

# Globally Optimal Matching Networks With Lossy Passives and Efficiency Bounds

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**Abstract**—Impedance transformation is one of the central concepts in high-frequency circuits and systems and is used ubiquitously for optimal power matching, noise matching, and high-efficiency power delivery to the antennas by power amplifiers. The matching network can be generally expressed as a path on the Smith chart and given the load and source impedances, there are theoretically infinite ways to achieve the transformation. When losses are included, each path will encounter a different loss, and currently, no comprehensive theory exist for finding the most optimal matching network. Furthermore, the networks will also provide different bandwidths of operation. Due to the matching network losses, it is often not optimal to force conjugate matching for maximizing end-to-end power transfer efficiency. In this paper, we provide a method toward finding 1) the globally most efficient path between two arbitrary impedances with lossy passives; 2) given the source and the load impedances, the optimal (typically non-conjugate) impedance to match and the highest efficiency path to reach the impedance; and 3) upper bounds on achievable efficiencies under the various scenarios. This paper also proposes ways to combine this method with nonlinear load-pull simulations for optimal combiner and matching network for integrated power amplifiers. This analysis creates interesting ways to maximize efficiency and bandwidths simultaneously and the paper also discusses this joint optimization. To the best of our knowledge, this is the first comprehensive analysis of globally optimal impedance transformation networks between arbitrary impedances with lossy passives.

**Index Terms**—RF, mm-wave, impedance matching, lossy passives, noise matching, smith chart, quality factors, power amplifier, LNA.

## I. INTRODUCTION

**I**MPEDANCE matching is ubiquitously employed in RF circuits and systems for a range of applications ranging from power matching for small signal amplifiers and power amplifiers to filter synthesis and noise matching for LNAs [1]–[12]. Typically, the impedance matching network is composed of passive devices (such as inductors, capacitors, transmission lines, transformers) to transform a reference or load impedance to the optimal impedance at the output of a source for maximal power transfer at the designed frequency. It is well known that for maximal power transfer with lossless passives, the two-port matching network needs to transform the load impedance into the complex conjugate of the source impedance at the

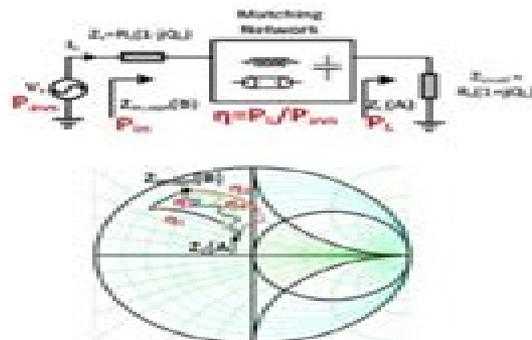


Fig. 1. Optimally efficient impedance transformation network to maximize power transfer efficiency  $\eta = \frac{P_L}{P_{in}}$  with lossy passives. Graphically, this is equivalent to finding the lowest loss path from  $Z_s(A)$  to  $Z_{in,opt}(B)$  among the infinite possible paths and determining the optimal value of  $Z_{in,opt}$ . In general,  $Z_{in,opt} \neq Z_s^*$ .

designed frequency. This does not hold when losses of the network are taken into consideration. Therefore, the choice of the path on the Smith Chart which uniquely represents the matching network becomes critical to maximizing efficiency. This is true for both small-signal and large-signal amplifiers. Additionally, when losses are considered, it may not be optimal to reach the conjugate or the load-pull impedance for maximization of net efficiency. Traditionally, analysis of matching network efficiency has been carried for a sub-class of networks with known topologies [1], [15], [16] or multi-dimensional optimization methods have been used to synthesize impedance transformation networks with minimum loss [17], [18]. However such a procedure is often ad-hoc, the number of elements in the network is often a guess estimate and to the best of the authors' knowledge there has been no systematic study of the globally optimum minimum loss path between two points on a Smith chart [19].

The contributions of the paper are as follows

- As illustrated in Fig. 1, we find the optimal matching network for maximum power transfer efficiency between two arbitrary impedances with lossy passives. If the network can be described by a path on the Smith Chart, we propose a method that designates the lowest loss path on the Smith Chart between two given impedance.
- In addition, we also seek to find the optimal impedance to match to ( $Z_{in,opt}(B)$ ) for the lossy passives, which is

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# Globally Optimal Design

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