The behavior of such updates is discussed in Section 5.

4.3 Step 2 — Source and Load Gammas

Step 2 defines the reflection coefficients used during network synthesis.

Source Reflection Coefficient ΓS

The source reflection coefficient is the required starting point for all matching-network designs.

NetworkSmith accepts source reflection coefficient input in magnitude-angle (MA) format.

Load Reflection Coefficient ΓL

The load reflection coefficient is optional.

When a load reflection coefficient is entered, both ΓL and its complex conjugate ΓL* are displayed on the Smith chart. This provides a visual target for the matching process.

Apply Source/Load

The Apply Source/Load button places the specified reflection coefficients on the Smith chart and initializes the network-design process.

Once the source and load have been applied, component placement and network synthesis may begin.

Open and Short Circuits

NetworkSmith accepts ideal open-circuit ($|\Gamma| = 1$, $\theta = 0°$) and short-circuit ($|\Gamma| = 1$, $\theta = 180°$ or $-180°$) conditions.

Internally, these conditions are handled in a manner that avoids mathematical singularities while preserving the intended electrical behavior.

4.4 Step 3 — Component Placement and Editing

Step 3 contains the component library used to construct and modify matching networks.

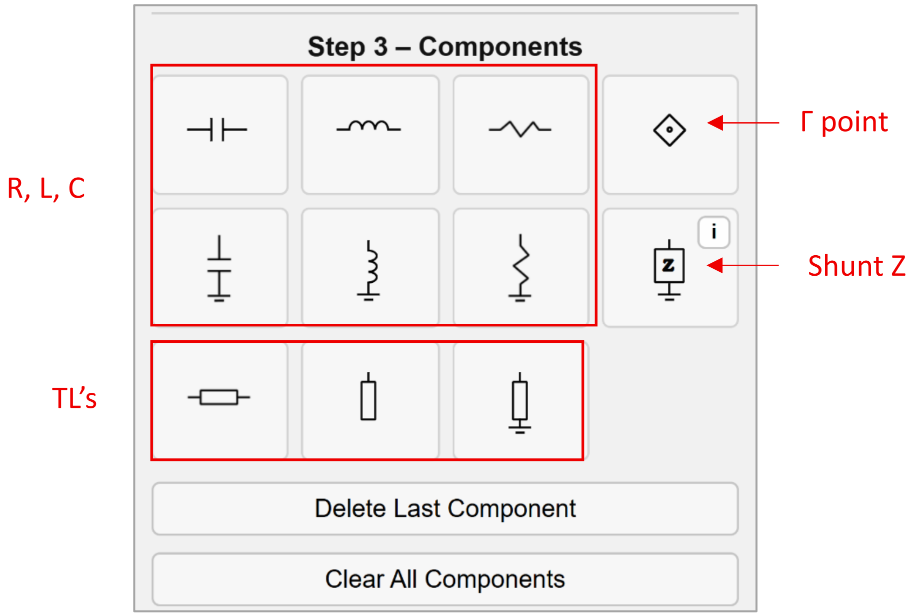

Figure 4.2 Component Library

Supported Components

Components in the library are grouped into four categories as shown in Figure 4.2:

1) Discrete R, L, C components

- Series resistor, R(s)
- Series capacitor, C(s)
- Series inductor, L(s)
- Shunt resistor, R(sh)
- Shunt capacitor, C(sh)
- Shunt inductor, L(sh)

2) Transmission Lines

- Series transmission line. TL(s)
- Shunt transmission line with open-circuit, TL(sh,o)

- Shunt transmission line with short-circuit, TL(sh,s)

3) Shunt impedance, Z(sh)

4) Gamma Point, Γ Point, it is a visual marker only and is not included in network calculations.

Component Placement

To add a component, select the desired component type first. The software initially displays a point along with a trace that follows the valid trajectory for the selected component type on the chart for component editing in the next step.

Component Editing

Component values may be modified after placement using either of two methods.

Edit Window

The Edit Window allows the user to specify a desired numerical value directly.

To open the Edit Window, left-click on a component point located on the Smith chart. A popup window, as shown in Figure 4.3, will appear allowing the component value to be edited.

The popup window also displays the reflection coefficient and Q value associated with the selected point. These values are provided for reference and are not editable. When the calculated Q is extremely large, NetworkSmith displays Q as N/A because the value is not useful as a practical bandwidth indicator near the open-circuit region of the Smith chart.

After the component value is updated, the network is automatically rebuilt and all downstream transformations are recalculated.

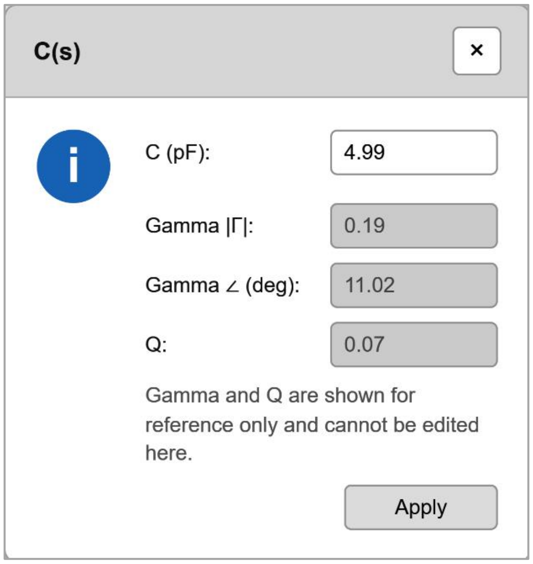

Figure 4.3 Component edit window

Mouse Dragging

Mouse dragging allows the user to move a component point to a desired location directly on the Smith chart.

To drag a component, left-click and hold the component point, move it to the desired location, and then release the mouse button.

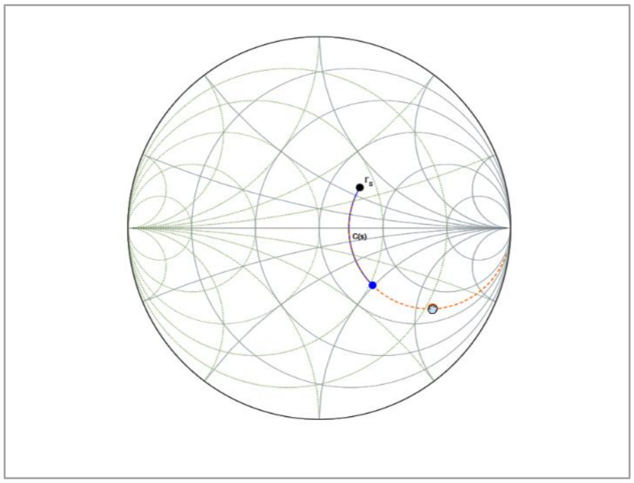

Figure 4.4 Mouse Dragging Component Point

In the web version of NetworkSmith, an extended component trajectory is displayed in orange (see Figure 4.4). This trajectory represents all valid locations that can be reached by varying the selected component value.

During the drag operation, the point may be moved freely on the Smith chart and is not constrained to the orange trajectory. When the mouse button is released, NetworkSmith automatically finds the point on the orange trajectory that is closest to the release location and updates the component value accordingly.

This approach allows rapid graphical tuning while ensuring that the final component value always corresponds to a physically realizable network.

In the desktop version, dragging is continuous and the component point is automatically constrained to the valid trajectory throughout the drag operation. As a result, the trajectory extension does not need to be displayed during dragging.

Component Removal

The software allows component removal in two modes: Delete Last Component and Clear All Components. Two corresponding buttons are below the Component library.

4.5 Toolbox Functions

The Toolbox panel provides supporting functions used during network design.

Guide Overlay

In component selection, the Guide Overlay (Figure 4.5) provides a guide for the movements of R, L, C in series and shunt configurations. It helps users to quickly select the appropriate component to move the network in the desired direction. Note that the arrows in the overlay indicate the direction of network movement as the specific component is connected to the network. It is not necessarily the direction in which the component value increases. For example, for series L, the arrow points in the direction of increasing L whereas for series C, it is the direction of decreasing C. In general, the limit point of a series component is an open circuit while that for a shunt component is a short circuit.

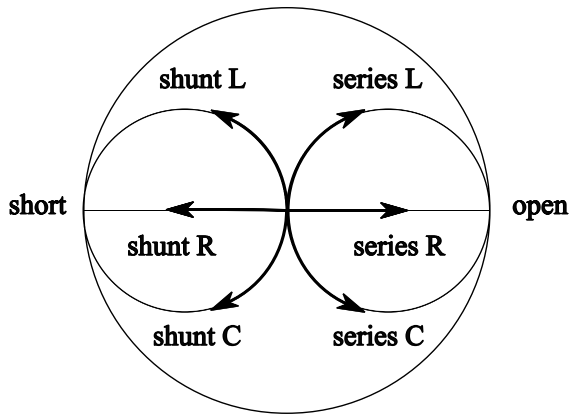

Figure 4.5 Guide Overlay

Conversion Chart

The Conversion Chart, as shown in Figure 4.6, displays equivalent representations of the selected point in multiple coordinate systems.

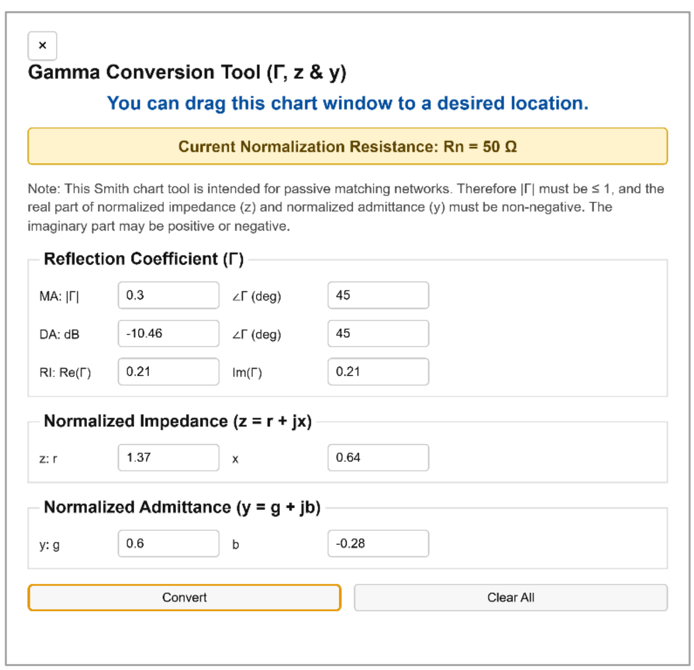

Figure 4.6 Conversion Chart

These include:

- Reflection coefficient (Magnitude-Angle)
- Reflection coefficient (Real-Imaginary)
- Reflection coefficient (dB-Angle)
- Normalized impedance
- Normalized admittance

The chart updates all fields each time Convert is clicked, using whichever field was most recently edited as the input.

The Conversion Chart allows rapid conversion among the coordinate systems traditionally associated with the Smith chart.

Q-Curve Display

Q curves may be displayed on the Smith chart as a design aid.

Q-curve display may be enabled or disabled at any time.

Report Generation

Figure 4.7 shows the Report function that generates a summary of the current network design.

The report includes:

- Network schematic,
- Component values,
- Source and output reflection coefficients,
- Smith chart image.

“Save Report” saves the report in HTML format in the Downloads folder.

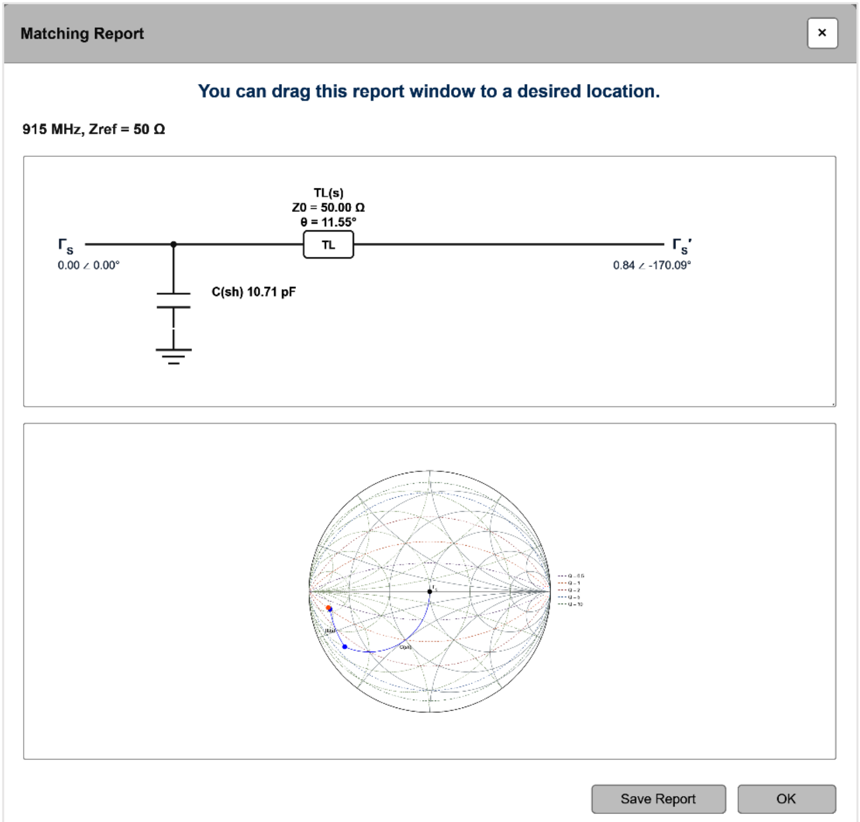

Figure 4.7 Report of Network in Circuit Schematic and Smith chart

Electrical Length Calculator

The Electrical Length Calculator shown in Figure 4.8 converts between physical length and electrical length.

Conversions may be performed using either effective dielectric constant or velocity factor.

This utility simplifies the use of transmission-line elements within matching-network designs.

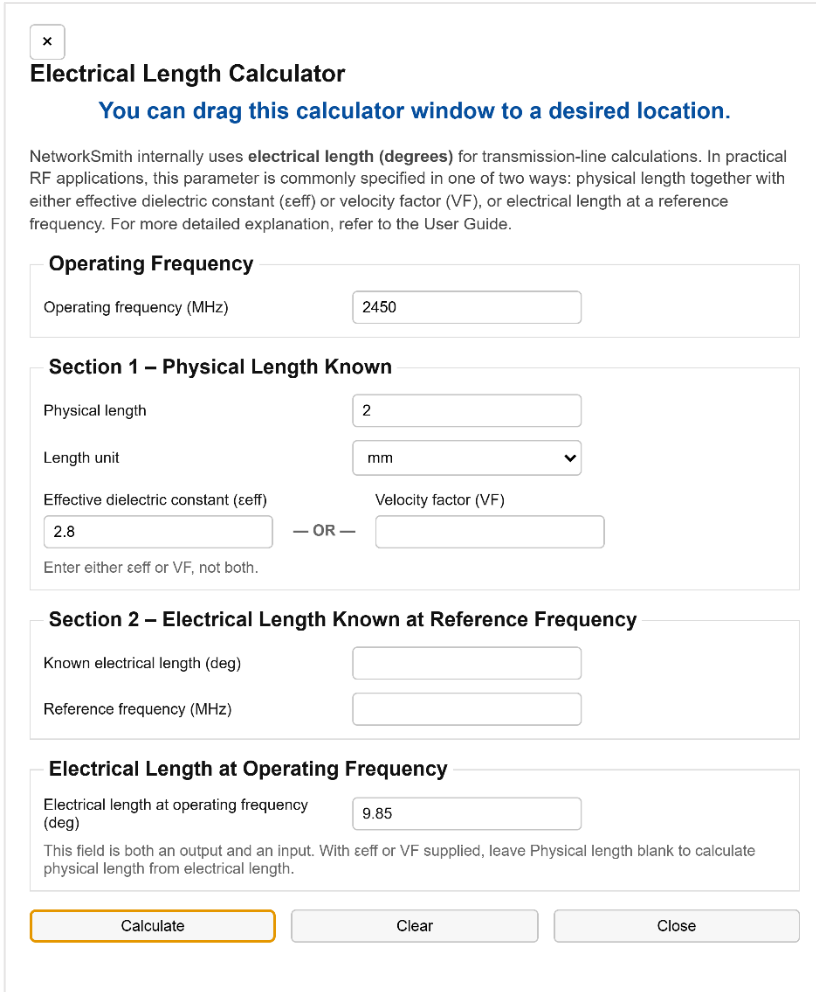

Figure 4.8 Electrical Length Calculator

5 Dynamic Update Behavior

5.1 Introduction

Unlike a traditional paper Smith chart, NetworkSmith maintains a complete network model and continuously updates the design as parameters are modified. Changes made to component values, operating frequency, source conditions, load conditions, or normalization parameters are immediately reflected in the Smith chart display and associated network calculations.

This dynamic behavior allows rapid exploration of design alternatives and provides immediate visual feedback during matching-network development. At the same time, it is important to understand how various parameter changes affect the network and how the software responds to those changes.

This section explains the update mechanisms used by NetworkSmith and provides recommended practices for modifying existing designs.

5.2 Component Updates

The most common type of update occurs when a component value is modified.

Component values may be changed by:

- Editing component parameters through the component editor,
- Dragging component endpoints on the Smith chart,

When a component is modified, NetworkSmith does not simply update that component in isolation. Instead, the software recalculates the entire network beginning with the defined source reflection coefficient and proceeding through the complete component sequence.

As a result:

- All downstream network transformations are recalculated,
- All component endpoints are updated,
- All trajectory traces are regenerated,
- The transformed source reflection coefficient ΓS' is updated automatically.

This approach ensures that the displayed network always remains mathematically consistent with the current component values.

Because the network topology itself is unchanged, component updates are generally the safest and most common form of design iteration.

5.3 Frequency Updates

Operating frequency is one of the most important parameters in RF network design. When the operating frequency is modified, NetworkSmith rebuilds the network using the new frequency and recalculates all associated impedance transformations. This dynamic frequency update allows users to examine the behavior of an existing network at a different frequency. Care, however, must be taken because some existing parameters must be updated by the user when the frequency is modified. The table below summarizes the required parameter updates in response to a frequency modification.

Parameters	Required User Update
RLC component values	No (reactance is calculated internally)
Transmission lines	Electrical length
Source Γ	Yes, unless is real (e.g. 50 Ω)
Load Γ	Yes, unless is real. No effect on network

Table 5.1 Required user updates when frequency is modified.

> IMPORTANT
>
> When the frequency in Step 1 is modified, parameters must be updated by the user according to Table 5.1. Failure to do so may reach an incorrect conclusion about the frequency behavior of the network.

5.4 Normalization Updates

NetworkSmith uses the normalization impedance Rn entered in Step 1 as the reference impedance for Smith chart calculations.

Because both normalized impedance and reflection coefficient depend on the selected normalization impedance (see Section 2.1), changing Rn generally changes:

- normalized impedance values,
- normalized admittance values,
- reflection coefficients,
- point locations on the Smith chart.

As a result, when Rn is changed in Step 1, ΓS and ΓL in Step 2 must be recalculated using the updated Rn value. The remaining parameters in the User Input Panel are not affected by the change in Rn. The updated Rn should also be used in the Conversion Chart.

In practical RF systems, Rn is normally chosen to be equal to the characteristic impedance of the measurement or transmission system, most commonly 50 Ω. However, engineers sometimes intentionally select a different normalization impedance to obtain a more useful graphical representation of a matching problem.

This approach is particularly useful when the impedances involved in a transformation are much larger or much smaller than 50 Ω. In such situations, using a different normalization impedance can effectively magnify the region of interest on the Smith chart and make impedance transformations easier to visualize and interpret. Example 5 in Section 7 demonstrates a practical application of this technique. Because NetworkSmith uses reflection coefficient as its primary input and display quantity, changing Rn affects not only impedance normalization but also the conversion between impedance and reflection coefficient. Consequently, the network is rebuilt using the new reference impedance and all associated chart locations are updated.

> IMPORTANT
>
> When Rn is changed, existing reflection-coefficient values may no longer represent the same physical impedances. After changing Rn, update the source and load definitions before continuing the design process. In particular, if impedance values are being converted using the Conversion Chart, Step 1 should be updated first so that the Conversion Chart uses the correct normalization impedance.

5.5 Source Reflection-Coefficient (ΓS) Updates

NetworkSmith allows the source reflection coefficient ΓS to be modified after a network has already been constructed.

When ΓS changes, the software automatically rebuilds the entire network beginning from the new source location and reapplies all existing components in sequence.

This capability provides a convenient method for evaluating how a matching network responds to different source conditions.

Such updates can be useful for:

- sensitivity studies,
- design exploration,
- comparison of alternative source conditions,
- evaluation of measured versus simulated source data.

However, users should recognize that source reflection coefficient is generally frequency dependent and determine whether the operating frequency should also be changed to correspond to the modified ΓS.

5.6 Load Reflection-Coefficient (ΓL) Updates

Unlike source reflection coefficient, the load reflection coefficient ΓL does not participate directly in the network rebuilding process.

The primary purpose of ΓL is to define the matching target through its conjugate value ΓL^*.

When ΓL is modified:

- The load point is updated,
- The conjugate load point ΓL^* is updated,
- The matching target changes,
- Existing component values remain unchanged,
- The existing network is not rebuilt.

This behavior allows users to compare an existing matching network against different load conditions without immediately altering the network itself.

As a result, changing ΓL should be viewed as changing the design objective rather than modifying the network.

In many practical situations, users first establish the desired source and load conditions and then synthesize a matching network. Once a matching network has been created, changing ΓL typically implies that the network should be redesigned or re-optimized to satisfy the new matching objective.

> IMPORTANT
>
> Changing ΓL changes the matching target but does not automatically modify the existing network. If the new load condition requires a different match, the matching network must be adjusted accordingly.

5.7 Recommended Update Practices

NetworkSmith supports a wide range of interactive updates. Some updates are particularly well suited for routine design iteration, while others should be interpreted more carefully.

The following activities are generally appropriate during normal matching-network development:

- Adjusting component values,
- Dragging component endpoints,
- Comparing alternative source conditions.

Additional care should be taken when:

- Making frequency changes,
- Changing normalization impedance,
- Reusing transmission-line electrical lengths at different frequencies,
- Comparing data obtained from different reference impedances.

In general, the most reliable workflow is:

1. Establish the operating frequency,
2. Select the desired normalization impedance,
3. Define source and load conditions,
4. Perform matching-network synthesis,
5. Use dynamic updates for refinement and evaluation.

Following this sequence minimizes ambiguity and ensures that all displayed quantities remain consistent throughout the design process.

5.8 Summary

The update behaviors described above can be summarized by a simple principle:

- ΓS defines where the matching network starts.
- ΓL defines where the matching network is trying to go (graphically it is ΓL*).

Changing the starting point requires the network to be rebuilt. Changing the destination changes the matching objective but does not automatically alter the existing network.

Table 5.2 summarizes the principal update behaviors within NetworkSmith.

Parameters changed	Required additional updates by user
Components in Step 3	none
Frequency in Step 1	Electrical length if TL's are used; May require updates to ΓS and ΓL if they are frequency dependent.
Rn in Step 1	ΓS and ΓL
ΓS in Step 2	May require updates to the frequency and ΓL, if they are frequency dependent.
ΓL in Step 2	May require updates to the frequency and ΓS, if they are frequency dependent. No effect on network.

Table 5.2. Principal update behaviors within NetworkSmith.

6 Incorporation of Other Circuit Functions

The primary purpose of a matching network is to transform one impedance or reflection coefficient into another. In many cases, multiple matching networks can accomplish exactly the same impedance transformation. As a result, practical RF design often involves considerations beyond simply achieving a match on the Smith chart.

The following factors frequently influence the selection of a matching-network topology.

6.1 DC Blocking

A series capacitor blocks DC current while allowing RF signals to pass. DC blocking is commonly required at the input or output of active devices such as amplifiers to prevent the DC bias conditions of adjacent circuits from interacting with one another.

When DC blocking is required, a matching network containing at least one series capacitor is often preferred over an otherwise equivalent topology that does not provide this function.

6.2 DC Return Path

Many active devices require a DC return path for biasing purposes.

A shunt inductor can provide a low-resistance path for DC current while presenting a relatively high impedance at RF frequencies. For this reason, shunt inductors are frequently used in matching networks associated with amplifiers and other active RF circuits.

In practical designs, the matching network and bias network are often closely related.

6.3 Component Count

For a given impedance transformation, the simplest network is often preferred because it:

- reduces component cost,
- reduces PCB area,
- improves manufacturability,
- may reduce insertion loss.

However, the network with the fewest components may not always satisfy other requirements such as DC blocking, bandwidth, or filtering performance.

As a result, additional components are sometimes intentionally added even when a simpler matching solution exists.

6.4 Bandwidth and Network Q

Bandwidth is closely related to the Q of the impedance transformation. In general:

- Lower-Q matching networks provide wider bandwidth.
- Higher-Q matching networks provide narrower bandwidth.

For a given source and load condition, several matching solutions may be available with different Q values.

NetworkSmith provides optional Q curves on the Smith chart to assist users in visualizing and comparing alternative matching paths.

6.5 Filtering Effects

Matching networks also affect the frequency response of a circuit. For example:

- Series capacitors and shunt inductors tend to suppress low-frequency signals.
- Series inductors and shunt capacitors tend to suppress high-frequency signals.
- Additional resonant structures may be incorporated to reject unwanted frequencies.

Consequently, a matching network frequently performs both impedance transformation and filtering functions simultaneously.

6.6 Transmission Lines versus Lumped Components

At sufficiently high frequencies, transmission lines are often preferred over lumped inductors and capacitors. As the operating frequency increases, the wavelength becomes shorter, and the physical length required to realize a given electrical length becomes correspondingly shorter. At microwave frequencies, transmission-line sections having the electrical lengths required for impedance matching can therefore be implemented conveniently as PCB traces or other transmission-line structures.

Transmission lines also offer several practical advantages:

- low loss,
- high power-handling capability,
- good repeatability,
- convenient implementation on printed circuit boards,
- reduced component count in many matching networks.

In high-power RF applications, transmission lines offer an additional advantage. High-quality RF power inductors can be expensive and may introduce additional loss, whereas a properly designed transmission-line section can often replace one or more lumped components while providing lower loss, higher power-handling capability, and lower cost.

However, transmission lines also require physical space, and their electrical behavior depends on frequency and substrate properties. At lower frequencies, the transmission-line length required to realize a desired electrical length may become impractically long, making lumped components the preferred implementation.

NetworkSmith supports both lumped-element and transmission-line matching techniques, allowing users to evaluate alternative implementations for a given matching problem.

6.7 Engineering Judgment

The Smith chart identifies possible impedance transformations, but it does not determine which solution is best for a particular application.

The final topology selection depends on the overall system requirements, including DC biasing, bandwidth, filtering characteristics, component availability, power-handling capability, physical size, and cost.

The worked examples in Section 7 illustrate how these practical considerations influence matching-network design and why multiple valid solutions often exist for the same matching problem.

7 Worked Examples

Examples in this section demonstrate how to use NetworkSmith in matching network design for several cases commonly encountered in RF engineering practice. In addition to demonstrating of the software workflow, each example contains a section of Engineering Discussion that provides insights into some related design considerations in practice.

In these examples, for illustration purposes the network endpoint is intentionally placed slightly away from the target point so that the target point is still visible. As a result, the numerical results in the Report do not correspond to a perfect matching.

7.1 Example 1: Output Matching of a Linear Amplifier

7.1.1 Design Objective

The data sheet of a linear amplifier IC provides its output reflection coefficient S22 = 0.54∠34° at 2.45 GHz. The design objective is to synthesize a lossless matching network that matches the amplifier output to a standard 50 Ω system.

This example demonstrates an important characteristic of RF matching-network design: multiple matching networks may satisfy the same impedance-transformation requirement, but practical considerations often determine which solution is preferred.

7.1.2 Input Data

Step 1

Frequency = 2450 MHz, Rn = 50 Ω

Step 2

Enter the amplifier output reflection coefficient S22 as the source reflection coefficient ΓS. Since the objective is matching to a 50 Ω system, the load reflection coefficient is ΓL=0∠0 (angle can be any value when |Γ| = 0, but not empty). ΓL and ΓL* overlap in this case.

7.1.3 Matching Strategy

The target point lies on the left-hand side of ΓS. Referring to the Guide Overlay, the shortest matching path begins with a shunt component. However, the shortest path is not necessarily the most desirable practical solution. Additional considerations such as DC blocking, DC return paths, component count, and implementation technology may influence the final topology selection.

Three alternative matching networks are considered.

7.1.4 Network A: Minimum Component Count

Figure 7.1 shows the first matching network. The matching network consists of:

- Shunt inductor L(sh)
- Series capacitor C(s)

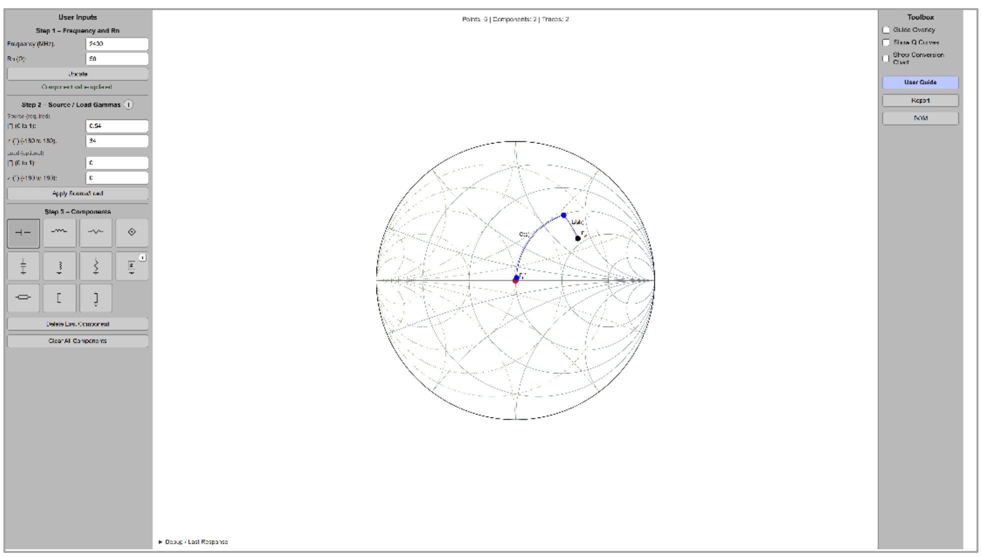

Figure 7.1 Matching for Linear Amplifier, Network A

This is the simplest matching solution for the specified impedance transformation and uses the minimum number of components.

In addition to providing the required impedance transformation, the shunt inductor creates a DC path to ground at the amplifier output. This characteristic may be useful in applications where a DC return path is required.

The report for the complete matching network is shown in Figure 7.2.

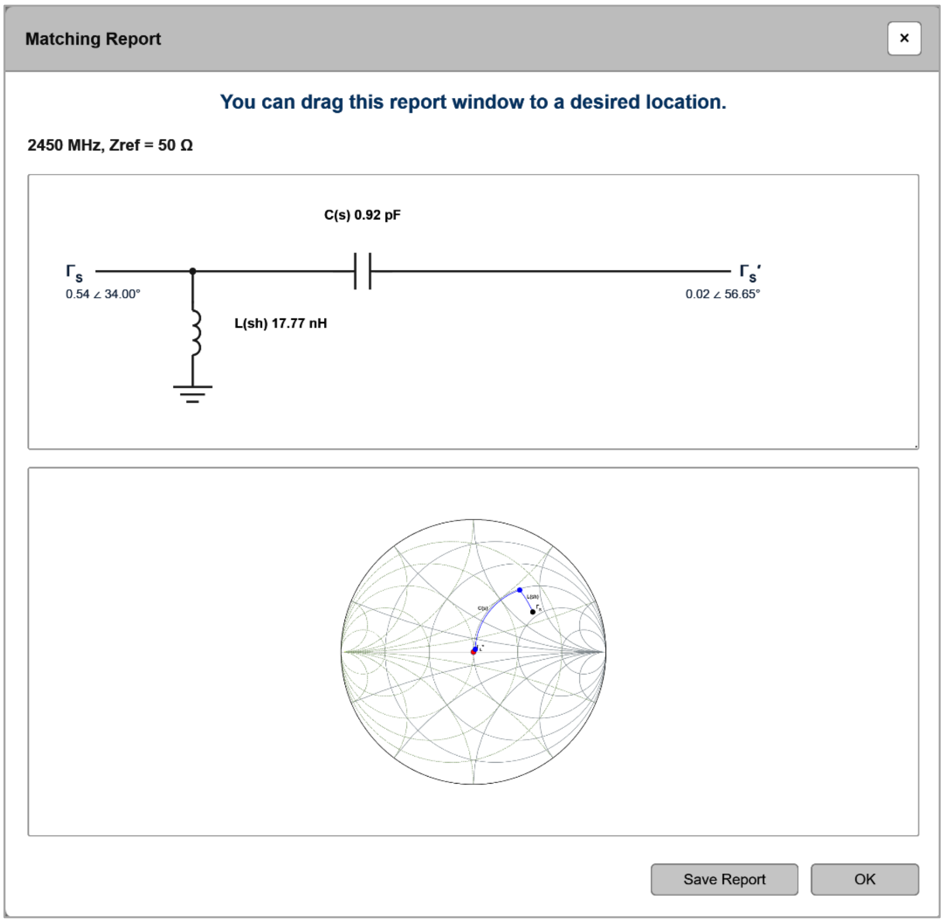

Figure 7.2 NetworkSmith Report, Linear Amplifier, Network A

Advantages

- Minimum component count
- Lowest implementation cost
- Provides a DC return path
- Compact PCB implementation

Disadvantages

- Does not provide DC blocking

7.1.5 Network B: DC Blocking Topology

Figure 7.3 shows a second matching solution.

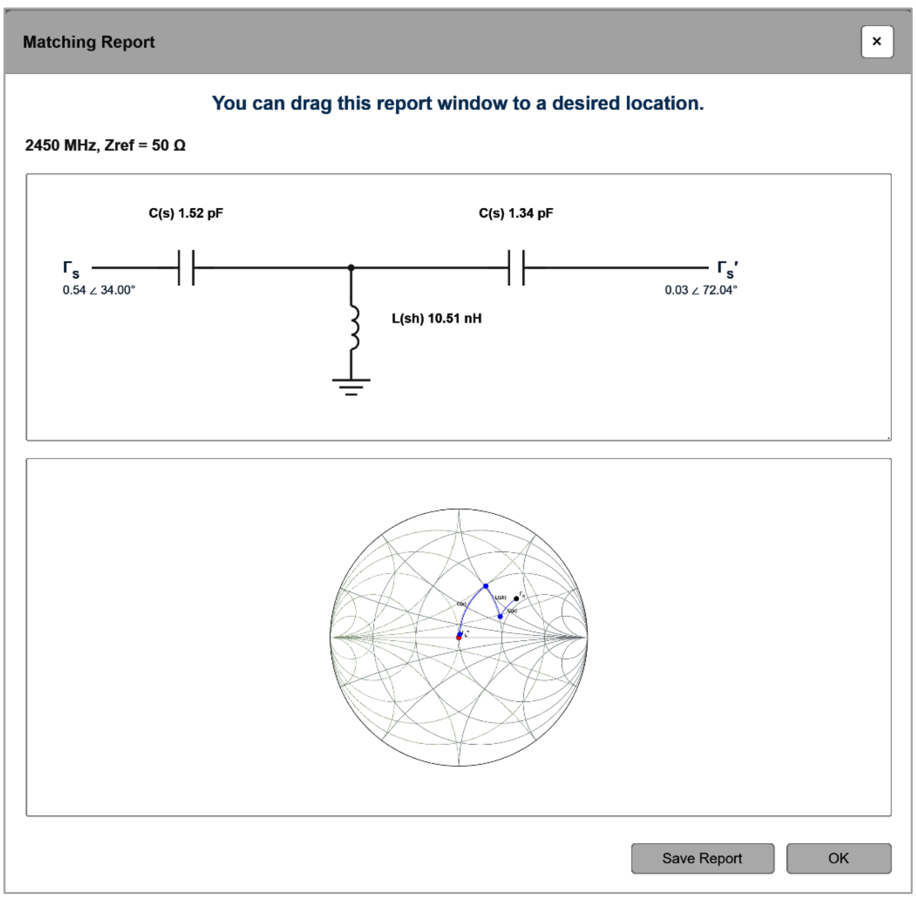

Figure 7.3 NetworkSmith Report, Linear Amplifier, Network B

In this network, a series capacitor is intentionally chosen as the first component. The capacitor provides DC blocking between the amplifier output and the following circuitry.

To complete the impedance transformation, an additional matching component is required. As a result, this solution uses more components than Network A.

Advantages

- Provides DC blocking

Disadvantages

- Higher component count
- Increased implementation cost
- Potentially greater insertion loss

7.1.6 Network C: Transmission-Line Implementation

Figure 7.4 shows a third matching solution.

As in Network B, a series capacitor is used first to provide DC blocking. However, the remaining impedance transformation is accomplished using a section of transmission line rather than a lumped inductor.

At microwave frequencies, transmission lines are often attractive alternatives to inductors because they typically exhibit lower loss, better repeatability, and higher power-handling capability.

Advantages

- Provides DC blocking
- Replaces a lumped component with a transmission line
- Potentially lower RF loss
- Good implementation choice for microwave PCB designs

Disadvantages

- Requires additional PCB area
- Physical dimensions depend on substrate properties
- Difficult to tune the length of the transmission line on a PCB because it requires cutting the trace to repositioning the series component. Section 8.2 provides an example where a section of transmission line in combination with a shunt component is used as a matching component.

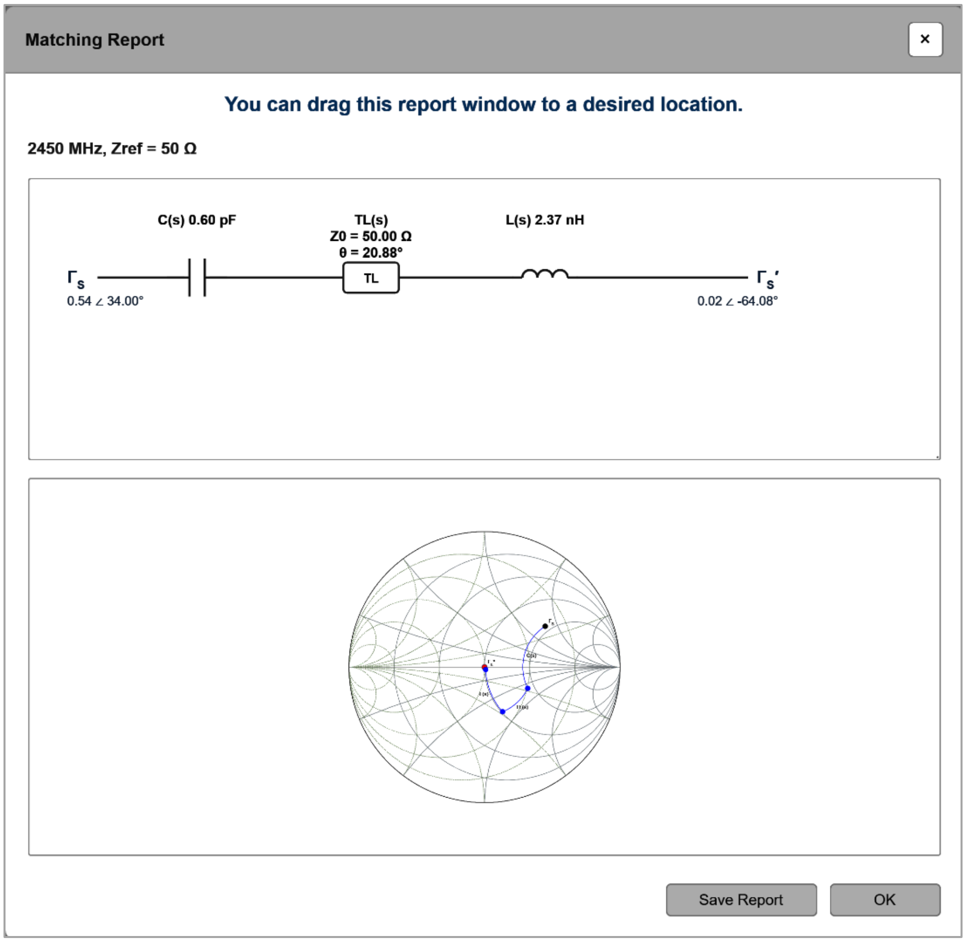

Figure 7.4 NetworkSmith Report, Linear Amplifier, Network C

7.1.7 Engineering Discussion

All three networks satisfy the same matching requirement and achieve essentially the same impedance transformation. The differences lie not in the Smith chart solution itself but in the practical characteristics of the resulting circuit.

If a DC return path is required, Network A may be preferred because the shunt inductor naturally provides a path to ground.

If DC isolation is required, Networks B and C become more attractive because the series capacitor blocks DC current. Regarding the DC blocking capacitor value, in Network B and C, its value is chosen based on the convenience for the next stage components. A more detailed discussion on the selection of DC blocking capacitor is covered in Section 8.2.

7.2 Example 2: Inter-Stage Matching Between Two Amplifiers

7.2.1 Design Objective

Two amplifier ICs are used in a cascade configuration as a driver stage and an output stage. The design objective is to synthesize an inter-stage matching network that provides the desired match between the driver output and the input of the following output stage at 1.8 GHz. The driver's output has S22 = 0.42∠67° and the input of the output stage IC has S11 = 0.54∠155°.

This example demonstrates one of the most important matching concepts used in NetworkSmith:

$$\Gamma S' = \Gamma L^*$$

The objective is not to transform ΓS directly to ΓL. Instead, the source reflection coefficient must be transformed to the conjugate of the load reflection coefficient.

7.2.2 Background

In many simple matching examples, one side of the network is a standard 50 Ω system. In inter-stage matching, however, both sides of the matching network are active-device ports. Neither side is necessarily equal to 50 Ω.

The driver output is represented by the source reflection coefficient ΓS. The input of the following amplifier stage is represented by the load reflection coefficient ΓL.

For maximum power transfer between the two stages, the transformed source reflection coefficient ΓS' should reach the conjugate of the load reflection coefficient ΓL*.

This distinction is important because new users often assume that the matching path should terminate at ΓL. In fact, ΓL identifies the load condition, while ΓL* identifies the conjugate matching target.

> IMPORTANT
>
> When both source and load reflection coefficients are entered, the matching target is ΓL* not ΓL. NetworkSmith displays both points so that the user can distinguish the physical load reflection coefficient from the conjugate matching target.

7.2.3 Input Data

Step 1

Frequency = 1800 MHz, Rn = 50 Ω

Step 2

Enter the driver output S22 as ΓS.

Enter the input S11 of the following output stage as ΓL.

When ΓL is entered, NetworkSmith automatically displays both ΓL and ΓL* on the Smith chart. The matching target is ΓL*.

7.2.4 Matching Strategy

The design task is to transform ΓS through a passive matching network until the transformed source reflection coefficient ΓS' reaches ΓL*.

Two possible inter-stage matching networks are considered. They are shown in Figure 7.5 and Figure 7.6. Both networks satisfy the same matching condition, but they differ in practical behavior, including DC characteristics, frequency response, and component count. They are summarized in Table 7.1.

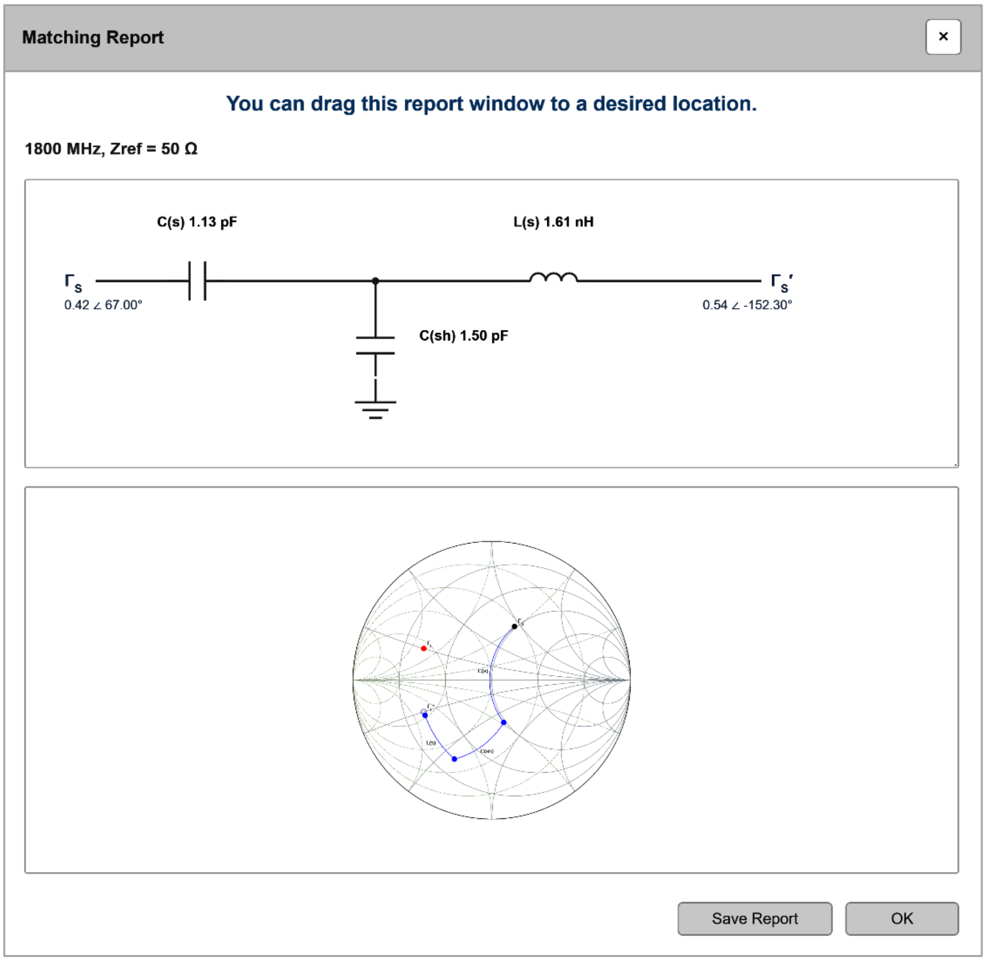

Figure 7.5 NetworkSmith Report, Inter-stage Matching, Network A

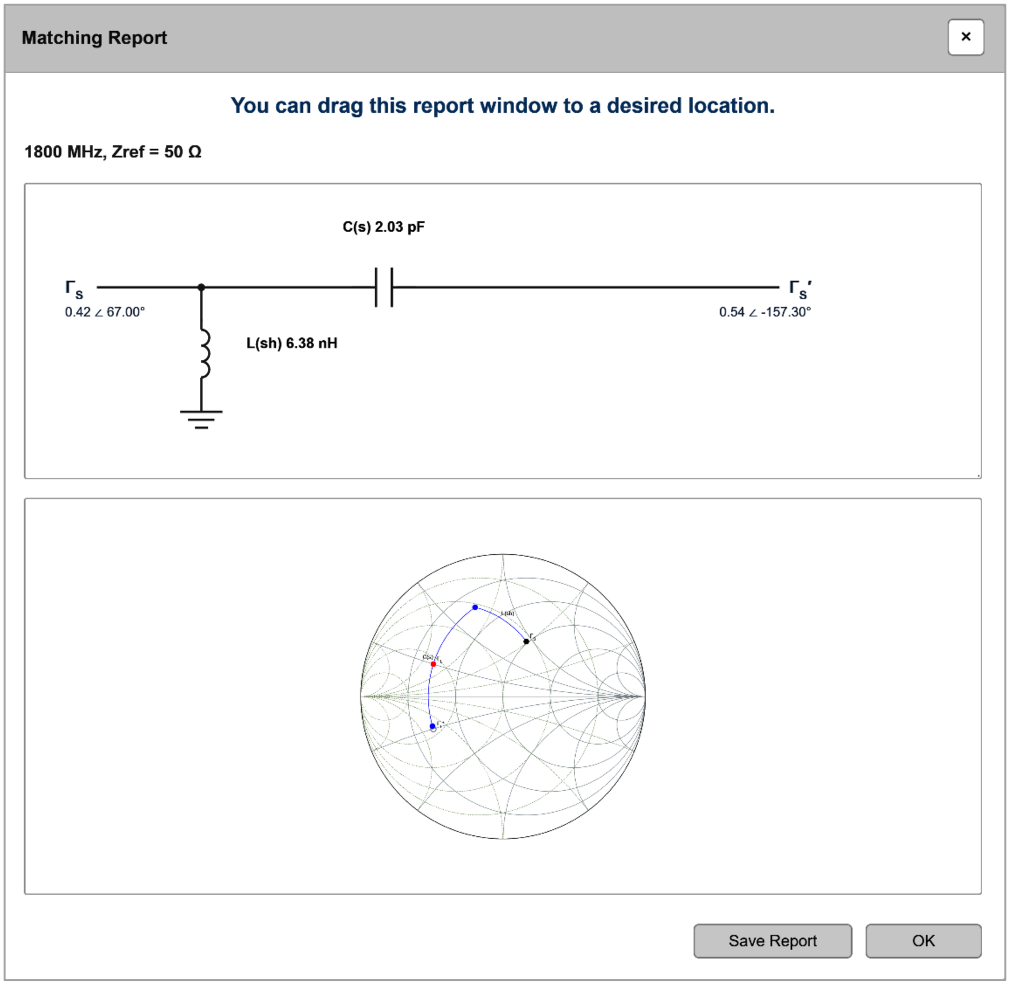

Figure 7.6 NetworkSmith Report, Inter-stage Matching, Network B

Circuit Functions	Network A	Network B
DC blocking	driver and output IC's	output IC
DC path to ground	None	driver IC
Low frequency characteristics	C(s) provides low-frequency rejection	Both L(sh) and C(s) provide low-frequency rejection
High frequency characteristics	C(sh) and L(s) provide high-frequency rejection	high-frequency pass
Component count	3	2

Table 7.1 Comparison of circuit functions for inter-stage matching networks A and B.

7.2.5 Engineering Discussion

This example illustrates that inter-stage matching is not simply a matter of connecting two reflection coefficients on the Smith chart.

The physical load reflection coefficient ΓL represents the input condition of the following amplifier stage. The matching target is its conjugate, ΓL*.

NetworkSmith displays both points to help the user distinguish between the physical load point and the required conjugate-match target.

Once the correct target is identified, multiple matching networks may satisfy the same condition. The final topology should be selected based on system-level considerations such as DC isolation, biasing, filtering response, and component count.

In this example, Networks A and B have different DC configurations as summarized in Table 7.1. As shown in the table, Network A provides moderate rejections in both low and high frequencies whereas Network B provides stronger low-frequency rejection but no high-frequency rejection.

7.3 Example 3: Output Matching of a Power RF Amplifier

7.3.1 Design Objective

An RF power transistor intended for operation in the 915 MHz ISM band is characterized by its optimum load impedance Zopt = 0.85∠-171° at the device output reference plane.

The design objective is to synthesize a matching network that transforms a standard 50 Ω system impedance to the required optimum load impedance.

This example demonstrates:

- matching to Zopt,
- the relationship between matching-network Q and bandwidth,
- the use of transmission lines in power-amplifier matching,
- conversion of electrical length to physical length.

7.3.2 Background

Unlike small-signal linear amplifiers, RF power amplifiers are often not matched simply for maximum gain.

Instead, the manufacturer may provide an optimum load impedance, Zopt, which represents the load impedance required at the transistor output reference plane to achieve a desired large-signal performance objective such as maximum output power, optimum efficiency, or a specified linearity target (such as an EVM specification). Figure 7.7 depicts the definition of Zopt in a network setting.

Depending on the data sheet or load-pull measurement format, Zopt may be provided as:

- reflection coefficient
- absolute impedance

In this example, a reflection coefficient is used. For ultra high power RF amplifiers, Zopt is often provided in absolute impedance. Section 7.5 is an example for such a case.

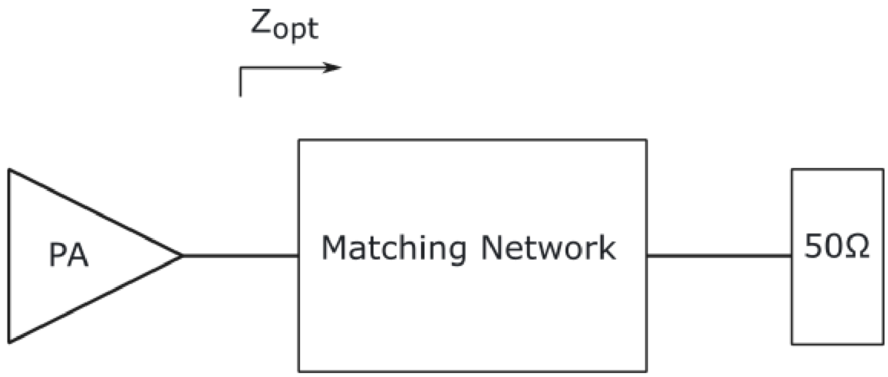

Figure 7.7 Definition of Zopt

7.3.3 Source and Target Definitions

It is clear from Figure 7.7 that the matching objective for power amplifiers is to transform the external 50 Ω environment into the required Zopt.

Thus the starting point for the matching network is 50 Ω (|ΓS| = 0) and the transformed source impedance (corresponding to ΓS') is Zopt.

> IMPORTANT
>
> Conceptually, power-amplifier matching is identical to the inter-stage matching example. In both cases, the objective is to present a desired impedance to an active device. The difference is that the target is now specified as Zopt rather than as ΓL*.

7.3.4 Input Data

Step 1

Frequency = 915 MHz Rn = 50 Ω

Step 2

Because the matching network starts from a standard 50 Ω system, ΓS = 0∠0 (angle can be any value but cannot be left empty).

There are three ways to place ΓS' on the chart as a target point, ΓL*, ΓL in Step 2 or Γ point in the component library. Γ point is used in this example, leaving ΓL empty in this step.

Step 3

First select component Γ point. In edit window enter 0.85 for magnitude and -171° for phase. This is the target point for matching network.

7.3.5 Matching Strategy

Power amplifiers often operate with relatively low optimum load impedances. As output power increases, the optimum load impedance frequently moves closer to the short-circuit region of the Smith chart. This has two important consequences:

- The matching transformation may require a relatively large impedance transformation ratio.
- The achievable bandwidth may be limited by the location of the target impedance.

For this reason, Q curves are useful in power-amplifier matching. They help visualize whether a candidate matching path passes through relatively high-Q or low-Q regions of the Smith chart.

In this example, Q curves are enabled and two alternative matching solutions are compared.

Transmission-line sections are also considered because they are often preferred in power-amplifier matching. Compared with lumped inductors, transmission lines can provide lower loss, higher power-handling capability, better repeatability, and lower cost in many high-power RF applications.

As output power increases, the optimum load impedance often becomes smaller and the RF current flowing through the matching network becomes larger. Under these conditions, lumped inductors that meet the current requirement may become relatively expensive and can introduce additional loss.

For this reason, transmission lines are frequently preferred in power-amplifier matching networks. A transmission-line section can often provide the required reactance with lower loss, lower cost, and superior power-handling capability compared with a high-power RF inductor.

7.3.6 Network A: Simple but Higher-Q Solution

Figure 7.8 shows the first matching solution.

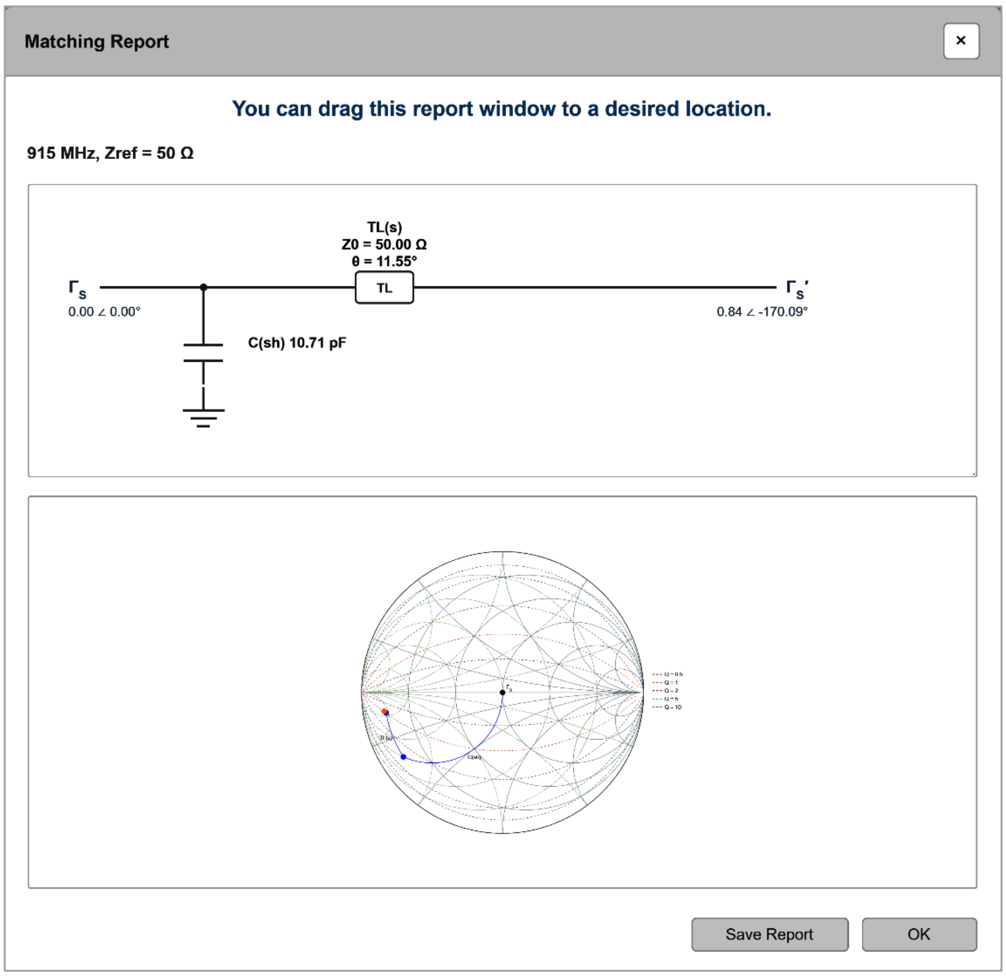

Figure 7.8 NetworkSmith Report, Power Amplifier, High Q Matching.

This network is the simplest possible transformation topology. It uses a shunt capacitor followed by a series transmission-line section.

The highest network Q value of the transformation is at the endpoint of the shunt capacitor C(sh). The component edit window shows Q = 3.08 at the point.

Advantages

- Simple topology
- Low component count
- Uses a transmission line instead of a lumped inductor
- Suitable when bandwidth requirement is modest

Disadvantages

- Higher Q
- Narrower expected bandwidth

7.3.7 Network B: Lower-Q Solution

Figure 7.9 shows a second matching solution.

This network reaches the same target impedance but follows a lower-Q matching path. The highest network Q of this network is Q=1.1 at the end of the second C(sh).

Compared with Network A, this solution may require additional transformation steps, but it can provide improved bandwidth.

Advantages

- Lower Q
- Wider expected bandwidth

Disadvantages

- May require additional components
- May occupy more PCB area
- May require additional tuning effort

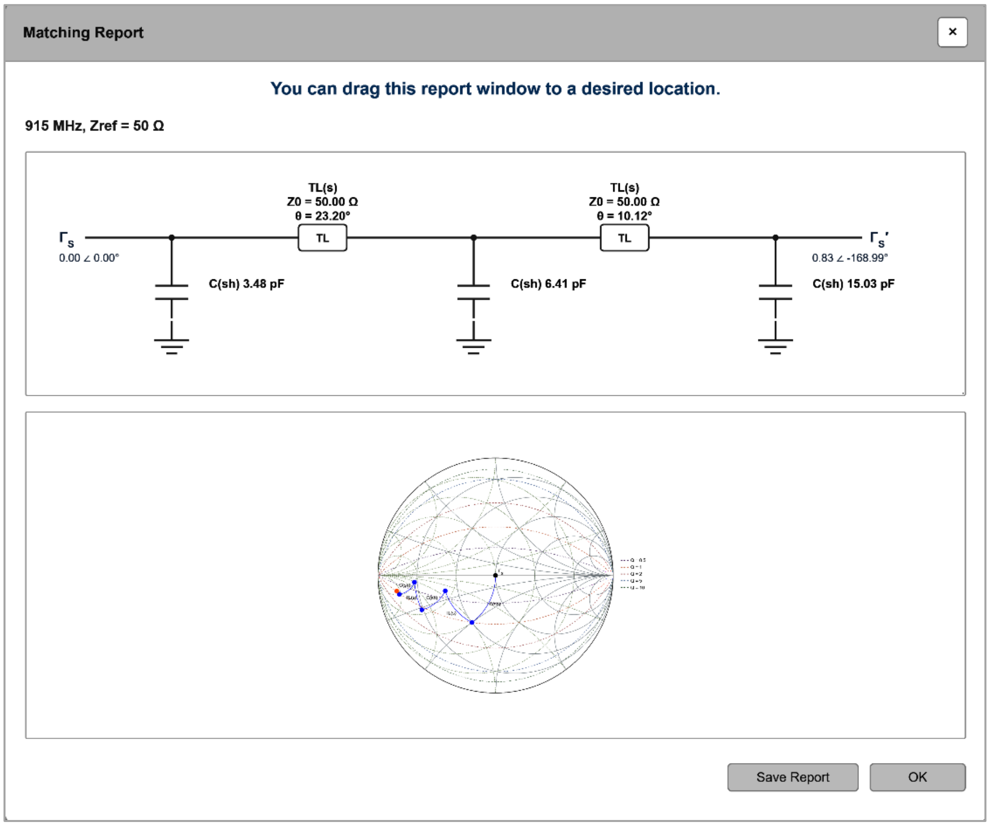

Figure 7.9 NetworkSmith Report, Power Amplifier, Lower Q Matching

7.3.8 Bandwidth and Q Discussion

The comparison between Network A and Network B illustrates a fundamental tradeoff in RF matching-network design.

Lower-Q matching paths generally provide wider bandwidth, while higher-Q matching paths generally provide narrower bandwidth.

NetworkSmith's Q-curve overlay provides a convenient visual aid for comparing alternative matching paths before committing to a topology.

An important observation is that the target impedance itself can impose a bandwidth limitation. If Zopt lies within a high-Q region of the Smith chart, the matching problem is inherently bandwidth-constrained.

In such cases, no matching topology can completely eliminate the band-width limitation imposed by the required impedance transformation.

This explains a common observation in RF power-amplifier design:

As output power increases and optimum load impedance decreases, achieving wideband matching generally becomes more difficult.

7.3.9 Converting Electrical Length to Physical Length

After the matching network has been synthesized, any transmission-line section must be implemented using a physical transmission medium such as PCB microstrip, stripline, or coaxial cable.

NetworkSmith reports transmission-line length in electrical length in degrees because impedance transformation depends directly on electrical length. Physical implementation, however, requires conversion to actual length.

Use the synthesized network in Figure 7.8 as an example, where TL(s) is

Z0 = 50 Ω, θ = 11.55° at 915 MHz.

If the line is implemented as a PCB microstrip having $\varepsilon_{\mathrm{eff}} = 2.8$

the Electrical Length Calculator can be used to convert the electrical length into physical length.

Input:

Operating Frequency = 915 MHz, Electrical Length = 11.55°, Effective Dielectric Constant = 2.8

Output:

Physical Length = 6.28 mm

The resulting value can then be used as the initial PCB layout dimension.

IMPORTANT

The Smith chart responds to electrical length rather than physical length. A transmission line designed for an electrical length at one frequency will have a different electrical length when operated at another frequency.

7.3.10 Engineering Discussion

This example illustrates several practical aspects of power-amplifier matching.

Similarly to the inter-stage matching example, the objective in this example is to present a specific impedance to an active device. The difference is that the target is now defined by the optimum load impedance Zopt provided by the manufacturer rather than by the input reflection coefficient of a second amplifier stage.

Once the correct target has been established, the path taken on the Smith chart becomes an important design consideration. Different matching paths may reach the same target while exhibiting different Q values, bandwidth characteristics, component counts, and implementation complexity.

Transmission lines are often attractive in power-amplifier matching because they can reduce lumped component count and avoid the use of expensive, lossy, high-power RF inductors.

When transmission lines are selected in a matching network, the electrical length is the component parameter used in NetworkSmith. The appropriate propagation characteristics of the intended implementation medium are required for conversion between the electrical length and physical length.

7.4 Example 4: Determining Equivalent Impedance for Shunt Z

Shunt Z component in NetworkSmith is introduced in Section 3.4. The basic concept of this component is that a complex circuit branch can be represented by an equivalent impedance Z = R + jX. This example demonstrates how the equivalent impedance (R and X) of an RCL series circuit shown in Figure 7.10 can be obtained graphically using the Smith chart rather than through direct circuit analysis. The operating

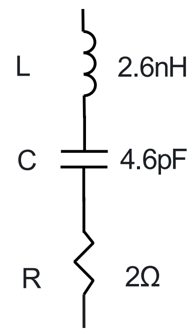

Figure 7.10 RCL Circuit Whose Impedance to be Determined

frequency is 2400 MHz. This type of circuit is often used in RF practice for a notch filter at a different frequency outside the operating frequency band.

7.4.1 Historical Perspective

Before modern circuit simulators became widely available, determining the equivalent impedance of a circuit branch often required manual circuit analysis or derivation of impedance formulas. Smith-chart techniques provided a convenient graphical alternative for many practical RF problems.

Today, equivalent impedances can be obtained easily using circuit simulators, spreadsheets, calculators, or AI-assisted tools. Consequently, the method presented in this example is no longer the most efficient way to determine R and X.

Nevertheless, the technique remains valuable because it illustrates an important Smith-chart concept: a circuit branch and a network transformation are simply two different views of the same electrical behavior. Understanding this relationship helps build intuition about how practical circuits interact with impedance transformations and matching networks.

In this context, this example is primarily an educational exercise rather than a practical RF design tool.

7.4.2 Circuit and Network Descriptions of Series and Parallel Circuits

To use the Smith chart in an analysis of a series or a parallel RLC circuit, the equivalence of the circuit and network viewpoints of them must first be established. The general rules are as follows:

For the series circuit, an equivalent network can be constructed by a sequence of Smith chart transformations of each series component starting from a short circuit;

Similarly, for the parallel circuit, it is by a sequence of Smith-chart transformations of each shunt component starting from an open circuit.

Figure 7.11 graphically demonstrates the equivalence for the case of a simple RC series circuit.

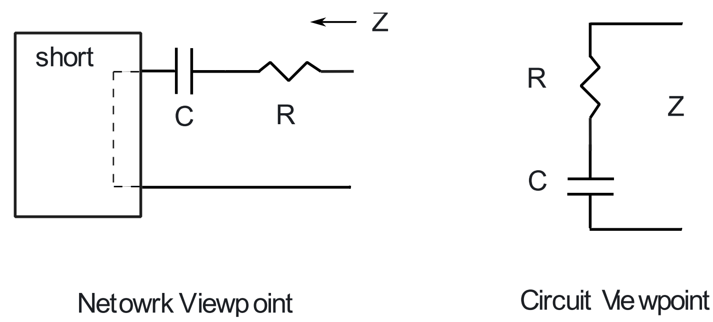

Figure 7.11 Equivalent Viewpoints of RC Series Circuit

7.4.3 NetworkSmith Procedure

Step 1

Frequency = 2400 MHz, Rn = 50 Ω

Step 2

ΓS = 1∠180° (short circuit)

Step 3

Add R(s), C(s) and L(s) using the values in Figure 7.10.

After the final component L(s) has been added, record the endpoint of the transformation from the component edit window as shown in Figure 7.12. It is |Γ| = 0.94 and θ = 127.2° .

Open the Conversion Chart and convert the final reflection coefficient into normalized impedance. Multiplying by 50 yields the final result:

Z = 2 + j25 Ω

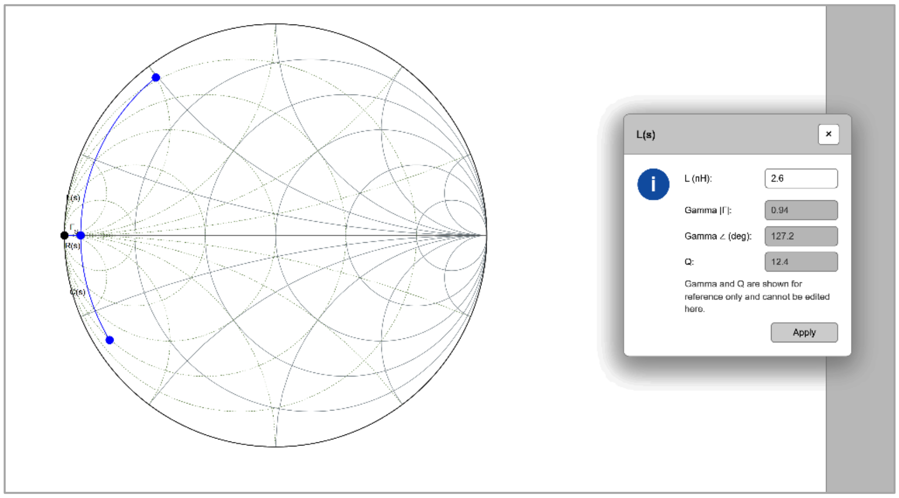

Figure 7.12 Network Representation of a RCL Circuit

7.4.4 Key Takeaways

- Any linear circuit branch can be represented by an equivalent impedance at a single frequency.
- The Shunt Z component uses this equivalent impedance representation.
- The equivalent impedance of an RLC series circuit can be obtained graphically using the Smith chart.
- A circuit branch and a network transformation are two different views of the same electrical behavior.
- Although modern software can determine equivalent impedance directly, the Smith-chart approach remains valuable for developing engineering intuition.

7.5 Example 5: Using Rn as a Visualization Tool

The Smith chart is fundamentally a chart of normalized impedance and admittance. As a result, the appearance of a network on the Smith chart depends on the selected normalization resistance Rn.

This example demonstrates how changing Rn affects the graphical representation of a network while leaving the physical circuit unchanged.

7.5.1 Why Use a Different Rn?

In the RF industry, most systems are designed for a 50 Ω environment. For this reason NetworkSmith uses 50 Ω as the default value for Rn. In practice, there are two common scenarios when a different Rn may be chosen.

- Systems using a different reference impedance, such as 75 Ω in cable TV industry.
- Impedances involved in a network transformation cluster near the short or open circuit region of the chart. Changing Rn allows users to zoom in on these regions.

In this example two Smith chart representations for Rn=50 Ω and 10 Ω are compared for a network transformation near the short circuit region.

7.5.2 Engineering background

For ultra-high power RF amplifiers (in the order of hundreds of watts), Zopt discussed in Example 3 can be in the order of 1 Ω at the die level. A direct matching network between 50 Ω and such low impedances is challenging in production due to tolerance constraints.

For packaged devices, this difficulty can be partially mitigated by a matching network that transforms Zopt at the die level to a higher value Zopt' at the package leads, as depicted in Figure 7.13. In fact, Zopt' is the device specification provided by the manufacturer. This strategy essentially breaks the matching task into two steps:

- Zopt → Zopt' by the device manufacturer and implemented inside the package,
- Zopt' to 50 Ω (or other desired impedance) by the user and implemented on PCB circuits.

Bonding wires and metal pads used for packaging structure can be conveniently incorporated in the Zopt → Zopt' matching network, as they function as series inductors and shunt capacitors respectively. Discrete components may be used for this purpose as well. In this example, an LC network is used for impedance transformation.

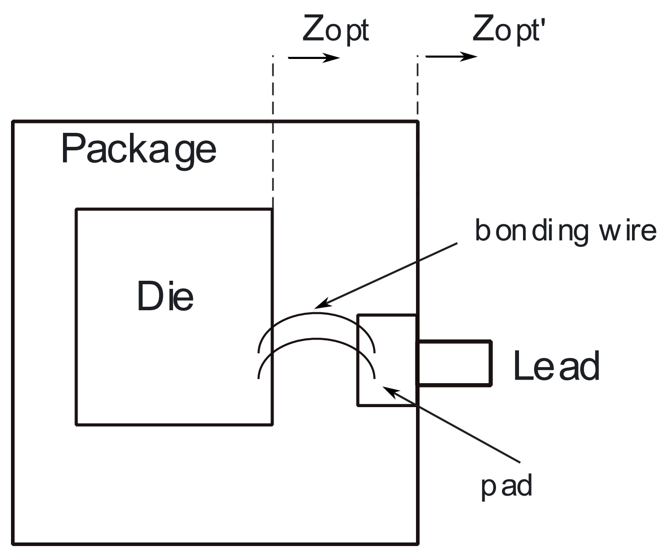

Figure 7.13 Zopt Transformation from Die to Package Lead

Unlike the preceding examples where source and load impedances are given in the reflection coefficient format, absolute impedance is used as the original data in this case. In VNA measurements on an exceptionally low or high impedance system, for improved data resolution and graphic display Rn is often chosen to be close to the impedance to be measured instead of the default setting of 50 Ω. To make data unequivocal, absolute impedance value, which is independent of Rn, is usually provided instead of the reflection coefficient. This example follows this practice. To enter the source and load data correctly in NetworkSmith, the absolute impedance values must first be normalized using the selected Rn. The resulting normalized impedances are then converted to their corresponding reflection coefficients using the Conversion Chart.

7.5.3 Design Objective

A 915 MHz high power RF transistor die has Zopt = 1 + j2.5 Ω at die. The design goal is to use an LC network to transform Zopt to a higher value Zopt' = 4 + j0 Ω at the package lead. Two Smitch chart representations for the same transformation are examined in NetworkSmith for Rn = 50 Ω and 10 Ω.

Source and Target Impedances

While the physical concept is to transform the impedance up from the die to the lead, in NetworkSmith the transformation starts from Zopt', that is, Zopt' and Zopt in Figure 7.13 correspond to ΓS and ΓS' defined in Figure 3.1 respectively. To use the software, Zopt’ and Zopt need to be first converted to the source and target reflection coefficients using the Conversion Chart. The results are summarized in the table below for Rn = 50 Ω and 10 Ω.

Rn, Ω	Zopt, Ω	Zopt’, Ω	Normalized Zopt	Normalized Zopt’	Source Γ (from Zopt’)	Target Γ (from Zopt)
50	1 + j2.5	4 +j0	0.02 + j0.05	0.08 + j0	0.85∠180°	0.96∠174°
10	1 + j2.5	4 +j0	0.1 +j0.25	0.4 + j0	0.43∠180°	0.83∠151°

Table 7.2 Source Γ and Target Γ for Rn = 50 Ω and 10 Ω

7.5.4 Case of Rn = 50 Ω

Data Input

Step 1

Frequency = 915 MHz Rn = 50 Ω

Step 2

ΓS = 0.85∠ 180,

ΓL, empty (Gamma point is used for the target point)

Step 3

Select Gamma point and set its values as |Γ|= 0.96 and ∠ = 174° according to Table 7.2

Matching Strategy

A matching network of C(sh) followed by L(s) transforms the source to the target impedance.

This network configuration, in principle, can be practically implemented in a packaged device by a metal pad at the lead (for C(sh)) and a bonding wire between the die and the lead (for L(s)), although the modern packaging technology can be much more sophisticated. Figure 7.14 is the Report for the transformation. Figure 7.15 shows a better view of the Smith chart plot for the same result (note the endpoint of the network is intentionally chosen to be slightly away from the target Γ for better illustration).

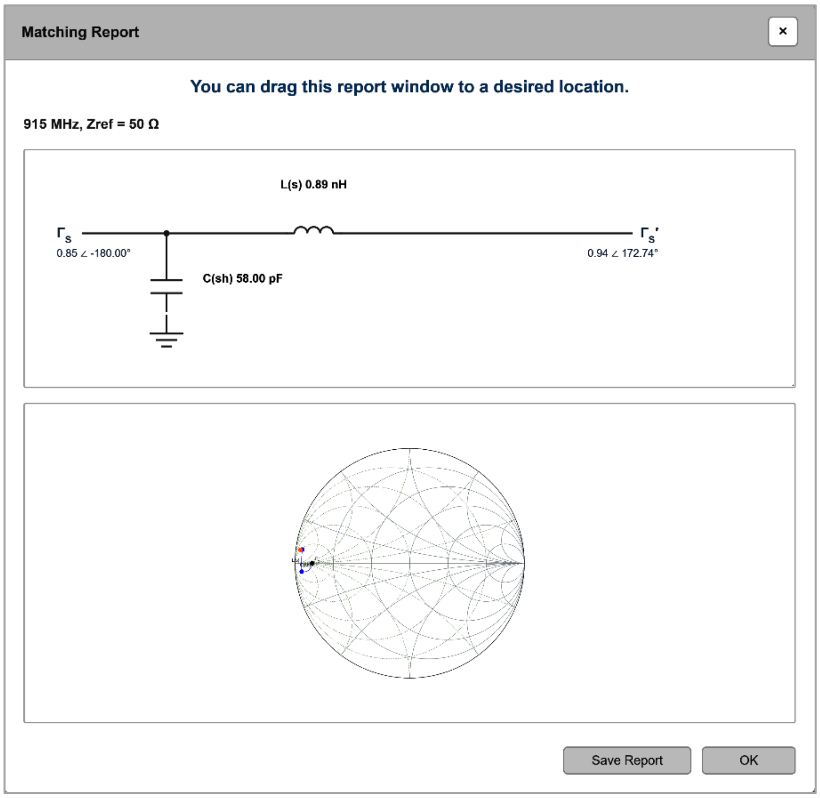

Figure 7.14 NetworkSmith Report, Rn = 50 Ω

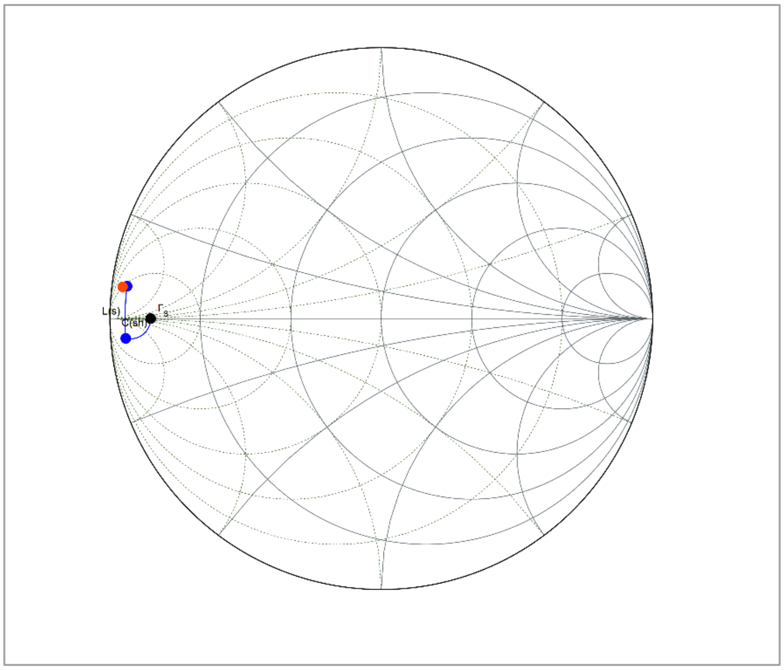

Figure 7.15 Smith Chart Plot for Rn = 50Ω

It is evident that the entire network clusters in a small region in the chosen scale.

7.5.5 Case of Rn = 10 Ω

Data Input

Change the following parameters according to Table 7.2 and leave the rest unchanged from the case of Rn = 50 Ω.

Step 1, Rn is changed to 10 Ω;

Step 2. ΓS is changed to 0.43∠180°

Step 3 Gamma point is changed to 0.83∠151°

The Smith chart plot for the same network but Rn=10 Ω is shown in Figure 7.16. It is clear the reduced Rn has rescaled the chart and produced a zoom-in view. In this view the seemingly small difference between the endpoint of the network and the target point in Figure 7.15 becomes clearly noticeable.

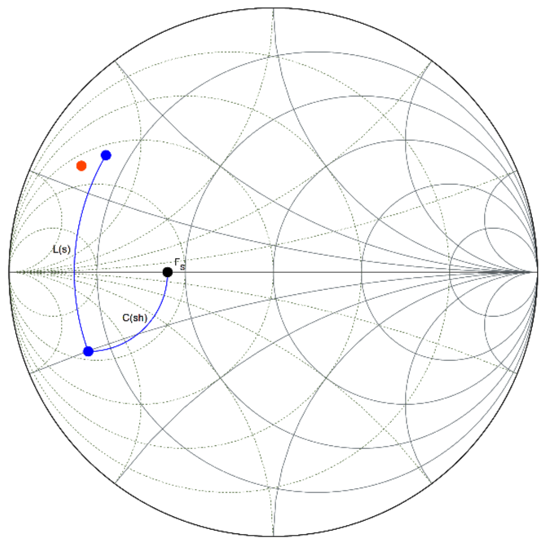

Figure 7.16 Smith chart Plot for Rn = 10Ω

7.5.6 Observed Changes

Several changes become immediately visible:

- The source and load reflection coefficients move to new locations.
- The network transformation path changes.
- The impedance and admittance coordinates are renormalized.
- The overall geometry of the matching trajectory changes.

Although the Smith chart display appears different, the actual component values remain unchanged.

What Does Not Change by Changing Rn:

- Component values
- Physical transmission-line dimensions
- Circuit topology
- Actual impedances within the circuit

Only the mathematical reference used to normalize the network has changed.

The physical circuit remains identical.

7.5.7 Engineering Discussion

Changing Rn should be viewed as a visualization tool rather than a design operation.

The underlying circuit does not change. Instead, the Smith chart is rescaled to provide a different perspective on the same network.

This capability is particularly useful when working with impedances that are far from the standard system impedance. By choosing an appropriate normalization resistance, the designer can often obtain a zoom-in view of the matching problem.

NetworkSmith automatically performs the required renormalization internally while continuing to display component values in their actual physical units.

8 Practical Design Notes for PCB Implementation of Matching Networks

In RF engineering practice, a Smith-chart based workflow such as those outlined in this document proves to be most effective in PCB circuit designs, particularly when it is used in combination with bench tuning. This final section contains additional design notes and observations that may be useful when implementing RF matching networks on PCBs.

8.1 PCB Bench Tuning and NetworkSmith as a Practical Aid

Necessity of PCB Bench Tuning

In general, a formula-based RF design tool such as NetworkSmith is insufficient to produce a circuit that performs perfectly in a practical implementation. As operating frequency increases, various parasitic effects associated with components, PCB traces, solder pads, vias, packaging, and manufacturing tolerances become increasingly significant.

For RF integrated-circuit development, where fabrication cost is extremely high, substantial effort is often devoted to developing accurate device and circuit models in order to minimize design iterations.

For PCB-based RF circuits, however, fabrication cost is generally manageable and does not always justify the effort required to develop highly detailed models. Instead, a common engineering practice is to begin with a reasonable design obtained from simulation, calculation, or prior experience and then optimize performance through bench tuning.

NetworkSmith in Bench Tuning

In the context of matching-network design, bench tuning is essentially a process of moving the network endpoint ΓS' around the Smith chart by experimentally adjusting component values and observing circuit performance.

One challenge of this approach is determining whether the tuning process has adequately explored the region around the optimum impedance.

NetworkSmith can help reduce this uncertainty. Although the exact component values predicted by the software may not produce the absolute optimum performance on a specific PCB implementation, the software generally provides accurate predictions of the direction and magnitude of impedance movement caused by component adjustments.

This allows users to explore nearby gamma points systematically rather than randomly changing component values. By observing the movement of ΓS′ in response to adjustments of individual components, the user can efficiently search for an optimum matching condition.

As an example, in the transmission-line matching network presented in Figure 8.1,

- Adjusting the electrical length of a series transmission line primarily moves ΓS′ along the vertical direction on the Smith chart.
- Adjusting a shunt capacitor, together with a corresponding transmission-line adjustment, can move ΓS′ in the horizontal direction.
- Repeating such adjustments allows the user to systematically investigate the neighborhood around an optimum matching point.

In this way, NetworkSmith serves not only as a synthesis tool but also as a practical aid for structured bench tuning.

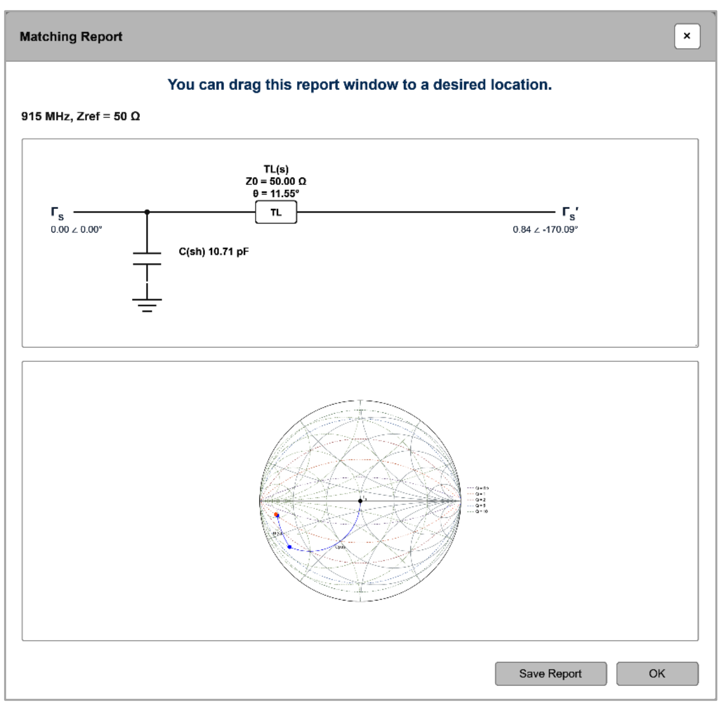

Figure 8.1 Matching Network for an RF PA (reproduced from Figure 7.8)

8.2 Practical PCB Implementation of Matching Networks

Figure 8.2 is a PCB layout commonly used in PCB implementation of RF PA matching networks such as the one shown in Figure 8.1. This subsection uses it as an example to explain how some techniques in PCB design and component selection may be employed to ease bench tuning in practice.

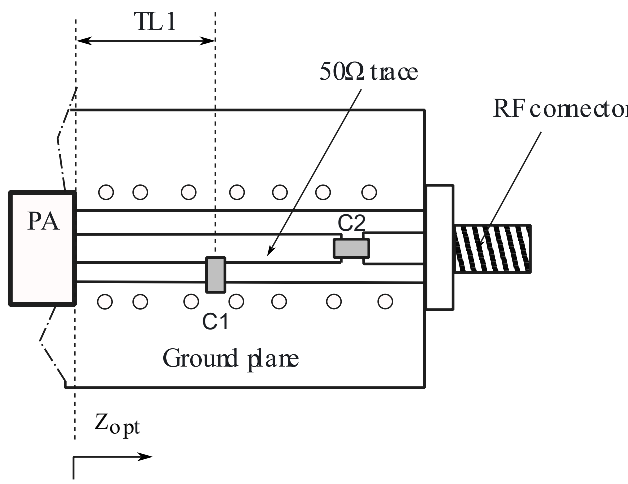

Figure 8.2 PCB implementation for the Network in Figure 8.1

Series Transmission-Line Sections

A series transmission-line matching section is particularly convenient for bench tuning when it is connected to a shunt component at one or both ends because its electrical length can then be adjusted directly on a prototype PCB by moving the shunt component along the transmission line. For example, moving C1 in Figure 8.2 to the left effectively shortens TL1.

This is in contrast to the situation of a transmission-line that is sandwiched between two series components such as the example in Figure 7.4.

For this reason, prototype RF boards are sometimes fabricated without solder mask in the tuning area so that component locations can be modified easily during laboratory evaluation.

Use of 50 Ω Interconnects

From a purely theoretical standpoint, there is no inherent advantage in using a 50 Ω transmission line as a matching element. Depending on the design requirements, other characteristic impedances may be advantageous or unavoidable.

Nevertheless, using 50 Ω traces between the RF connector and the matching network is often convenient because it moves the matching-network reference plane from the RF connector to the first matching component (C2 in this case).

This simplifies matching-network design because it removes the trace between the RF connector and C2 from the matching network.

DC Blocking Capacitor Selection

In many RF circuits, particularly power amplifiers, an external DC blocking capacitor is required. The placement and value of this capacitor deserve careful consideration because they influence both circuit functionality and matching-network behavior.

Placement

A common practice is to place the DC blocking capacitor near the RF connector so that the entire RF circuit is isolated from external DC voltages.

While electrically convenient, this arrangement introduces an additional series reactance into the matching network. As a result, the actual matching network on the PCB begins at C2 rather than at C1 suggested by the network synthesis. The blocking capacitor and the transmission line between it and the first matching component (between C1 and C2 in Figure 8.2) become part of the overall matching structure.

Effect of Series Resonance Frequency (SRF)

For an ideal capacitor, choosing a sufficiently large capacitance would make the component nearly transparent at RF frequencies.

Real capacitors, however, exhibit parasitic inductance. As a result, every capacitor has a series resonance frequency (SRF) at which its capacitive reactance and parasitic inductive reactance cancel.

Above the SRF, a capacitor behaves inductively rather than capacitively.

Therefore, selecting an arbitrarily large capacitance is not always desirable. A large-value capacitor generally exhibits a lower SRF and may behave poorly at the operating frequency.

Many component manufacturers publish SRF data. A common engineering practice is to choose a capacitor whose SRF is near the operating frequency. Under this condition, the residual reactance is minimized and the capacitor introduces minimal disturbance to the matching network.

When this assumption is valid, TL1 and C1 in the PCB implementation of Figure 8.2 correspond to TL(s) and C(sh) in the schematic of Figure 8.1 respectively. Once this relationship is established, the insight of the network behavior gained from NetworkSmith analysis in Section 8.1 can be applied as an aid to practical bench tuning.

References

(1) Smith, P.H. *Electronic Applications of the Smith Chart*, Noble Publishing, 1995.

(2) Dong, M., *RF Circuits and Applications for Practicing Engineers*, Artech House, 2021.

(3) Gonzalez, G., *Microwave Transistor Amplifiers Analysis and Design*, Prentice Hall, 1997.

Software Limitations and Engineering Cautions

NetworkSmith is intended as a practical matching-network design and visualization tool. The software uses idealized component models and therefore does not include many effects encountered in real implementations.

Users should be aware of the following limitations:

- Component parasitics are not modeled.
- Component quality factor (Q) is not modeled.
- PCB discontinuities, vias, and layout parasitics are not modeled.
- Manufacturing tolerances are not modeled.
- Active-device nonlinear behavior is not modeled.
- Thermal effects are not modeled.

Consequently, NetworkSmith should be viewed as a tool for network synthesis, visualization, design exploration, and bench-tuning support rather than a substitute for full-wave electromagnetic simulation or laboratory measurement.

Final circuit performance should always be verified through measurement and, when appropriate, more detailed simulation methods.