

PLANNING AND DESIGN OF FRONT-END FILTERS AND DIPLEXERS FOR RADIO LINK APPLICATIONS

Kjetil Folgerø and Jan Kocbach

Nera Networks AS, N-5020 Bergen, NORWAY. Email: kfo@nera.no, jko@nera.no

Abstract— High capacity radio links with data rate up to 155 Mbps per channel operating in the frequency range from 4 GHz to 40 GHz are used in mobile infrastructure and backbone networks. The frequency bands are crowded, and therefore subject to strict regulation from national and international governing bodies. Despite efforts of standardization, there exist numerous region-specific requirements to which equipment manufacturers must comply. Hence, there is a need for a large number of filters and diplexers to cover the complete range of frequencies. It is important with efficient planning and short design cycles when such a large number of variants are to be designed. This paper describes an efficient way of planning and designing front-end diplexers using automated design procedures and commercial electromagnetic solvers

I. INTRODUCTION

A radio link system uses frequency division duplexing to separate transmitted and received signals. Fig. 1a shows an example of a channel plan in the lower 6 GHz frequency band. To minimize RF channel interference, all transmit frequencies on one terminal station are either in the lower or upper side-band and the receive frequencies are in the other side-band. For example, if channel 2 in the lower side-band is used for transmitting at one terminal, channel 2' in the upper side-band will be used for receiving as illustrated in Fig. 1b. The adjacent station will obviously have transmit and receive frequencies in the other side-band.

The filtering needs for access radio systems (such as mobile infrastructure networks) are connected to regulatory and interference issues; and the driving concern is that the filtering must suppress signals from own transmitter to interfere with the received signals (cfr. Fig. 2). The receive filter therefore needs a high rejection at the transmit frequencies, and the transmit filter needs to suppress the leakage from the transmitter at receive frequencies. In addition, the transmit filtering must ensure that the spurious and harmonics from the transmitter are attenuated below regulatory levels, and the receive filtering must ensure that interfering signals outside the frequency band is suppressed before entering the LNA. Usually, transmit and receive filtering is combined in a diplexer. It is important that one diplexer can cover as many channels as possible. The frequency plan is divided into sub-bands in order to make realizable diplexer requirements as shown in Fig. 3. The

diplexer is often made mechanically symmetrical such that the same unit can be used both for transmitting in the upper and lower side-band.

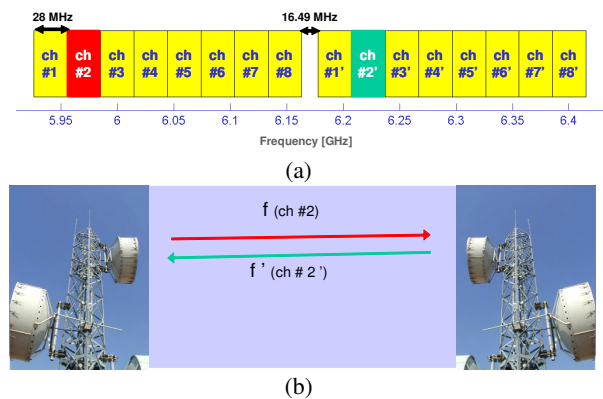


Fig. 1. (a) Frequency plan in the lower 6 GHz frequency band, (b) Radio link hop utilizing frequency division duplexing .

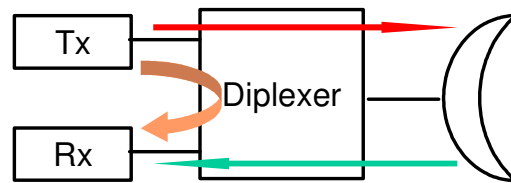


Fig. 2. Filtering

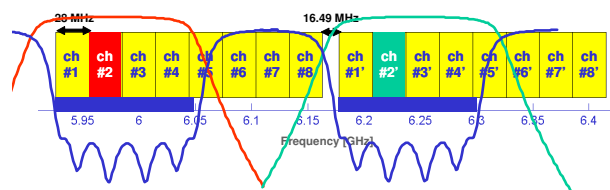


Fig. 3. The frequency plan is divided into sub-bands. A diplexer covering one sub-band is shown

Despite efforts of standardization, there exist a large number of channel plans. Fig. 4 shows an example for 28-40 MHz plans in the 8 GHz frequency band. Effort must be made to reduce the number of variants to a minimum in order to lower the manufacturing cost and logistics. Nevertheless, a large number of diplexer variants have to be designed. There is therefore a need for reliable and automated design procedures for diplexers. This paper presents an efficient way of planning and designing front-end diplexers using automated design procedures and commercial electromagnetic solvers.

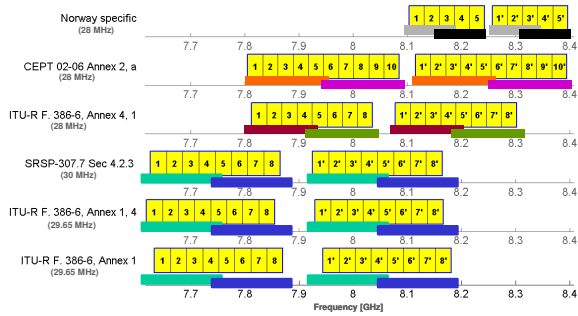


Fig. 4. Example of frequency plans (28-30 MHz) in the 8 GHz frequency band). Division into diplexer sub-bands is also shown.

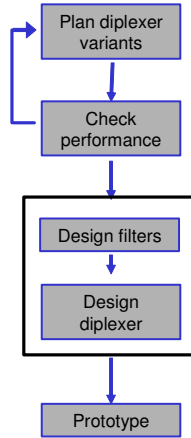


Fig. 5. Procedure for planning and designing diplexer variants.

II. DESIGN APPROACH

The suggested planning and design procedure can be divided into the steps shown in Fig. 5. In the following we describe these steps in more detail.

A. Variant planning and performance evaluation

A first attempt of defining the diplexer variants for optimum coverage of the channel plans is done based on experience, or by simply guessing. Filter parameters (i.e. centre frequency, bandwidths, filter order and return loss) for various sub-bands are chosen (see example in Fig. 4), and the filters' responses are calculated using an accurate trained circuit model. If the requirements are fulfilled, we can proceed to the next step. If not, the filters' parameters need to be redefined, and new calculations must be made. This process is repeated until the requirements are fulfilled. It is obvious that a fast method of calculating the filter response is needed if numerous iterations have to be made. Further on, it is important that the response calculated is as close as possible to the response that can be realized. It is also important to consider practical issues such as temperature effects, tolerance influence and tuning margins already at this stage. Hence, effective planning of variants highly relies upon using reliable circuit

models instead of less accurate ideal models or time-consuming full-wave simulations of complex filters. In the following section we describe such a reliable circuit model.

1) Trained circuit model

The basic circuit model [1], [2] shown schematically in Fig. 6 consists of a chain of K-inverters and transmission lines with phase constant β and length l . The K-inverters $K_{i,i+1}$ for the individual couplings are calculated directly from the filter specifications (i.e. centre frequency, bandwidth, filter order and pass-band ripple) [1], [2]. The phase $\phi_{i,i+1}$ for an ideal K-inverter is given as $\phi_{i,i+1} = \pm\pi$.

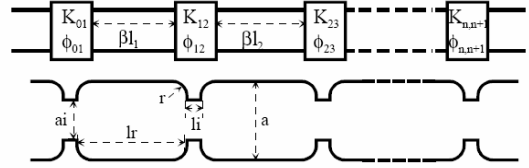


Fig. 6. Circuit model

The K-inverters of the ideal circuit model is independent of frequency. In order to increase the accuracy of the model, a Taylor expansion is applied to the K-inverters and phases as a function of frequency to include the frequency dependency of the couplings in the circuit model;

$$K(f_0 + \Delta f) \approx K(f_0) + \Delta f \alpha_f, \quad \alpha_f = \frac{\partial K(f_0)}{\partial f}$$

$$\phi(f_0 + \Delta f) \approx \phi(f_0) + \Delta f \kappa_f, \quad \kappa_f = \frac{\partial \phi(f_0)}{\partial f}$$

The expansion coefficients α and κ are calculated from CAD simulation of the couplings. Typically, the frequency dependency (and the value of the expansion coefficients) will increase with increasing iris thicknesses. A similar Taylor expansion can also be applied to small changes in the dimensions, and this can be utilized to perform tolerance analysis in short time frames. More details are found in [3]. The trained circuit model can also be generalized to included conductor losses and temperature effects, but this is not described any further here. Fig. 7 illustrates that the ideal Chebychev response differs from the full wave simulations by approximately 8 dB at 16 GHz, while there is excellent agreement between the trained circuit model and full-wave simulations.

Fig. 8 shows an example of using the trained circuit model in planning of diplexer variants. The response of a diplexer including tolerances is calculated within a few seconds, and it can automatically be determined if the requirements are satisfied.

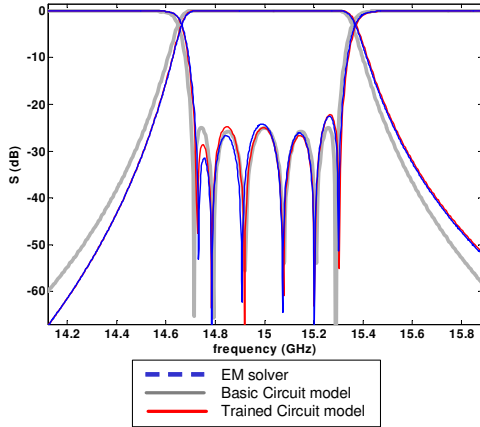


Fig. 7. There is excellent agreement between trained circuit model and full wave simulations.

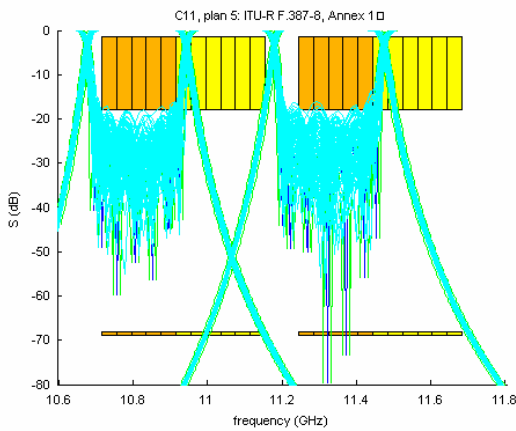


Fig. 8. Fast estimation of diplexer response with the trained circuit model.

B. Filter design

The next step in the process is to design the diplexers for each sub-band. The shape of the diplexer is first chosen based on the mechanical outline of the product. The two filters that constitute the diplexer are then designed independently to the exact shape wanted. The realization procedure may be divided into simple steps (see Fig. 9), leading to a design-process well suited for implementation as an automatic procedure on a computer. Each step involves the tuning of one dimension (coupling size or cavity length) in a simple waveguide structure until the simulated s-parameters fit the s-parameters of the representative circuit model. The waveguide structure is kept simple by only including the couplings and resonators that interact strongly, i.e. either a single coupling, a single cavity or two coupled cavities. Thus, even a 3D EM tool such as HFSS can be used for the design [4].

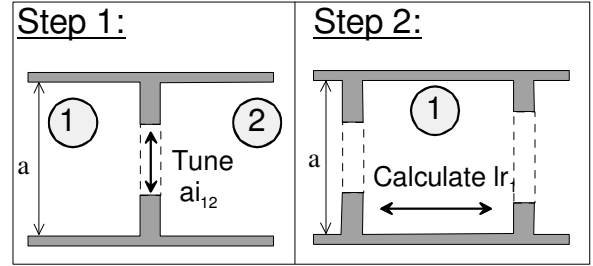


Fig. 9. Step-by-step illustration of the design procedure for an in-line direct-coupled inductive iris filter.

A fast convergence for each step is obtained because (i) the simulated substructure is very simple, (ii) only one variable is tuned, (iii) only one or a few frequency points are considered and (iv) the tuning goals are easy to achieve with few iterations. The procedure is described in detail in [4] and [5]. Here, we repeat the main steps for an in-line direct coupled filter:

1. Calculate the theoretical $|S_{21}|$ for the couplings as reference values. Then simulate a waveguide with a single iris in a full-wave simulator (see Fig. 9) at ω_b , and change the dimension of the iris until the simulated $|S_{21}|$ equals the reference values.
2. Calculate the length of the cavities as

$$l_r = \left(\pi - \frac{1}{2} (\phi_1 + \phi_2) \right) \frac{\lambda_{g0}}{2\pi}$$

where ϕ_1 and ϕ_2 are the phases of S_{11} for the input and output coupling of the corresponding resonator, respectively, as found in step 1, and λ_{g0} is the guide wavelength at ω_b . Alternatively, simulate a cavity with a full-wave solver and tune the length of the cavity until the simulated $|S_{21}|$ curve has a peak at the centre frequency ω_b .

To meet the exact shape requirements of the filters, it is often required to use folded filters or filters with cross-coupling. A thorough description of the design process applicable for such filters is given in [5]. The method described has been fully automated using Matlab and the mode-matching/finite element program Wasp-Net [6]. Fig. 10 and Fig. 11 show examples of filters with a flexible shape that are designed automatically from specifications with this process.

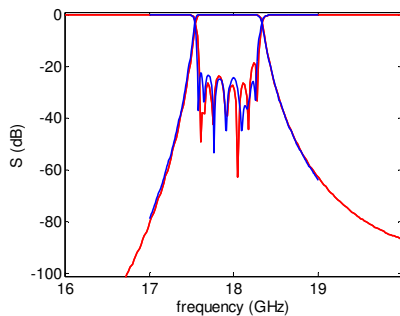
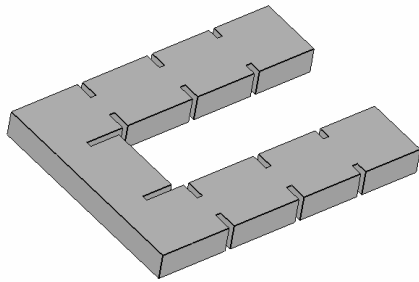


Fig. 10. Folded filter designed with the automated procedure

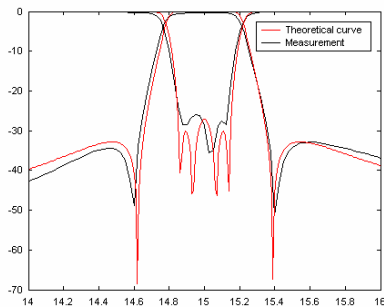
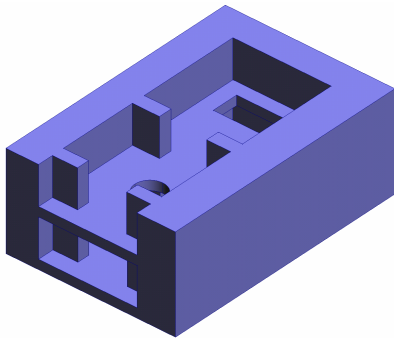


Fig. 11. Cross-coupled filter designed with the automated procedure

C. Diplexer design

Next, the two filters must be combined with a three-port junction to form a diplexer. The simplest diplexer design is achieved if a Y-junction is chosen [7], but in most cases there are strong mechanical restrictions on the shape of the junction such that T-junctions are more applicable. The procedure for adapting separate filters and junction to form a diplexer is as follows

1. Connect the filters to the junction and adjust the distance between the filters and the junction until

the reflection coefficients at the common port is optimized.

2. Adjust the two couplings and the length of the two resonators closest to the junction until the reflection coefficients at the common port is optimized.
3. Successively add adjacent couplings and resonators to the optimization variables, and adjust the dimensions until the return loss requirements are fulfilled.

Fast convergence is obtained if optimization is only done on the filters' transmission poles.

This method has also been fully automated using Matlab and Wasp-Net [6]. Fig. 12 shows measurements and simulations of a metal insert diplexer designed using this approach.

III. EXAMPLE

Fig. 13 shows an example of a diplexer variant planned and designed using the approach described in this paper. It was found that a seventh order filter was necessary to cover 4 channels in the lower 6 GHz frequency plan. Temperature effects are taken into account but tolerance effects are neglected because diplexer tuning is used to account for mechanical inaccuracies in this case.

IV. CONCLUSION

Short time-to-market requires clever planning of diplexer variants and short (preferable automated) design cycles. In this paper we have shown that this can be achieved by using accurate trained circuit models and accurate CAD tools in combination with reliable design methodology.

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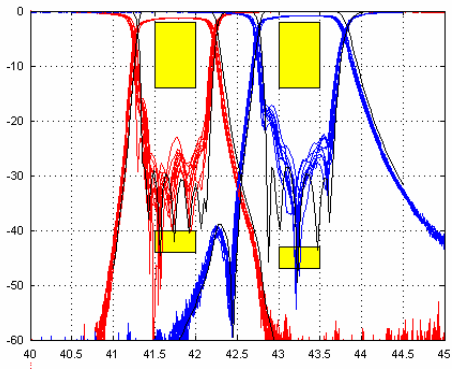
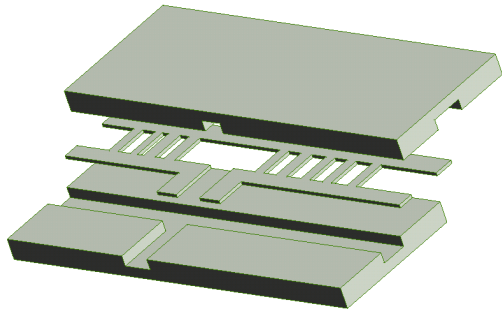


Fig. 12. Metal-insert diplexer.

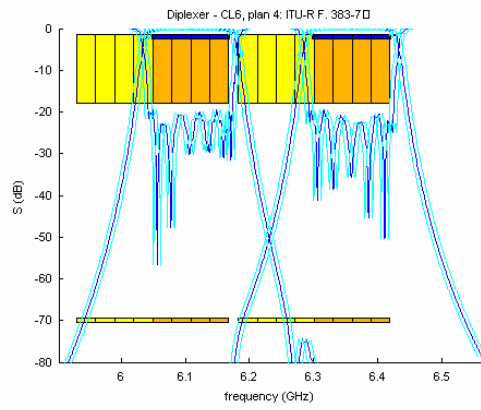
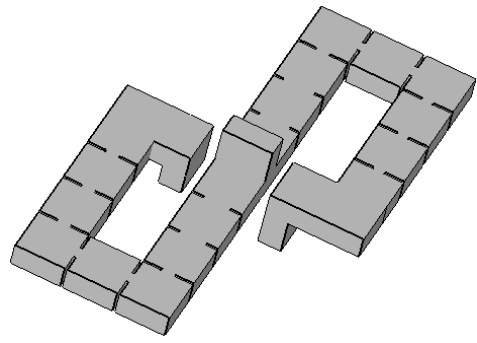


Fig. 13. Folded diplexer