Hindawi
International Journal of RF and Microwave Computer-Aided Engineering
Volume 2023, Article ID 8302207, 8 pages
https://doi.org/10.1155/2023/8302207

Research Article

Applied Cavity Perturbation Used for Frequency Identification of Channel Ports in Manifold-Coupled Multiplexers

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Received 12 January 2023; Revised 10 November 2023; Accepted 13 November 2023; Published 28 November 2023

Academic Editor: Anna Pietrenko-Dabrowska

We investigate a practical technique for deembedding the channel filter S-parameters of manifold-coupled multiplexers (MUXs), without detaching filters from the manifold. The method is applicable for MUXs with an arbitrary number of channels and can be used for the device regardless of its bandwidth, guard band, or loss of filters. We reconfigure the N-port MUX to two simpler networks cascaded to each other. We assume that the manifold response is unknown and use the idea of applied perturbation on the channel filter, and then by comparing the response of the overall cascaded network, before and after the perturbation, we approximate the channel port response. The technique is useful in fast detecting the unexpectedly detuned channels or likely faults in the device without unnecessary plugging/unplugging; it is also useful in roughly tuning of the channel filers at the early stage of MUX tuning. The technique can be easily traced by the telecommunication community.

1. Introduction

Manifold-coupled multiplexers (MUXs) are critical components of satellite communication payloads which, despite their simple configuration, render reliable and compact structure. These devices are composed of N-channel filters connected to a common junction. The manifold is fundamentally an almost lossless line with no directional element in its connecting ports to the channel filters. This feature though provides simplicity of the structure and leads to complexity in both its design and tuning processes [1].

Filter tuning is an essential postproduction process in manifold MUXs; the channel filters are conventionally equipped with tuning screws which can be adjusted to reach optimal response. In satellite components, severe limiting in/out of band margins are applied to the operating frequency range, which makes tuning a time-consuming task. Despite this, for filters as individual components, there exist well-known parameter extraction techniques such as H_2 approximation [2] or vector fitting [3, 4] in the frequency domain for the purpose of tuning.

The design and tuning of the manifold-coupled multiplexers conventionally entail a comprehensive full wave analysis in the RF domain, and in this regard, there is a clear discrepancy between these structures and the optical multiplexing device/techniques proposed for the satellite wireless communication [5]; in the latter, which provides THz channels and compact architecture, wavelength [6] or spacial multiplexing schemes [7] may be used, depending of the application.

While many computer-aided techniques have been proposed for tuning filters in the literature [8–11], only a few methods are developed for MUXs for which there is no need to detach connected filters. The hurdle is clear; tuning a multiport network (i.e., a MUX) has much more theoretical and practical complexity than a simple two-port filter. Although, it is initially preferred to shrink the problem (i.e., MUX tuning) to individually tuning the connected filters, for practically important reasons, it is strongly recommended to tune MUXs without detaching their components. The reason is lucid; assuming that plugging/unplugging of filters is feasible, then one has to repeat this task many times during the tuning stage, and these tests might probably damage intermediate connections. On the other side, deembedding a MUX without detaching its components is expected to be helpful in diagnosing the defects that occurred in the structure during the manufacturing stage [12]. Moreover, developing a deembedding technique for MUX is advantageous in particular for configurations manufactured in one piece; thereby, detaching the channel filters is impossible.

To deembed a MUX without detaching its filters, a conceivable method is to directly optimize characteristic polynomials of the MUX and find the optimal matching to their measured scattering parameters. However, this approach is substantially time-consuming and costly in terms of computer processors required [13]. As another approach, deembedding is described as a rational approximation problem. In [12, 14], the manifold MUX is modeled as a cascaded system in which a filter—that is planned to be tuned—is terminated in a load composed of manifold and remaining filters in a short circuit form. The deembedding problem is then expressed in a Pade interpolation form for which the interpolation values are determinable functions of the transmission zeros and their associated derivatives. With this, the filters' response is recovered up to their adjacent cavity to the load. It remains, however, some degree of uncertainty in the computed response. Beside this, stability is not also guaranteed in the technique. Despite this, the approach does not require prior knowledge of the frequency response in the manifold. Techniques based on neural networks are another approaches that are mainly proposed for tuning filters [15]. Although response convergence in those techniques is proved, they give no physical understanding of tuning [12, 15]. In addition to these, several deembedding techniques are proposed solely for specific MUXs such as diplexers [16, 17], and in some others, deembedding of MUX is subject to configurations with lossless filters, which hardly occurs in practice [13].

In this study, we follow our recent work on frequency identification of multiplexers (see [18]) and propose a practical technique to deembed the frequency parameters of channel ports of manifold-coupled MUXs for the purpose of tuning. The technique is based on simplifying the complex N-port system of MUX to a two-port network, before deembedding. In the proposed approach, there is no prior knowledge of S-parameters in the manifold. We, then, apply a perturbation in the frequency response of the interested filter, and by analyzing the measured responses of the overall two-port network, before and after the perturbations, S-parameter s_{22} of the interested filter is extracted. Beside this, a simple method is proposed to identify transmission zeros of channel filters. With regard to the second technique, we establish an appropriate formulation for the deembedding problem and study the necessary conditions to achieve results.

The organization of the paper is as follows. First, we describe the structure of the manifold-coupled MUX and reconfigure it to a two-port network. In section 3, we apply perturbations to the new network and evaluate the transmission zeros of the selected filter, as well as the scattering parameter S_{22} of the filter. Finally in section 4, we employ the proposed technique to some case studies and report the results.

2. Preliminaries and Modeling

We consider a manifold-coupled MUX as schematically brought in Figure 1. A MUX is composed of a junction (i.e., manifold), which is connected to N channels Ch k. The manifold is assumed to be lossless, which is close to its realization as a low loss, nonresonating transmission line [19]. Filters in contrast can be lossy in our model; this situation is most often expected in manifold-coupled MUX.

We can reconfigure this multiport network model to a two-port one, by short-circuiting all ports except port In and Ch k as shown in Figure 1. Assuming that the network between ports In and Ch k is $T_{\mathrm{In-Chk}}$, from network theory, we have [20].

$$T_{\mathrm{In-Chk}} = T_{\mathrm{Rk}} T_{\mathrm{k}}, \tag{1}$$

where $T_{\mathrm{In-Chk}}$ is the overall frequency response of the two-port network (between port In and outport Ch k) measured before applying any perturbation in the filter F_k.

3. Deembedding via Applied Perturbations

In our previous study in [18], we assumed that the scattering parameters of the manifold are known to us. Thereby, we were able to determine the network T_{Rk} at each stage of deembedding. There are, however, circumstances where this prior knowledge is not available. For instance, if we have not designed the MUX, its simulation might be unknown to us. For these situations, here, we concentrate on an approach toward deembedding the S-parameters of channel filters, without the need to detach them from the manifold.

To begin deembedding the parameters of the interested channel filter F_k, we first reconfigure MUX to the form shown in Figure 1. Next, we apply a small change on the scattering parameters of the network T_k, via slightly changing the tuning screws of its associate filters (i.e., F_k). By a slight change, the overall scattering components of the cascaded network $T_{\mathrm{In-chk}}$ experience a small difference from its previous value inside the filter passband. Again, we measure the overall frequency response. Note that the network T_{Rk} is remained unchanged after the perturbation. Furthermore, filters in T_{Rk} are not in highly detuning situation; this allows poles/zeros of the short-circuited filters to contribute in forming appropriate response of T_{Rk} within the bandwidth of F_k, as will be seen in later case studies. After applying the perturbation, we have

$$T'_{\mathrm{In-Chk}} = T_{\mathrm{Rk}} T'_{k}, \tag{2}$$

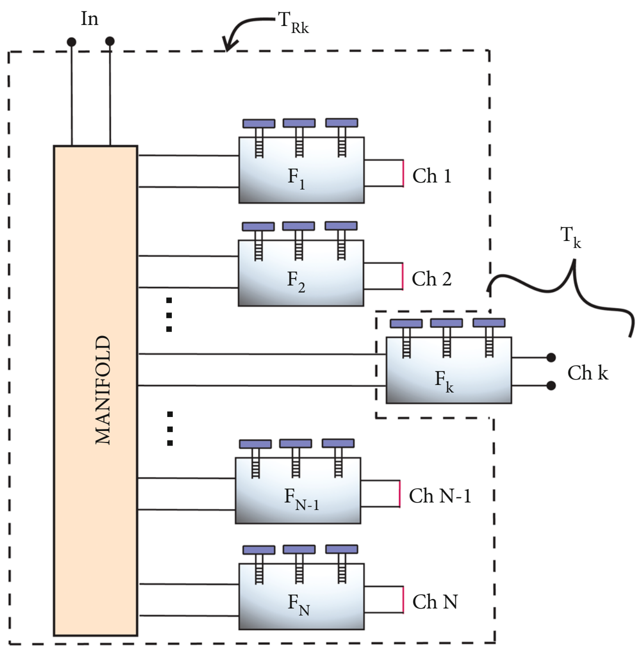

Figure 1: The schematic of a MUX composed of N channel filters. All channels except Ch k are short-circuited.

where $T'_{\text{In-Chk}}$ is the overall frequency response of the two-port network after detuning the filter F_k (T'_k denotes the filter response after perturbation). We rearrange (1) in terms of T_{Rk} and substitute in (2).

$$T_k^{-1} T'_k = T^{-1}_{\text{In-Chk}} T'_{\text{In-Chk}}. \tag{3}$$

The left-hand side of (3) appears like a cascaded system, composed of two networks T_k^{-1} and T'_k. Although T_k^{-1} is not a real microwave network, its transmission matrix components still show interesting properties of a microwave network, including reciprocity and poles/zero locations. The latter means that no poles or zero are added or removed in the T_k^{-1} in comparison to T_k. These features makes T'_k beneficial in theoretical analysis of our deembedding technique. While the scattering parameters of these two networks are unknown, it is expected that T'_k and T_k have very similar responses as we have made only a slight change in tuning screws of the filter. Regarding the right-hand side of the (3), the two matrices $T^{-1}_{\text{In-Chk}}$ and $T'_{\text{In-Chk}}$ are known from measurements. However, their multiplication does not form a real transmission matrix, and hence, poles and reflection zeros of T'_k and T_k do not explicitly appear in the matrix component. Therefore, it is impossible to extract—and then identify—the characteristic polynomials of the filter via conventional frequency identification techniques. Despite this, the transmission zeros of the filter can be identified by comparing the scattering components in $T^{-1}_{\text{In-Chk}}$ and $T'_{\text{In-Chk}}$. In the following section, we discuss this and then apply reasonable approximations to estimate the scattering response of the filter F_k after perturbation.

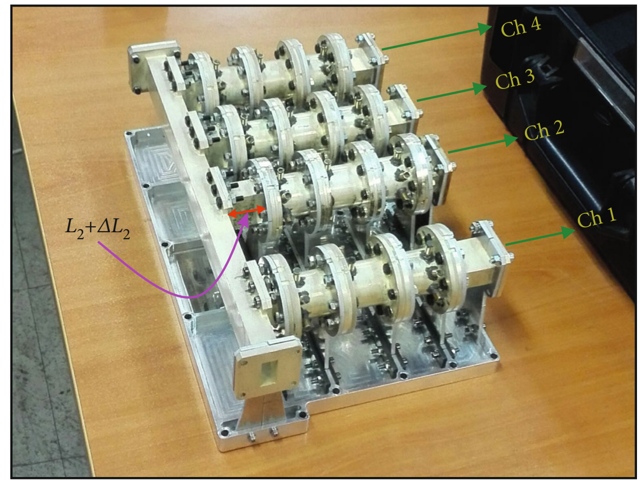

Figure 2: A fabricated manifold MUX composed of four dual-mode channel filters of degree 6.

3.1. Deriving Transmission Zeros of F_k. Perturbation is a simple technique to deembed transmission zeros of filters in a MUX. In its conventional approach, one has to measure then analyze the scattering response of the whole MUX to identify the transmission zeros of each filter. In contrast, in the perturbation technique, we need only two ports; this can greatly reduce the complexity of the required analysis. Let us consider the scattering parameter s_{21}^{Ik} of $T_{\text{In-Chk}}$ (tthe superscript Ik denotes the cascaded system between port In and outport Ch k), expressed in terms of S-parameters of T_{Rk} and T_k

$$s_{21}^{\text{Ik}} = \frac{s_{21}^{\text{Rk}} s_{21}^{\text{k}}}{1 - s_{22}^{\text{Rk}} s_{22}^{\text{k}}}, \tag{4}$$

in which s_{21}^{Rk} is the s_{21} component of the network T_{Rk}. To obtain (4), we used the relation $s_{21} = 1/(T_{\text{In-Chk}}, 11)$ [1]. Therefore, the transfer matrices T_{Rk} and T_k are first obtained from their corresponding scattering parameters. Then, the cascaded network is calculated using their product as brought in (2). Equation (4) can be rewritten in terms of characteristic polynomials of the scattering parameters:

$$s_{21}^{\text{Ik}} = \frac{N_{21}^{\text{Rk}} N_{21}^{\text{k}}}{D_{21}^{\text{Rk}} D_{21}^{\text{k}} - N_{22}^{\text{Rk}} N_{22}^{\text{k}}}, \tag{5}$$

in which N_{ij} and D_{ij} are the numerator and denominator of ijth component of scattering matrices. Looking to the denominator of s_{21}^{Ik} clearly show that poles in T_k and T_{Rk} are not distinguishable. However, from the numerator, the overall zeros are composed of zeros in T_k and T_{Rk}. Now, assuming that we make a change in the tuning screws of F_i, the zeros of T_{Rk} remain unchanged while those of T_k varies. Thus, a comparison between the two situations facilitates deembedding the zeros.

We evaluate the perturbation technique on the MUX shown in Figure 2. The scattering parameters are shown in

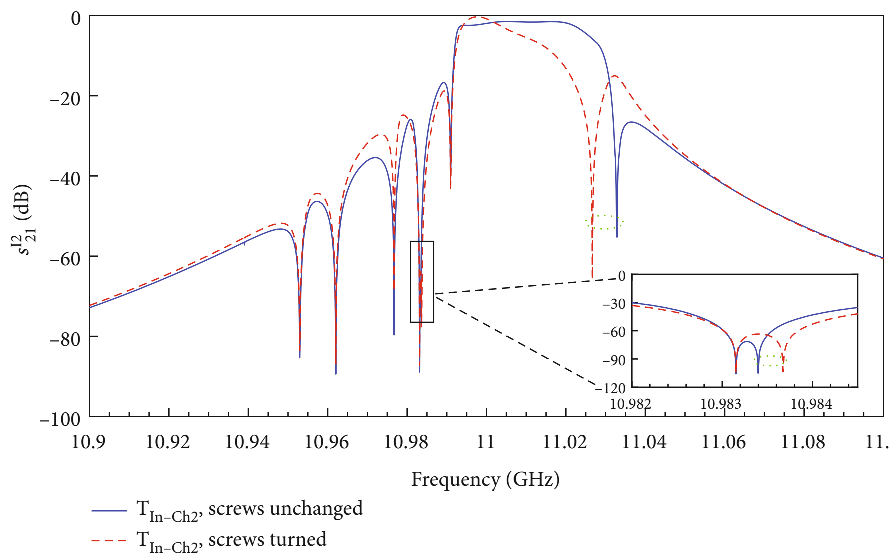

FIGURE 3: The scattering parameter s_{21}^{I2} of the network in dB, before (solid blue) and after (red dashed) applied perturbations. The two frequency deviations are shown with green dotted ellipses.

Figure 3, where s_{21}^{I2} (solid blue) and $s_{21}^{I2'}$ (red dashed) indicate the S-parameters before and after applying perturbations on the MUX, respectively. From the figure, except at two frequencies 10.983 GHz and 10.9835 GHz, the location of other transmission zeros is remained unchanged. This apparently indicates that the transmission zeros (TZs) of the perturbed filter are at the relocated frequencies. In the case of lossy filters, the TZs are complex quantities. In order to extract the real part of the zeros, a prior knowledge of unloaded Q -factor in the filter cavities is required, or we might rely on computations via interpolation techniques, in this case.

3.2. Evaluating $S_{22}^{k'}$. The most exciting aspect of the idea of applied perturbation is its application in deriving the approximate value of the scattering components of channel filters. In the following, we establish our formulation to derive the component $s_{22}^{k'}$ of the filter F_k, after the applied detuning. The $s_{22}^{k'}$ corresponds to the port of F_k that is not connected to the manifold.

We begin with (3) and expand it in terms of its constituent transmission matrices, i.e., T_k^{-1} and T_k'.

$$T_k^{-1}T_k' = \begin{bmatrix} T_{22}^k & -T_{12}^k \\ -T_{21}^k & T_{11}^k \end{bmatrix} \begin{bmatrix} T_{11}^{k'} & T_{12}^{k'} \\ T_{21}^{k'} & T_{22}^{k'} \end{bmatrix} := \begin{bmatrix} T_{11}^{\text{tot}} & T_{12}^{\text{tot}} \\ T_{21}^{\text{tot}} & T_{22}^{\text{tot}} \end{bmatrix}, \tag{6}$$

where the defined matrix in the right-hand side of the equation is a known matrix from measurement (see (3)), which can also be expressed in terms of the unknown scattering parameters of T_k^{-1} and T_k'.

$$T_{21}^{\text{tot}} = \left(T_{12}^{\text{tot}}\right)^* = \frac{s_{11}^{k'} - s_{11}^{k}}{s_{12}^{k} s_{12}^{k'}}, \tag{7}$$

$$T_{22}^{\text{tot}} = \left(T_{11}^{\text{tot}}\right)^* = \frac{\left(s_{12}^{k'}\right)^2 - s_{11}^{k'} s_{22}^{k'} + s_{11}^{k'} s_{22}^{k}}{s_{12}^{k} s_{12}^{k'}}, \tag{8}$$

in which * denotes complex conjugate. Next, we substitute (7) into (8). After simplifying the equation, we have

$$s_{22}^{k'} = \frac{R - T_{22}^{\text{tot}}}{T_{21}^{\text{tot}}}, \tag{9}$$

where the ratio R is

$$R = \frac{s_{21}^{\text{tot}'}}{s_{21}^{\text{tot}}} \frac{1 - s_{22}^{\text{R}k} s_{11}^{k}}{1 - s_{22}^{\text{R}k} s_{11}^{k'}}. \tag{10}$$

The expression for $s_{22}^{k'}$ in (9) provides us with the exact value of this quantity. However, to calculate R, we need to have the scattering parameters of the filter F_k, which are in general unknown values (see (10)).

The expression for R is composed of two terms; the first term $s_{21}^{\text{tot}'}/s_{21}^{\text{tot}}$ is known—from measurement—while the second fraction is unknown. Let us assume that under certain circumstances, the magnitude of the second fraction tends to unity, so that R is approximated solely with the first fraction (i.e., $R \approx s_{21}^{\text{tot}'}/s_{21}^{\text{tot}}$). In this situation, the scattering parameter $s_{22}^{k'}$ can be computed without the need to prior knowledge of the filter status. We should note that since the S-parameters of the filter F_k are unknown, the above approximation is fulfilled in the case that $|s_{22}^{\text{R}k}|$ in (10) is sufficiently small. Fortunately, this condition is most often achieved in manifold MUXs. Provided that there is no interference between the channels and coarse tuning is roughly performed, this situation is satisfied. We will see in the late case studies that factors such as the number of channels, the guard band between them, and the S-parameters of

Table 1: A comparison between recent deembedding techniques proposed for filters in a multiplexer.

Technique	Validation	Features	Reference
Computing a rational model	Theoretically	High accuracy Stability not guaranteed Junction prior knowledge not required	[2, 12, 21]
Recursive Schur's algorithm	Theoretically	Assuming a lossless system Limited to diplexers	[22]
Polynomial approximation	Theoretically	Quick and accurate Simple implementation	[17]
This work	Practically	Reasonable accuracy No prior knowledge required	

adjacent filters do not have negative effect on the technique. In addition, assuming only a slight perturbation, the two terms $1 - s_{22}^{Rk} s_{11}^{k}$ and $1 - s_{22}^{Rk} s_{11}^{k'}$ are expected to be close to each other, which further push the magnitude of this fraction to unity.

We summarize the described steps toward deembedding the S-parameter $s_{22}^{k'}$ as follows:

(1) Short circuit all ports except the channel Ch k

(2) Measure S-parameters of the network $T_{\text{In-Chk}}$

(3) Slightly detune the filter F_k

(4) Measure S-parameters of the network $T'_{\text{In-Chk}}$

(5) Determine the ratio R from (10)

(6) Estimate the S-parameter $s_{22}^{k'}$, from (9)

Table 1 provides a comparison on the main features of important deembedding techniques introduced in the literature, and in this study.

4. Case Studies

We, here, study the demonstrated technique in three case studies. The first case is deriving the s_{22} parameters in a realized two-channel MUX. Two other case studies refer to exploring the technique in designed—but not fabricated—MUXs.

4.1. Deembedding $s_{22}^{2'}$ in a Fabricated Two-Channel MUX. In the first case study, we examine our technique on a fabricated MUX shown in Figure 4. The device is composed of two channels, each with a dual-mode cavity filter having four cavities. The MUX is roughly tuned, and we intend to examine the S-parameters of the channel ports.

For this and according to the proposed technique, we short-circuit channel Ch1 and measure the S-parameters between port In and Ch2, before and after slightly perturbing the second filter. Perturbation was performed by slightly changing one of the tuning screws of the second filter. Then, using (9), we compute the s_{22} for the perturbed channel. Then, we unplug the filter and, again, measure s_{22}. Results are compared in Figure 5.

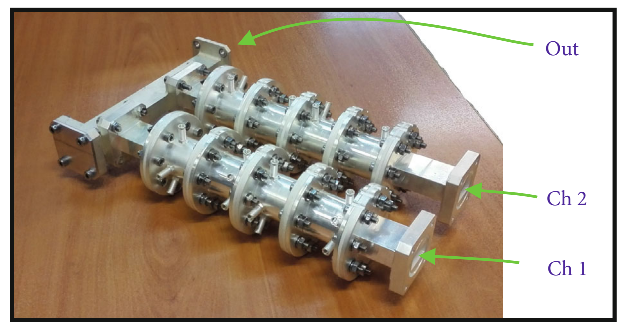

Figure 4: The fabricated two-channel manifold-coupled MUX composed of two dual-mode filters of degree 8.

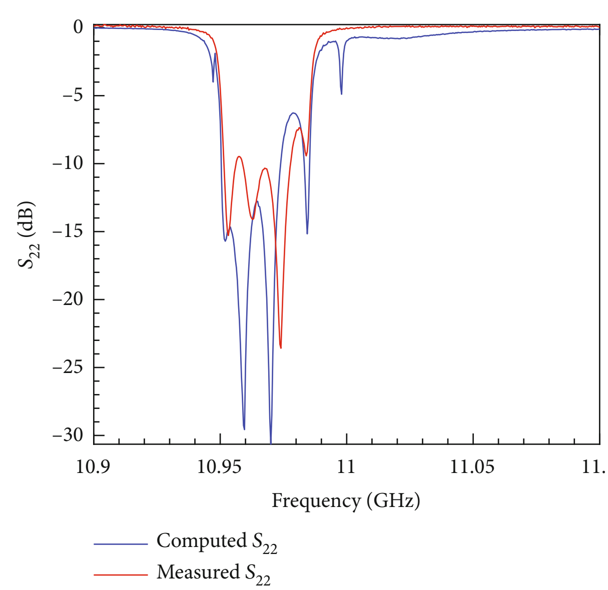

Figure 5: The computed (blue) and measured (red) s_{22}—in dB—from the second channel (Ch 2) in the two-port MUX shown in Figure 4.

As can be seen, there exists a reasonable agreement between the two graphs. This indicates that one can deembed the approximate amplitude of the frequency response of the channel ports with only a practically simple

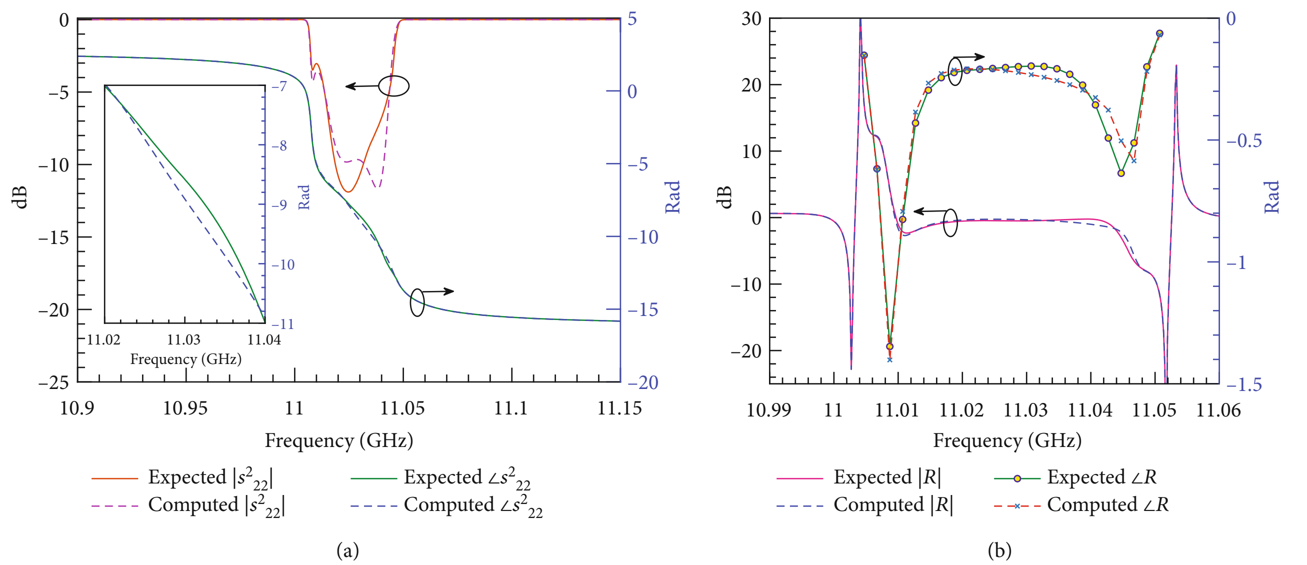

Figure 6: A comparison, both in (a) magnitude and phase, between the exact and computed values of $s^{2'}_{22}$ of filter F_2 in the MUX shown in Figure 2. (b) Comparison of the magnitude and phase of the exact and approximate values of R in the case study.

method. In addition, if an error has occurred in the device, one can detect its position, without multiple plugging/unplugging the connected filters.

4.2. Deembedding $s^{2'}_{22}$ in Channel 2 of a Four-Channel MUX. In the second case study, we examine our technique on the second channel of the MUX shown in Figure 2 (we here use the simulated frequency response of the structure). Figure 6(a) compares the magnitude and phase response of the computed $s^{k'}_{22}$ (dashed pink) calculated by (9), with its exact value obtained by detaching the filter F_2 (solid orange). From the figure, the computed $s^{k'}_{22}$ attempts to follow the general trend of the expected $s^{k'}_{22}$ in both magnitude and phase. There is a very good match between the two graphs, both in magnitude and phase—at band edges. There also exists a deviation between the two graphs around the central frequency, which is practically rather small (about 2 (dB) at 11.02 GHz and 4.2 (dB) at 11.04 GHz, respectively), which is caused due to the approximation we have made in (9). The graphs in Figure 6(b) show the magnitude and phase of the ratio R in the frequency range of the filter F_2. As we expected, the magnitude of R is close to one at the band pass of the filter. Moreover, both magnitude and phase responses of the computed ratio are in a very good agreement with their expected values obtained via (10). The small deviation between the approximation and the exact results at 11.04 GHz can also be observed in Figure 6(b) between the computed and expected graphs of R. From this example, the applied approximation is reasonable and leads to responses which are effectively useful for operators during the tuning stage.

4.3. Deembedding $s^{2'}_{22}$ in a Two-Channel MUX. In the last case study, we examine the impact of scattering parameters of adjacent channels on the achievable response of the interested channel filter in MUXs with narrow guard bands. This

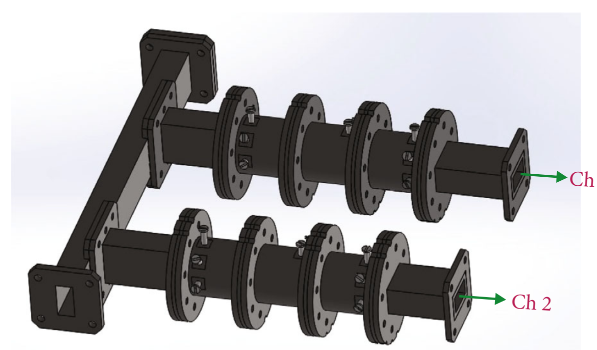

Figure 7: Schematic of the structure 2-channel manifold-coupled MUX composed of two dual-mode filters of degree 6.

is an important issue as, in practice, there is no prior knowledge of other channel filter response, and this might lead to ambiguity on the effectiveness of our technique. Figure 7 shows a schematic of a two-channel manifold-coupled MUX composed of two filters designed to operate at the central frequencies 10.972 GHz (Ch1) and 11.012 GHz (Ch2), each operating with the bandwidth 36 MHz. The guard band between the two channels is only 4 MHz, which is much smaller than in the previous four-channel MUX with the guard band of 20 MHz. To evaluate the effect of F_1 on deembedding the S-parameters of F_1, we compute three different responses of F_1, via arbitrarily changing the position of its tuning screws in the model. The scattering component s^1_{22} for the three situations are shown in Figure 8(a), in which substantial differences exist among the responses. Then, we derive the s^{R2}_{22} for the network T_{R2} as shown in Figure 8(b). As can be seen, despite various responses in Ch1, s^{R2}_{22} remains almost unchanged. In addition, and like the previous example, the magnitude of s^{R2}_{22} is significantly decreased (≈-17 (dB) at 11.01 GHz) within the passband of Ch1.

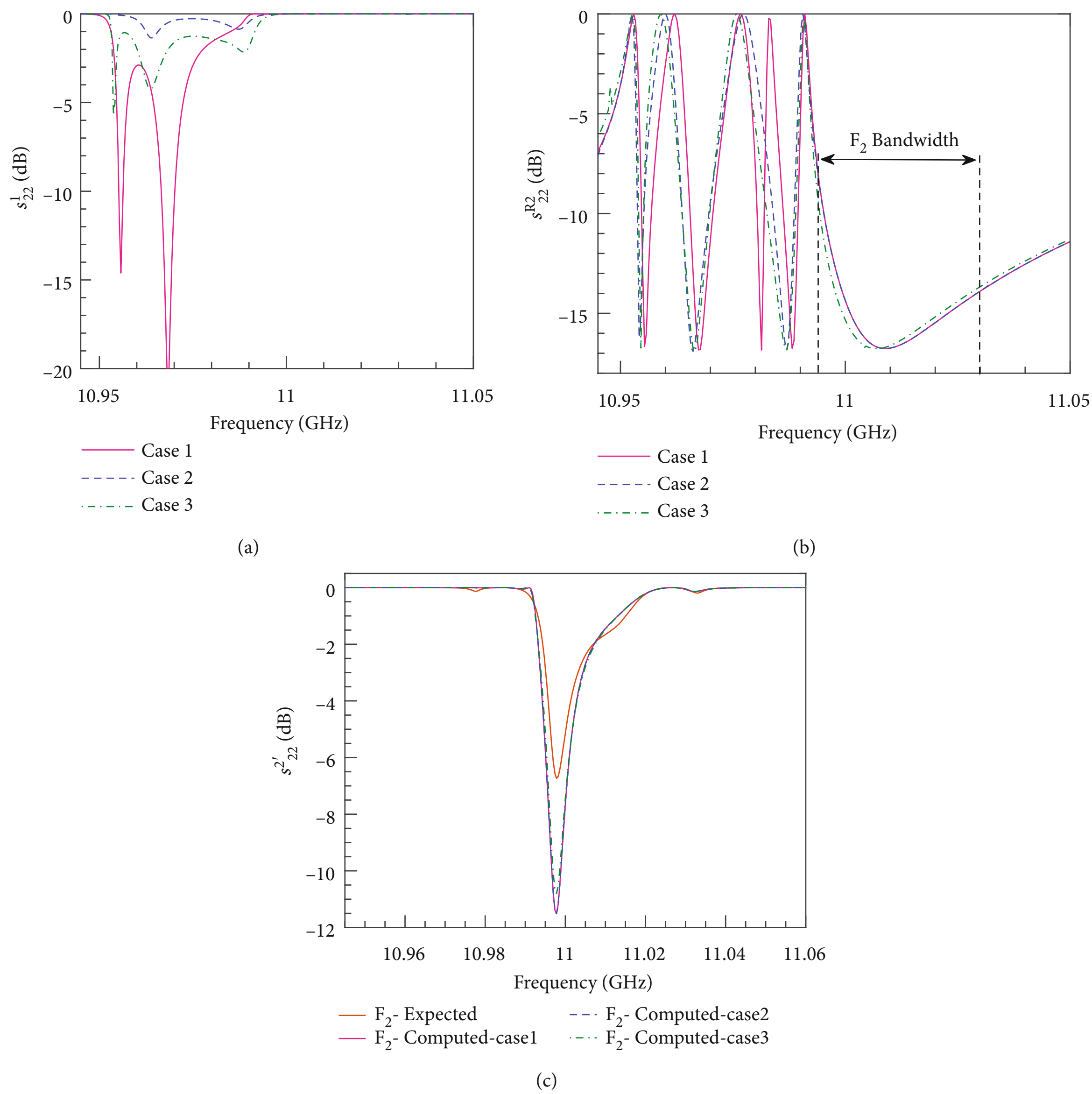

FIGURE 8: (a) The scattering parameter s^{1}_{22} of the channel filter F_1 in three different applied perturbations. (b) The corresponding s^{R2}_{22} in dB. The bandwidth region of the filter F_2 is also shown with vertical dotted black lines. (c) The deembedded response of the channel filter F_2 in dB obtained for the three different situations of F_1. The computed responses are compared with the expected response.

Therefore, the approximation we made in this section should be applicable for deembedding the parameter $s^{2'}_{22}$. The extracted frequency response of $s^{1'}_{22}$ is shown in Figure 8(c) for the three situations of channel 1. As can be seen, there are negligible differences between the deembedded responses of $s^{2'}_{22}$. In addition, the computed responses follow the expected response (solid orange) of the filter appropriately through the bandwidth. This example underlines the effectiveness of the technique for MUXs with narrow guard bands, and its independence to prior knowledge of other channel filter response.

5. Conclusion

A practical technique to deembed the frequency response of channel ports in manifold-coupled MUXs was presented in this paper, which do not require detaching filters from their connected manifold. The technique was applicable in MUXs with even lossy filters at any tuning conditions they have; the N-port network was reduced to a simple two-port network composed of a channel filter cascaded to network with short-circuited channel ports. It was assumed that no prior knowledge is available about the manifold, and the idea of applied perturbations was employed. The tuning screws of filter—with unknown S-parameters—were slightly detuned. Then, by analyzing the responses before and after the perturbation, characteristic parameters of the filter were extracted. This technique was, in particular, useful for the situation that one needs to analyze the performance of a filter in a MUX with an unknown response, without detuning other channel filters nor detaching any filter from the manifold. Moreover, the technique speeds up tuning for sophisticated operators whose knowledge on approximate response of a channel filter can effectively help them to adjust the appropriate cavity, without the need to identify the whole S-parameters of the MUX network.

Data Availability

The simulated and experimental data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

Acknowledgments

This study was supported by the Iran Telecommunication Research Center (ITRC).

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