Efficient CAD of Wideband Contiguous Channel Multiplexers

A. Morini, *Member, IEEE*, T. Rozzi, *Fellow, IEEE*, and M. Mongiardo, *Member, IEEE*

Abstract— **A systematic procedure for the efficient CAD of multiplexers is presented and applied to the design of wideband contiguous channel multiplexers using manifolds consisting of interconnected Y-junctions. The procedure starts by connecting *N* separately designed filters to the manifold at appropriate distances. All parameters are then optimized by computing the multiplexers sensitivities by the Adjoint Network Method (ANM). The latter is specialized to account for the multiplexer topology. Moreover the ANM is applied to the optimization of *both* the prototype and the final component. The proposed algorithm takes advantage of the efficiency of the ANM, while also reducing code complexity and memory resources.**

Keywords: **Microwave multiplexer, Adjoint network method, Y-junction manifold**

I. Introduction

The necessity of an efficient occupation of frequency bands in modern satellite systems [1] renders mandatory the use of wideband contiguous channel multiplexers, whose design requires both an appropriate choice of the manifold and an efficient design procedure. The first point has been recently discussed in [2], [3], where it was found convenient to use a manifold made by interconnected Y-junctions.

As far as the design is concerned, although many techniques were developed [4], [5], [6], [7] which work very well for the non-contiguous case, they require further optimization steps for wideband and/or contiguous cases. Other researchers have developed methods based on straightforward optimization approaches [8], [9], [10], [11]. Starting from a simple prototype of the multiplexer, consisting of a manifold and filters, they vary all the parameters in such a way as to obtain the prescribed specification. The procedure, however, seems to be a little fragile, since the optimization cannot be performed directly on the entire circuit, but segmentation is required in order to circumvent local minima problems. This fact is mainly due to the choice of the starting point that should be as close as possible to the final solution. The procedure called *soft tuning* introduced in [12] seems interesting; its application, however, could be too expensive when applied to multiplexers having many channels.

In this paper we address the problem of a systematic and an efficient procedure for multiplexers CAD. The procedure is constituted by the two following steps:

- Initial design of multiplexer
- Optimization

The optimization is further divided into two distinct stages, i.e. optimization of the prototype and the final full-wave optimization of the actual multiplexer.

For non-contiguous multiplexers, i.e. when the guardbands separating the channels are at least equal to the corresponding passbands, and when the number of channels is less than 4-5, the design of multiplexers employing the proposed manifold is performed directly by means of simple closed formulae [3]. On the other hand, for closely spaced channels, or when their number is larger than four or five, optimization is necessary in order to compensate for the interactions due to the rapid phase variations of the filters. In this case, since the optimization problem typically involves more than one hundred parameters, it is important to devise an efficient strategy for the computation of the objective function and its derivatives (sensitivities). Note that this strategy should possibly work on both the prototype and the final structure.

The most direct way to evaluate the objective function and its derivatives consists in changing each parameter and performing a new analysis of the entire multiplexer. It is readily observed that this process is largely redundant since most of the time is wasted in computing blocks which have not been changed at all. As an example, the calculation of the sensitivity of the reflection coefficient at the common port with respect to the length of the $2nd$ cavity of the $i-th$ filter, requires calculation of the response of all the other $N-1$ filters that are unchanged.

In order to avoid this redundancy, it is convenient to employ the adjoint network method (ANM) for both the prototype optimization [13] and the full-wave optimization [14]. However, direct application of the ANM,

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as formulated in the general case of networks of arbitrary topology, fails to take advantage of the particular structure of the multiplexer. In order to devise an efficient CAD procedure it is necessary to specialize the ANM to the multiplexer case. In particular, this is done by noting that the multiplexer combines only *two kinds of blocks with different topologies*, namely the *manifold* and the *filters.* It is therefore convenient to calculate separately their sensitivities by means of the ANM and to compute then the global one. This approach, while being easier to implement, also shows improved efficiency with respect to the general formulation. Moreover, since we consider the sensitivity of each block at a time, the resulting matrix sizes are noticeably smaller expecially in connection with the full-wave optimization procedure. In the next section we briefly describe the design of the prototype, while in section III we describe the application of the ANM to the optimization of both the prototype and to the full-wave case.

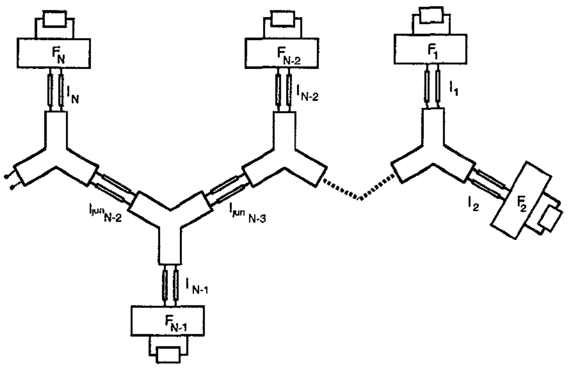


Fig. 1. Layout of the proposed Y-manifold multiplexer

II. Initial multiplexer design

As already noted, it is convenient to choose a manifold topology consisting of interconnected Y-junctions, [2]. In fact, it was proved, [2], that the three-port junctions have to fulfill the following constraints:

α) $|s_{11}| = |s_{22}| = |s_{33}|$

β) $|s_{ii}| \approx 1/3$

γ) $s_{ii}(f)$ is approximately constant over the whole waveguide band

which are indeed satisfied by Y-junctions. Note that, for two given filters the above choice ensures the maximum diplexer bandwidth. As a consequence of this choice, a good design is obtained by connecting separately designed filters to the manifold according to the closed-form formulae provided in [2], [3] and here repeated for reference purposes.

In order to design the multiplexer (see Fig. 1), N Filters F_i of scattering matrices S_{F_i}, ordered in such a way that $f_i > f_{i+1}$, where f_i is the midband frequency of F_i, are connected to $N-1$ identical Y-junctions of scattering matrix S_Y as indicated in the following.

i) The first module, corresponding to a diplexer (the module at the right of Fig.3), S_{dpx} is built by connecting the two filters F_1 and F_2 respectively to arms 2 and 3 of the Y-junction at the distances l_1 and l_2, as given by [2]:

$$l_1 = \frac{1}{2j\beta} \ln \frac{S_{Y33}}{\Delta S_Y \, S^*_{Y11} \, S_{F1_{11}}} \qquad : f = f_2 \quad (1)$$

$$l_2 = \frac{1}{2j\beta} \ln \frac{S_{Y22}}{\Delta S_Y \, S^*_{Y11} \, S_{F2_{11}}} \qquad : f = f_1 \quad (2)$$

where ΔS_Y is the determinant of S_Y.

ii) N-2 modules of 3x3 matrices $S^{(i)}_{jun}$ are obtained , each by closing port 2 of a Y-junction by the filter F_i at distance l_i where

$$l_i = \frac{1}{2j\beta} \ln \frac{S_{Y33}}{\Delta S_Y \, S^*_{Y11} \, S_{F1_{11}}} \qquad : f = f_{M(i)} \quad (3)$$

Where

$$f_{M(i)} = \frac{1}{i-1} \sum_{k=1}^{i-1} f_i$$

is the midband frequency of the (i-1)-channel multiplexer

iii) The N-1 modules thus obtained, S_{dpx} and $S^{(i)}_{jun}$, i=1,N-2, are then assembled to realize the N - port multiplexer. This procedure starts by connecting arm 3 of $S^{(1)}_{jun}$, the 2nd module, to the common port (1) of the diplexer, the 1st module, at a distance $l^{(1)}_{jun}$. Then arm 3 of $S^{(2)}_{jun}$ is connected to the common port of the triplexer now obtained at a distance $l^{(2)}_{jun}$ and so on . The expressions of the distances $l^{(i)}_{jun}$ are given by

$$l^{(i)}_{jun} = \frac{1}{2j\beta} \ln \frac{S_{Y22}}{\Delta S_Y \, S^*_{Y11} \, S^{(i)}_{11}} \qquad : f = f_{i+2} \quad (4)$$

where $S^{(i)}_{11}$ is the reflection coefficient at port 1 of the $(i+2)$ x $(i+2)$ matrix (i=1,N-2), derived from connecting the first i modules.

III. Optimization

In order to find an efficient optimization procedure it is convenient to split the problem into two steps. First we act on the prototype where the three-port junctions are simulated by means of their lumped equivalent circuits and filters are modelled as distribuited ideal prototypes consisting of impedance inverters and transmission lines. Once the parameters of the prototype have been optimized, we design the corresponding multiplexer and optimize its physical parameters by applying the procedure to the full-wave model.

It is expedient to adopt the same strategy in both steps. In particular, we avoid solving the network by cascading the various elements, which introduces a very time consuming redudancy. On the contrary, we consider the entire network as consisting of two distinct blocks: the manifold, depending on $N-2$ parameters (i.e. the lengths of the lines separating the Y-junctions), and the filters, each depending on $2(M+1)$ parameters if its degree is M.

A device can be characterized either by input-output(s) scattering matrix, indicated by $\mathbf{S}$, or by its global scattering matrix $\mathcal{S}$, as required by the ANM. The latter is a sparse diagonal matrix, whose elements are the scattering parameters at the internal ports of the device, that is K-inverters and cavities for the filters, or Y-junctions for the manifold.

The manifold is therefore represented by means of its global scattering matrix $\mathcal{S}^{man}$, a sparse matrix whose $i-th$ diagonal block corresponds to the scattering matrix of the $i-th$ Y-junction employed in the manifold.

Each filter block is treated by considering its global scattering matrix, $\mathcal{S}^{F_i}$,a sparse matrix in which the diagonal blocks represents the scattering matrices associated either to the inverters or to the transmission lines forming the filter. As a first step, we separately calculate the sensitivities of the filters and of the manifold with respect to their own parameters by applying the ANM. Then, we recover the sensitivity of the entire multiplexer as a combination of the sensitivities of the single blocks. The advantages in using such an approach can be summarized as follows:

1. The construction of the GSM of each block is simpler than that of the entire network. In order to give an idea let us consider how complex the port numbering of the entire network is, expecially in the full-wave analysis. Moreover, since in our case there are only two distinct topologies, the first one pertaining to the manifold and the second to the filters, only two simple distinct subroutines have to be implemented in order to calculate the sensitivities of the blocks.
2. The maximum dimension of the global scattering matrices involved is given by $\max(2(M+1), 3\times(N-1))^2$ instead of $(2(M+1)\times N+3\times(N-1))^2$ required by the general method, resulting in large memory savings.

IV. Results

The proposed technique has been applied to the design of contiguous and not contiguous multiplexers in rectangular waveguide employing both E-plane and H-plane Y- junctions. It has to be emphasized that the properties of the proposed topology are absolutely independent on the waveguide employed, being based just on general properties of the scattering matrix of lossless, reciprocal and symmetrical three-port junctions. We present here just one example, referring to a 7 channels contiguous wideband multiplexer - employing 6-poles, 300 MHz bandwidth, 26 dB mrl Chebyshev filters - with 60 MHz guardband.

The response of the multiplexer before optimization is shown in Fig. 2. Apart from the apparent deterioration due to the kind of filters used as their phases change too rapidly in the guardband, nonetheless these results represent a good starting point for the optimization procedure.

Fig. 3 shows the results obtained by optimizing all the 103 multiplexer prototype parameters in a single step. The optimization is based on a quasi-Newton algorithm and it takes 163 minutes to run on a workstation Digital α DEC 3000/300x. Note that alternative strategies, consisting of either repeating the optimization when a further channel is added (step iii) or of subdividing into subsets the parameters and optimizing just one subset at a time, required at least twice as long. Finally, in order to estimate the accuracy of the initial design formulae, Fig. 4 shows the ratio between each element (lengths or k-inverters) of the solution $\mathbf{X}_f(i)$ and that of the starting point $\mathbf{X}_0(i)$. The optimization time reduces by a factor 20 when ANM in the form discussed above is applied.

We are at present implementing the physical model, which uses H-window filters and H-plane Y-junctions.

V. Conclusions

A procedure for the efficient CAD of wideband contiguous channel multiplexers has been presented. The manifold design consists of interconnected Y-junctions which are connected to separately designed filters according to analytical formulae.

An overall optimization is then performed by computing the multiplexers sensitivities by the Adjoint Network Method (ANM). The latter has been specialized to account for the multiplexer topology, i.e. by noting that only two kinds of blocks with different topologies, namely the manifold and the filters, are present.

Moreover, the ANM has been applied both to the optimization of the prototype and to the final full-wave optimization of the component.

The procedure indicated reduces considerably the time required for the synthesis.

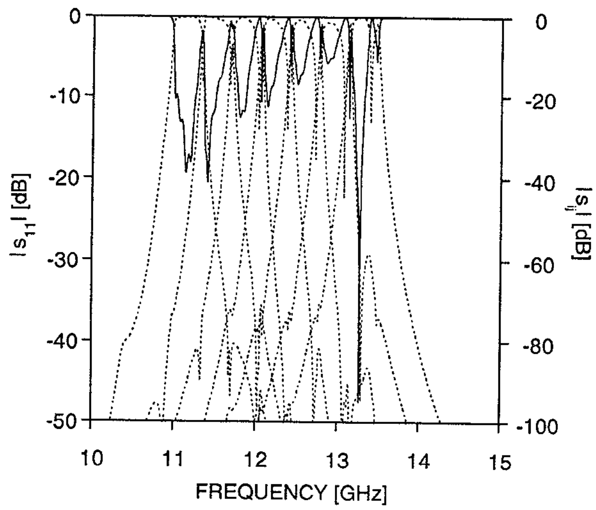
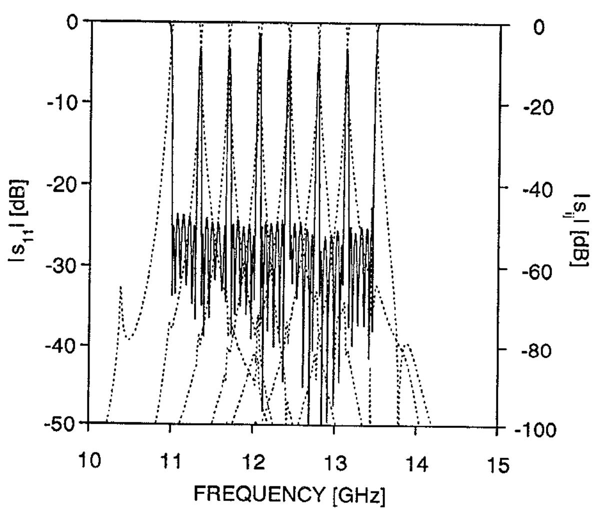


Fig. 2. Reflection at the common port (continuous line) and transmissions (dashed lines) of a 7-channel wide band contiguous multiplexer before the optimization



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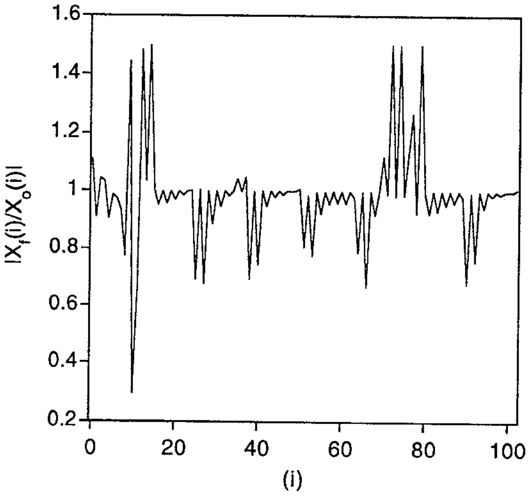

Fig. 4. Ratio between the multiplexer parameters, i.e. normalized distances and k-inverters computed after and before the optimization procedure

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