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System identification of microwave filters from multiplexers by rational interpolation☆

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ABSTRACT

Microwave multiplexers are multi-port structures composed of several two-port filters connected to a common junction. This paper addresses the de-embedding problem, in which the goal is to determine the filtering components given the measured scattering parameters of the overall multiplexer at several frequencies. Due to structural properties, the transmission zeros of the filters play a crucial role in this problem, and, consequently, in our approach. We propose a system identification algorithm for deriving a rational model of the filters' scattering matrix. The approach is based on rational interpolation with derivative constraints, with the interpolation conditions being located precisely at the filters' transmission zeros.

1. Introduction and motivation

Microwave multiplexers are present in nearly every transmission or reception unit of communication systems. They are composed of two-port filter structures (Fig. 1) connected to a common support, referred to as a junction (Fig. 3). Consequently, the multiplexer is a multi-port system with a large number of inputs and outputs. The practical realization of such devices is difficult because the computer simulated characteristics of the multiplexer, previously obtained from the design specifications, cannot be manufactured exactly. Therefore, filters are equipped with screws which can be tuned in the final realization phase to match the desired specifications. Tuning is a time consuming operation for microwave engineers in terms of person-hours, so algorithms aimed at solving this problem would offer great benefits. While tuning a multiplexer, it is often not possible to detach the filters because the multiplexer has been manufactured in one piece, or because the repeated plugging and unplugging may lead to defects. Thus, developing tuning techniques for multiplexers which rely solely on external measurements, in particular on frequency domain scattering measurements, is an important research problem.

We refer to the problem of determining a rational description of the filters composing a multiplexer as the de-embedding problem and its statement is the following: Given multiport scattering measurements of the multi-port multiplexer structure for several frequencies, we wish to derive the scattering matrix of each reciprocal filter composing the structure.

Methods currently available for de-embedding rely on neural networks (Michalski, 2010) or on the minimization of a tuning criterion (Yu & Tang, 2003). However, these gradient algorithms might suffer from the issue of reaching a local minimum of their tuning criterion rather than the desired global one. Moreover, these optimization-based techniques give no real insight into the internal physical state of the multiplexer.

Our approach is based on a two-step procedure. First, a rational continuous-time stable model is built from the measured multiplexer's scattering parameters using the reader's preferred frequency domain system identification method for MIMO systems (a general method as Lefteriu & Antoulas, 2010 or a more dedicated one Olivi, Seyfert, & Marmorat, 2013). Structural properties make filters' transmission zeros play a key role in the algorithm: the values of the filters' reflection coefficients and a number of their derivatives evaluated at the (finite or infinite) transmission zeros can be decrypted from those of the multiplexer.

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This leads to a multipoint rational interpolation problem with derivative constraints, where the interpolation conditions are located at the filters' transmission zeros. Hence, the second step of the proposed strategy yields a rational representation of the scattering parameter matrices of the filters by solving this interpolation problem for each filter successively. Due to the inherent indetermination, filters are recovered up to a constant matrix (as shown in Section 5.4), which, in practice, corresponds to the resonator closest to the junction (see Seyfert, Oldoni, Olivi, Lefteriu, & Pacaud, 2015).

Previous publications on this topic (Lefteriu, Oldoni, Olivi, & Seyfert, 2013; Seyfert, Oldoni, Olivi, Lefteriu, & Pacaud, 2014; Seyfert et al., 2015) address the same problem in a similar way, by regarding de-embedding as an interpolation problem, but develop different techniques. Lefteriu et al. (2013) presents a method based on a recursive Schur algorithm for the ideal case where filters are assumed lossless and measurements are exact. Subsequent papers (Seyfert et al., 2014, 2015) propose an alternative solution to the same Padé rational interpolation problem by determining the coefficients of two pairs of polynomials from an overdetermined linear system. The obtained polynomials yielded the rational scattering matrices of each filter and the approach was validated on real world examples (e.g., a manifold diplexer manufactured in one piece). In the present paper, instead, we propose a linear fractional representation of the solutions to the associated interpolation problem. This provides insight into the theoretic foundations of the method, a unified framework to compare the ideal and practical cases and last, but not least, allows for easy state-space computations.

The paper is organized as follows. Section 2 describes general concepts related to the problem we address. Section 3 shows that, due to structural properties, the de-embedding problem can be regarded as an interpolation problem with derivative constraints at the filters' transmission zeros. We show how to determine the transmission zeros and the interpolation values in Section 4, while Section 5 provides all solutions to this rational interpolation problem. Section 6 shows that the proposed algorithm applied to exact data obtained from lossless devices translates to Nevanlinna–Pick interpolation. Lastly, Section 7 validates the method on several numerical examples.

2. Background

This section starts by introducing notation. Lowercase boldface letters (e.g., $\mathbf{v}$) denote column vectors, uppercase boldface letters (e.g., $\mathbf{A}$) denote matrices, while non-boldface letters denote scalar quantities. If $\mathbf{M}$ is a complex matrix, $\mathbf{M}^T$ is its transpose and $\mathbf{M}^*$ is its complex conjugate transpose; $\mathbf{A} \geq \mathbf{B}$ (resp. $\mathbf{A} > \mathbf{B}$) means that the matrix $\mathbf{A} - \mathbf{B}$ is positive semidefinite (resp. definite). If $\mathbf{F}(s)$ is a matrix valued function, then $\mathbf{F}^*(s) = \mathbf{F}(-\bar{s})^*$ is the para-Hermitian conjugate of $\mathbf{F}(s)$, where $\bar{s}$ denotes the complex conjugate of s. Last, i denotes the unit imaginary number $\mathrm{i} = \sqrt{-1}$ and $\mathbb{C}^+$ denotes the open right-half of the complex plane.

2.1. What is a filter?

The term "filter" refers to a 2-port microwave device with a prescribed linear time invariant (LTI) response (Figs. 1 and 2). *Scattering parameters (S-parameters)* relate the power of outgoing (reflected) waves to incoming (incident) waves. For a 2-port network (as in Fig. 2), we have that

$$\begin{bmatrix} a(\mathrm{i}\omega) \\ b'(\mathrm{i}\omega) \end{bmatrix} = \mathbf{S}(\mathrm{i}\omega) \begin{bmatrix} b(\mathrm{i}\omega) \\ a'(\mathrm{i}\omega) \end{bmatrix}, \tag{1}$$

where $\omega = 2\pi f$, with f being the excitation frequency, a', b, the incident waves and a, b', the reflected waves. Our notation

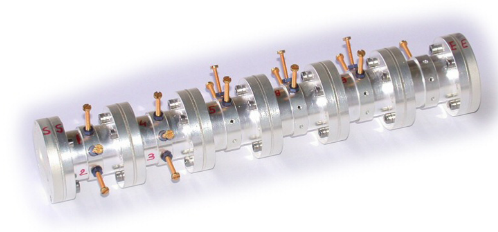

Fig. 1. A microwave filter.

Fig. 2. Filtering device with incoming and outgoing power waves.

differs from the standard of using a, a' for incoming and b, b' for outgoing waves. When connecting filters to a common junction and regarding the network as a multiplexer, the waves at the common ports are incoming for the junction (hence they could be denoted by a) and outgoing for the filter (hence denoted by b). To avoid double notations and keep the notation simple, we define the waves as in Fig. 2.

The scattering matrix is a proper rational matrix function and, for reciprocal filters, it is symmetric (Anderson & Vongpanitlerd, 1973, Th. 2.8.1):

$$\mathbf{S}(s) = \frac{1}{q(s)} \begin{bmatrix} p_1(s) & t(s) \\ t(s) & p_2(s) \end{bmatrix}, \tag{2}$$

where $p_1(s)$, $p_2(s)$, $q(s)$ and $t(s)$ are polynomials. The order n (or McMillan degree) of the filter is given by the degree of $q(s)$, provided that the condition q divides $p_1p_2 - t^2$ is satisfied (Anderson & Vongpanitlerd, 1973). The roots of $t(s)$ are referred to as the *finite transmission zeros* of the filter. There are n transmission zeros, with the difference between n and the degree of $t(s)$ yielding the number of transmission zeros at infinity. In practice, at least one transmission zero at infinity is assumed, so that $t(s)$ is of degree smaller or equal to $n - 1$.

Transfer scattering or chain parameters (T-parameters). relate waves at one port to waves at the opposite port:

$$\begin{bmatrix} b' \\ a' \end{bmatrix} = \mathbf{T} \begin{bmatrix} b \\ a \end{bmatrix}. \tag{3}$$

T-parameters cannot be measured directly, unlike S-parameters, but they can be easily obtained from S-parameters (see Proposition 2.1). However, the representation in terms of T-parameters is especially useful when cascading devices, as the T-parameters of the interconnection are obtained by multiplying the T-parameters of the components.

Proposition 2.1. *The filter's scattering and transfer scattering matrices defined by (1) and (3) are related by:*

$$\mathbf{T}(s) = \begin{bmatrix} S_{21}(s) - \dfrac{S_{11}(s)S_{22}(s)}{S_{12}(s)} & \dfrac{S_{22}(s)}{S_{12}(s)} \\ -\dfrac{S_{11}(s)}{S_{12}(s)} & \dfrac{1}{S_{12}(s)} \end{bmatrix}, \tag{4}$$

which is known as the Ginzburg transform. $\mathbf{T}(s)$ *is defined when* $S_{12}(s)$ *is non-zero. The filter is reciprocal if and only if* $\det(\mathbf{T}(s)) = 1$.

2.2. Description of a multiplexer

We consider a multiplexer composed of an $N+1$-port junction and N filtering devices (Figs. 3 and 4).