

## A DESIGN PROGRAM FOR DIGITAL AND ANALOGUE FILTERS: PANDDA

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INTRODUCTION

A number of software tools have been introduced [1-5], capable of producing high-quality integrated filter circuits automatically from initial attenuation and phase specifications. Modern IC filters pose more difficult design problems which cannot easily be solved by traditional methods. There is a wider choice of filter structures and an increase in the complexity of their design procedures. Requirements of non-classical frequency responses are introduced by sampled-data systems and modern communications specifications. The constraints imposed by the realisation technology imposes certain design limitations such as stray-capacitance insensitivity, capacitance area limitations and non-ideal circuit parameters. A good filter design usually involves some trade-off between these factors. With these problems in view, PANDDA, a new filter design system, is introduced. It has the following distinguishing features:

1. The design of general forms of amplitude and group delay response.
2. Easy construction and comparison of the many different filter structures, especially to allow new structures to compete with the popular, well-tested ones.
3. Optimisation methods to improve the performance of circuits within physical constraints.

PANDDA has a very general and flexible approximation capability allowing frequency responses to be tailored very closely to the specifications. A wide variety of different filter realisations can be designed and compared quickly. Although the emphasis is on switched-capacitor filters, active-RC and digital filters can also be derived. All filters are stray-insensitive and based on a regular structure suitable for automatic layout on gate-array type chips. The main sections of the program are indicated in Fig.1 and their salient features are now described.

PROGRAM FEATURESSpecification

The frequency response is defined either by parameters of a classical approximation or as a piece-wise linear tolerance plot of filter attenuation and group delay.

Filter options require selection of design method (biquad, LUD, coupled biquad, leapfrog etc.), circuit implementation (switched-capacitor, active-RC, digital), non-ideal circuit parameters (unit capacitance, switch resistances, op-amp parameters, wordlength) and scaling directives.

Approximation

Classical approximation methods have been implemented, most notably the elliptic approximation by Darlington's method [6].

Specialised amplitude responses may be designed by a combination of Remez-exchange [7] and Newton [8] approximation algorithms. Recent theoretical work has revealed that the Remez exchange method is a special case of a more general minimax approximation algorithm based on Newton's method. The new approach permits the order of tangency of certain extreme points (touch points) of the amplitude response to attenuation boundaries to be specified. A combination of the algorithms offers a stable and efficient method of designing a wide class of transfer functions. Passband forms which lie between conventional equiripple and maximally-flat may be designed. High order touch points may be used to smooth the amplitude function near the band-edge to reduce the delay peaking, and improve sensitivity.

The designer has the freedom to specify the sequence of passbands and stopbands and the distribution of touch points in each. The attenuation function in each band is specified by a pair of arbitrary piece-wise linear boundaries between which a linear-phase FIR, IIR or multi-rate transfer function will be fitted. Arbitrary weighting functions may be superimposed onto the passband or stopband specifications such as those required to correct  $\text{sinc}(x)$ , LDI termination error or transmission line attenuations.

All-pass transfer functions are designed by a new algorithm [9] to equalise the group delay response of amplitude filtering stages. In general, the group delay can be fitted between a pair of arbitrary piece-wise linear boundaries specifying group delay against frequency. High order touch points may also be introduced into the delay response.

Prototype Design

The basis of the succeeding filter design stage is either a normalised doubly-terminated LC ladder or a transfer function in factorised form.

Design of passive ladder networks is accomplished by an extension of an iterative design method due to Orchard [11] in conjunction with a simplified insertion-loss synthesis [12] program. The latter is used to set up the structure and provide initial component values for the iterative part. Features of the iterative algorithm are very good accuracy and the ability to design high order networks (up to 100th). It is therefore useful for accuracy refinement and order augmentation.

Passive ladder networks are of particular interest for operational simulation by active and digital circuits because the low-sensitivity properties of the original passive prototypes are usually inherited by their simulations. Ladders with minimum node configurations can be most efficiently simulated. Negative element values are permissible and are even useful to eliminate certain excess components in the filter. These special considerations are provided for in the ladder prototype synthesis software.

Filter Design and Scaling

A variety of filter designs are available, including type-E, type-F or all-pass biquads [14] and coupled-biquad, LUD or leapfrog bilinear ladders [15]. Among several new ladder simulations [13], LUD structures are notable because of the absence of unswitched capacitor loops and good capacitance spread for narrow bandpass applications. Simulation of highpass ladders is achieved by the modulation method of [16] and bandstop ladders by the new twintor circuits [17]. Interesting comparisons of the sensitivities, component value spreads and size of the different structures can be quickly made.

All filter structures are designed by matrix methods [13]. A matrix system is a very concise and flexible means of representation of a wide variety of networks. Each non-zero entry in a matrix represents the connection of a building-block between nodes. Building-blocks may belong to a variety of different technologies e.g. Miller integrator in active-RC, LDI integrator in switched-capacitor (SC) and delay element in digital. The sparse structure of the matrices is known at the design stage and this information is used to provide a fast internal analysis for dynamic range and capacitance spread scaling. Some tradeoff between these two factors is available to reduce any large capacitors.

Various permutation strategies for pairing the poles and zeros of biquad cascade networks are available to improve their total capacitance. A similar result is obtained by re-ordering of the sequence of zero removals for passive ladder simulations.

#### Analysis

An internal network description may be translated into an external format suitable for layout or analysis by standard programs SWAP, SWITCAP, SCNAP or SPICE. It is intended that this will only be necessary as a final independent verification of the filter response since PANDDA contains fast internal analysis programs making it possible to monitor the status of the design at all stages. Sensitivity, amplitude and group delay evaluation are all available.

#### Optimisation

Fast frequency analysis of non-ideal switched-capacitor circuits is available from the QUICKSCNAP program [18]. Results of a passband analysis of a filter with realistic switch resistance and op-amp parameters will reveal some deviation from the designed frequency response. Correction of the error is achieved by pre-distorting the attenuation specifications and re-designing the filter. This simple optimisation scheme has the advantages of reducing the order of the problem and permitting easy control by the designer. The amount of computation involved is based, not on the number of components in the final structure but on the original filter order (e.g. a typical 10th order SC filter has 40 capacitors). Experience has shown that some improvement can be obtained for many realistic problems. Re-design time is small compared to analysis time.

#### Filter System Design

Filter blocks such as anti-aliasing filters, amplitude filters, delay equalisers and decimators can be compiled separately using the above steps and linked together in some sequence for overall analysis or layout. Some overall approximation for the filter system is possible by optimising the response of each block for the influence of other blocks.

#### DESIGN EXAMPLES

*Example 1* : A 10th order bandpass filter response was designed to meet a set of non-classical amplitude specifications (Fig. 2). The passband edges are 300Hz and 3400Hz and sampling frequency is 240kHz. A third order notch is placed at 0Hz in the lower stopband and the passband is sloping and ripple is tapered. A 10th order all-pass delay equaliser was then designed to correct the group delay of this filter to within 50 $\mu$ s over the range 600Hz to 3000Hz (Fig. 3).

*Example 2* : A sixth order LUD filter circuit, designed to typical modem channel filter specifications with sloping passband, is illustrated in Fig. 4. Simulation with severe circuit parameters, shows a distortion of the passband, removal of a ripple and shift of band edge frequencies (Fig. 5). An optimisation sequence to restore the sloping passband, required 6 iterations and 5mins CPU time on a MicroVax II computer.

*Example 3* : A 20th order bandpass LUD ladder filter is shown in Fig. 6. Distortion due to long settling times as signals oscillate around the chains of capacitors and op-amps is particularly severe in high order ladder networks. In this example, Fig. 7, the chains have been broken by the introduction of negative element values in the ladder prototype causing certain capacitors in the simulation circuit to be omitted. Figs. 8a, b show the frequency response. Notice that the passband ripple is designed to be smaller near the passband edges for better sensitivity [19].

#### CONCLUSIONS

A new program for filter design has been introduced. Several advanced facilities which remove traditional design limitations have been illustrated. Amplitude and group delay responses with high order touch points and arbitrary weightings can be designed to meet non-classical filter specifications. A wide variety of filter realisations can then be quickly obtained.

Both ladder and biquad topologies are available plus several new structures. PANDDA also offers a set of efficient optimisation facilities to improve the final designs within physical constraints. Filter blocks can be compiled individually and then linked into an overall filter system comprising anti-aliasing filters, delay equalisers, amplitude filters and decimators.

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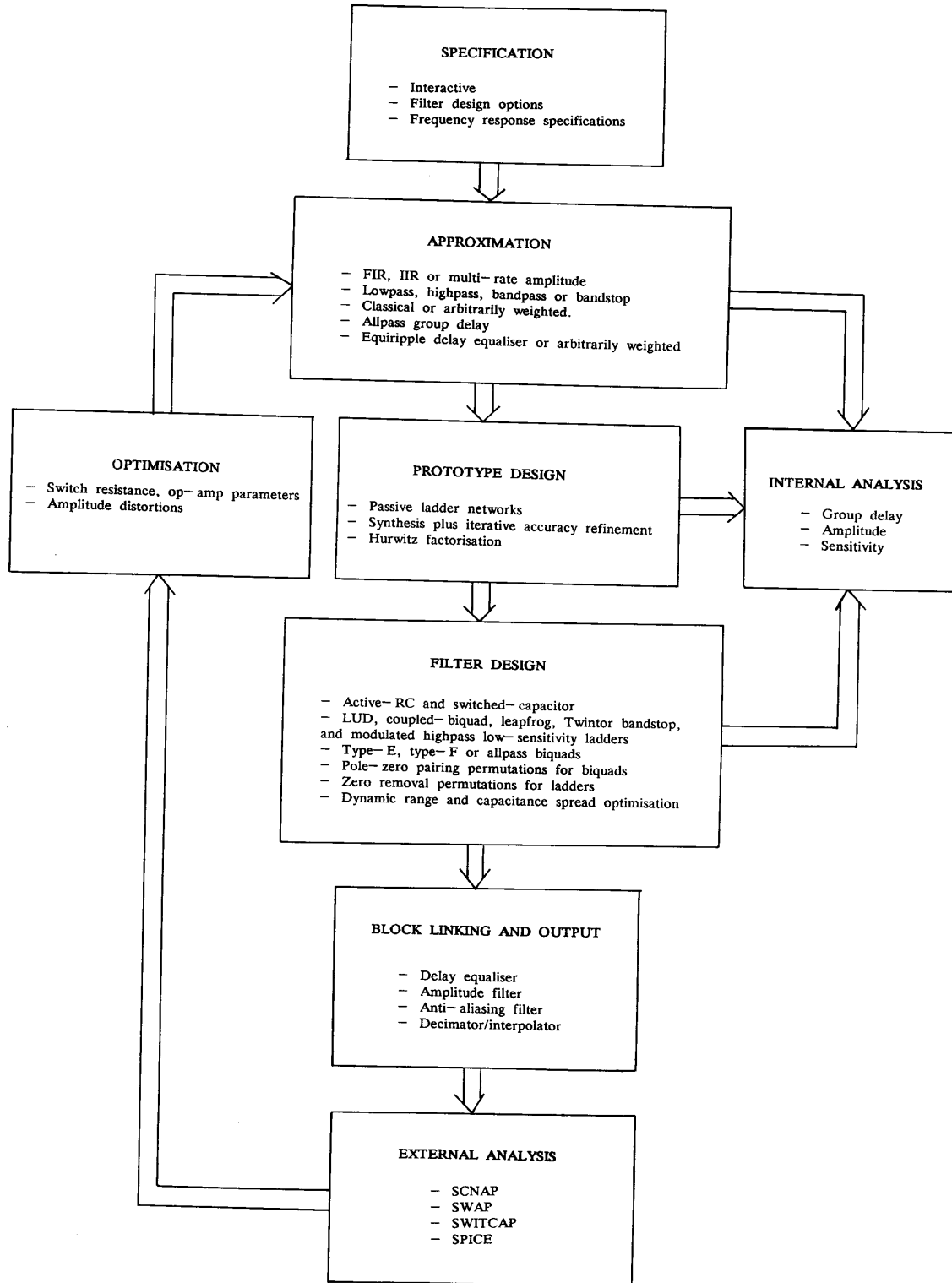


Fig. 1. PANDDA filter design system

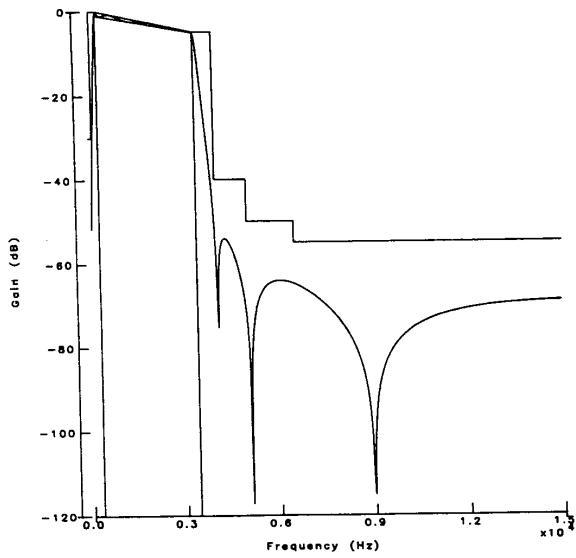


Fig. 2. 10th order bandpass amplitude approximation

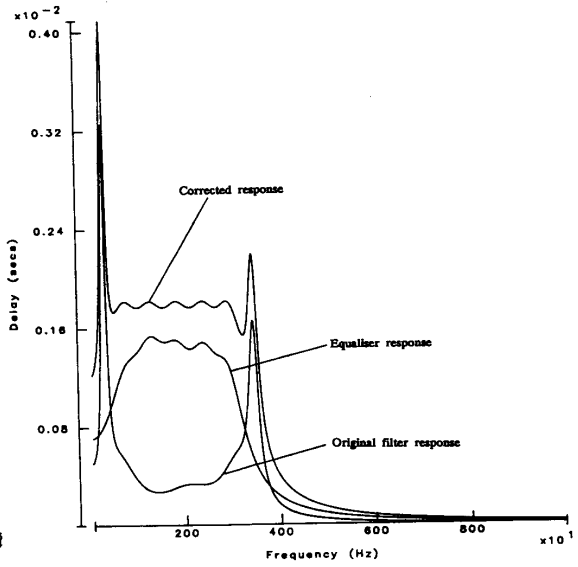


Fig. 3. Group delay equalisation of the 10th order bandpass filter

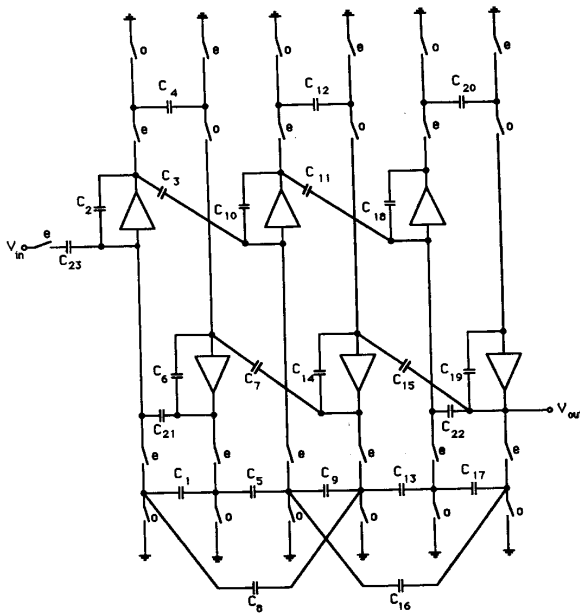


Fig. 4. 6th order SC LUD filter realisation

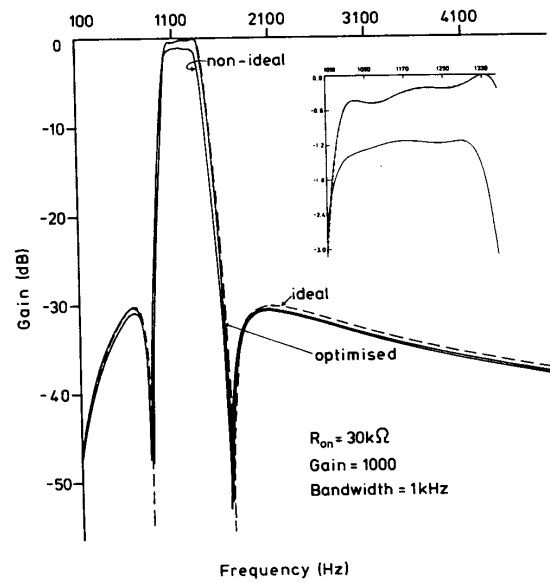


Fig. 5. Comparison of ideal, non-ideal and optimised frequency response of a 6th order bandpass SC filter.

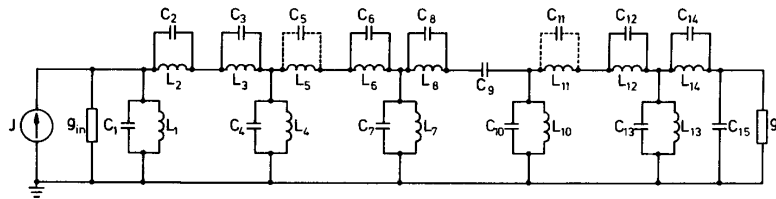


Fig. 6. A 20th order ladder prototype.

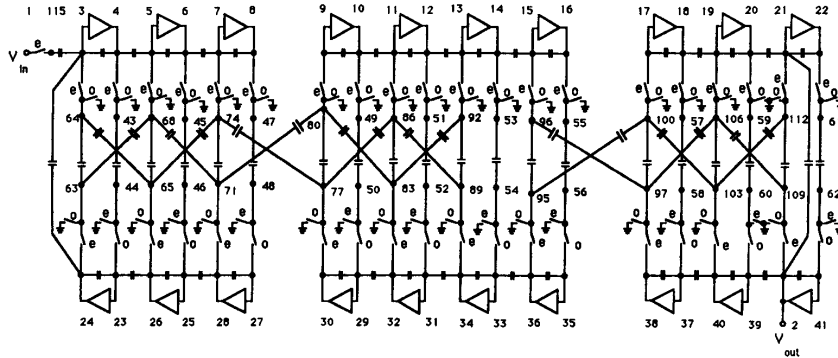


Fig. 7. An LUD SC realisation of the 20th order ladder.

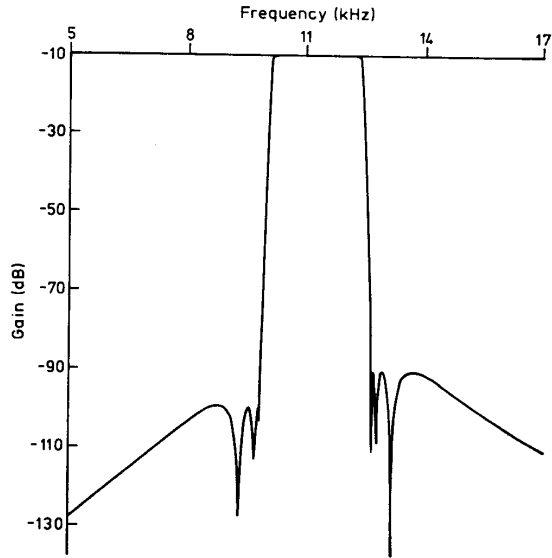


Fig. 8a. Frequency response of the 20th order LUD filter.

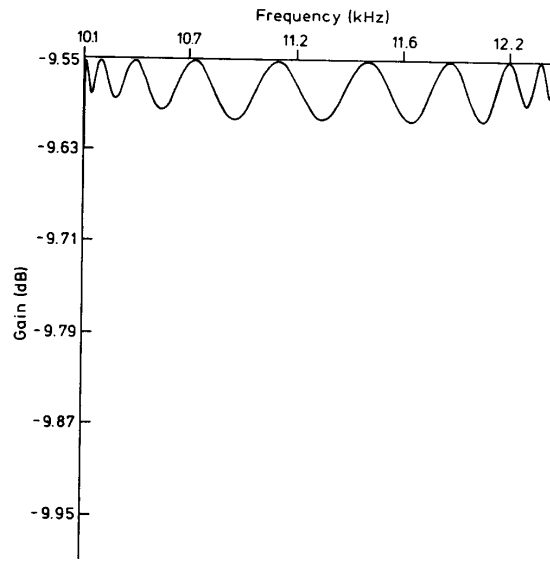


Fig. 8b. Passband detail of the 20th order LUD filter.