Review Article

Enhanced Digital Acoustic Perception in Hearing Aid Device Using Reconfigurable Filter Bank Structure: A Systematic Review with Recommendation

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Citation: Karuppaiah R, Seerengasamy U, Boobalakrishnan N. Enhanced Digital Acoustic Perception in Hearing Aid Device Using Reconfigurable Filter Bank Structure: A Systematic Review with Recommendation. Aud Vestib Res. 2025;34(2):?-?.

Article info:
Received: 20 Jul 2024
Revised: 02 Oct 2024
Accepted: 05 Oct 2024

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Short running title: Enhanced Digital Acoustic Perception in…

Highlights:

- Addressing hearing loss with portable hearing aid enhances the quality of life
- Design of filterbank is the crucial component of digital hearing aid device
- The optimal filter architecture maximizes the performance of filterbank

ABSTRACT

Background and Aim: Untreated hearing loss can severely impact quality of life, mental and physical health, and cognitive performance. Digital hearing aids can mitigate these effects, with the filter bank being a crucial component. It divides signals into frequency bands, compresses, amplifies, and processes speech based on the user's hearing profile. This study focuses on optimizing filter bank architecture in terms of hardware cost, processing speed, and adaptability to enhance the efficiency of digital hearing aids.

Recent Findings: Each filter bank in digital hearing aids relies on Finite Impulse Respons (FIR) filters, and optimizing their architecture is crucial for optimal device performance. Literature suggests that reconfigurable digital FIR filters are preferred for filter bank structures. However, their performance may vary based on specifications such as filter length, bandwidth, sampling frequency, and coefficients. Therefore, this review aims to identify an optimized reconfigurable FIR filter design that improves hearing aid performance while ensuring its parameters remain independent of these specifications.

Conclusion: A hardware-efficient, optimized, and adaptable parallel computing architecture for hearing aid filter banks has been identified from the literature survey. This proposed architecture features reconfigurable sub-band frequencies tailored to the user's specific hearing loss, utilizing a Coefficient Scanning Mechanism (CSM) and

Floating Point-Computation Sharing High-speed Mechanism (FP-CSHM). The CSM dynamically adjusts sub-band selection and reorganizes the FIR structure in each filter bank to reduce multiplication counts based on coefficient matching. The FP-CSHM enhances computation speed by eliminating redundant calculations through parallel processing.
Keywords: Hearing aid; hearing loss; audiogram; hearing threshold

Introduction

A hearing aid device is an electroacoustic transducer that compensates for hearing loss by boosting specific frequencies based on hearing impairments. Individuals with noise exposure, hereditary disorders,or limited healthcare access due to cost and less availability of audiologists, could benefit from customized hearing aid device [1]. The lack of sufficient hearing aid device leads to communication difficulties, social isolation and safety risks. As of 2024, World Health Organization (WHO), majority of hearing-impaired people with hearing loss reside in areas with few resources. Based on age, India has high rates of hearing loss affecting 2.4% of children, 9.5% of adults under 65,and 48% of seniors over 65 years. Research and innovation are essential for addressing these challenges and for enhancing the availability, affordability, and functionality of hearing aid devices. These advancements aim to improve global hearing healthcare, especially in resource-limited settings, for better access and effectiveness [2].

The filter bank architecture significantly affects the cost and complexity of hearing aid manufacturing. The proposed review suggests design alternatives for the filter bank structure, incorporating CSM and FP-CSHM in each bank's of FIR filter to enhance the efficiency.

Architecture of digital hearing aid device

The major functional component in digital hearing aid includes analysis filter bank, processing unit, and synthesis filter bank as shown in Figure 1. A multi-band filter bank structure as shown in Figure 2 uses multiple bandpass filters to separate the sound into distinct frequency bands [3, 4] to meet individual hearing needs.

The input audio signal is converted into an electrical signal using a microphone (transducer), and the digital signal X(n) has been arrived by passing the electrical signal to the analog to digital converters, which is passed through a bandpass filter structure. Each filter isolates specific frequency bands and processes it individually. The output of each filter represents a subcomponent X0(n), X1(n) corresponding to each isolated frequency band. This is down-sampled for differing gain based on the hearing loss and acoustic environment [5]. An audiogram is used to determine the required gain for each band [6]. Hearing aids are designed for an audio range from 20 Hz to 20 kHz, with increased sensitivity between 2 kHz to 5 kHz, where speech sounds occur. Aging reduces high frequency hearing due to damage of hair cells and basilar membranes. For enhanced auditory compensation, fewer sub-bands should be allocated to the mid-frequency range (250 Hz to 4 kHz), compared to the lower (20 Hz to 250 Hz) and higher frequency ranges (4 kHz to 20 kHz) [7]. Improved frequency resolution could aid those with severe high frequency loss, with the number of subbands tailored to individual hearing profile.

The processed bands are combined back into a reconstructed audio signal X^(n) by using a synthesis filter bank as shown in Figure 3. After processing, the individual frequency bands are up-sampled to obtain high quality output. In hearing aid, multi-rate filter bank system reduces computational load, memory usage, power consumption, and simplifies filter design, while optimizing processing and improving sound quality. Selecting the right filter bank is mandatory [8] for natural sound reproduction.

Filter bank types in hearing aid device

Hearing aids utilize linear and non-linear digital filters to enhance sound processing, improve speech clarity, reduce noise, and customize sound based on the user's hearing profile. Digital filters are vital in modern hearing aids due to its flexibility, programmability, accuracy, and efficiency, especially with Very Large Scale Integrated Circuits (VLSI) advancements [6]. Linear filters produce outputs that are linear functions of the input, to attenuate gain of specific frequency ranges to reduce noise, and use notch filters to suppress feedback. Non-linear filters adapt dynamically to input signals, providing soft range compression, advanced feedback suppression, dynamic noise reduction, and customized listening experience.

As shown in Figure 4, digital filters are divided into FIR and Infinite Impulse Response (IIR) filters. FIR filters, with finite impulse responses, are used for equalization, noise attenuation, and echo cancellation. They ensure phase response and stability, but requires more computational power. IIR filters with infinite impulse responses, are computationally efficient with fewer coefficients, but may introduce phase distortion. They are used for adaptive filtering in hearing aids. FIR filters [6] are ideal for precise frequency shaping, while IIR filters are suitable for adaptive filtering.

FIR filters in hearing aids shape frequency response to compensate for hearing loss by processing discrete-time signals. The FIR filter is designed by using the gain from the user's audiogram [9], and by using appropriate filter design algorithms. The filter coefficients are monitored and adjusted as needed. Depending on the application, multiple sets are generated manually or algorithmically. Different sets of coefficients are applied to the FIR filter, and the performance is evaluated using frequency response, time domain response, and error metrics.

Filter banks are categorized into uniform and non-uniform types based on sub-band distribution. Uniform filter bank divides the input signal into equal bandwidth frequency bands, useful for noise reduction, equalization, and speech enhancement. Non-uniform filter banks, which mimics the human ear, divides the signal into varying bandwidths, use it for precise frequency analysis and better align with audiogram, particularly for cases like sensorineural hearing loss.

Early hearing aid systems used uniform filter banks, based on techniques like Discrete Fourier Transform (DFT) [10, 11] and cosine modulation [12, 13], or interpolation methods [14], which often resulted in poor audiogram matching. Non-uniform filter banks, designed using logarithmic or non-uniform spacing, adapt better to individual audiograms [15], despite potentially higher Maximum Matching Error (MME) [16].

Filter banks are classified into non-reconfigurable (fixed sub-band distribution) or reconfigurable type (adjustable sub-bands) [17]. Reconfigurable filter banks dynamically adjust parameters like center frequency to meet user needs. High-order FIR filter banks could be computationally complex, with increased fabrication area and power consumption. Multiplier-less architectures helps to reduce this complexity with improved performance and efficiency. In hearing aid design, the Frequency Response Matching (FRM) [18] approach uses sharp narrowband filters with sparse coefficients to reduce computational complexity when combined with half-band filter designs. Half-band filters, requiring fewer multiplications, are suitable for multi-rate processing [19]. FRM offers a sharp response with reduced filter order, thereby enhancing power efficiency and real-time processing.

Additional techniques include frequency warping [20] for alignment with human hearing, Interpolated FIR (IFIR) [21, 22] for desired frequency response, and multi-rate [23] processing for optimization. The 1/3 octave filter bank aids frequency analysis [24]. Transposed direct form FIR filters provide linear phase and stability with reduced complexity. Uniform and non-uniform linear-phase non-subsampled filter banks are used in real-time audio processing, while selective filter banks require the high-order linear-phase FIR filters.

Conventional digital hearing aids use fixed-bandwidth filter banks with fixed [25] passband edge frequencies to adjust sub-band gain based on the audiogram, which could lead to increased power consumption and complex architectures for accurate fitting. Most commercial hearing aids are limited by these fixed-band filter banks [26], struggling to accommodate steep slope audiograms [27, 28] and higher cost [25, 27] with more frequency bands. Variable filters referrerd to as ,"tunable", "adjustable", or "programmable", offer improved audiogram matching by adjusting gain and edge frequencies using sampling rate conversion or non-linear optimization as shown in Figure 5. This approach maintains filter order with varying bandwidth [29], and achieves good fitting with low-order sub-filters. Other new design approaches similar to the Interpolated Bandpass Method (IBM) [30, 31] use variable Low Pass Filter (LPF), variable Band Pass Filter (BPF), and variable High Pass Filter (HPF) to match audiograms to reduce the number of multipliers [32] while maintaining filter order [33] and power consumption [25].

While designing filter banks for hearing aids, key factors for consideration include minimizing matching error (up to ±3 dB) [34], ensuring high flexibility [6] for precise fitting for clarity, minimize power dissipation by minimizing hardware complexity with reduced number of multipliers. Smaller and less visible devices are preferred, though non-uniform filter design cause significant delays [35]. As portable devices, hearing aids must have minimal power consumption to prevent overheating and extended battery life [6]. Reconfigurable digital FIR filters should comply with International Electrotechnical Commission (IEC 60118-15) standards, and processed signals should be evaluated using International Telecommunication Union-Telecommunication Standardization Sector-Peseptual Evaluation of Speech Quality (ITU-T-PESQ) [36] for speech quality. Filters should achieve atleast 60 dB gain and a high stop-band attenuation to minimize feedback and improve magnitude response programmability [6].

Methods

In this systematic review, we analysed and evaluated filter bank structures in hearing aid by searching English language studies across online databases, including PubMed, Scopus, and Google Scholar. Using keywords like "filter bank", "hearing aids", "digital signal processing", "frequency response", "filter design", and "performance metrics", we identified 617 articles published from 2000 to 2024. After applying inclusion and exclusion criteria, we focused on studies accessing filter bank designs, their impact on hearing aid performance, and the methodologies used for optimizing frequency response and computational complexity.
To refine the selection process, we reviewed titles and abstracts, followed by full-text evaluations to extract data on design, filter bank methodologies, performance metrics, and key findings. The extracted data were organized and synthesized to provide a comprehensive overview of filter bank structures in hearing aids. A narrative synthesis approach was used to summarize the findings from the selected studies, detailing various filter bank designs such as uniform and non-uniform configurations, and their impact on hearing aid performance and their efficacy in improving auditory processing, power consumption, and overall hearing aid functionality.

Results

Reconfigurable filter bank structure for hearing aid device

Reconfigurable filter banks could be adjusted for the desired number of channels and control parameters to improve its adaptability in noisy environments. These modify parameters like sub-band bandwidth that changes the bandwidth dynamically, filter coefficients that change the filter response, sub-band method to select the required bandwidth, number of sub-bands selection to control location [37], filter selection based on the required cut-off frequency [38], and bandwidth along with central frequency to suit individual needs, without altering the filter structure. Reconfigurable filters alter filter parameters to reduce the discrepancy between the ideal and desired output. The reconfigurable filter bank used in hearing aid is as shown in Figure 6.
Reconfigurable filter banks allows for dynamic adjustment to fit individual hearing needs and addresses issues like delay, error, and power consumption seen in existing filters. They optimize key parameters like signal quality, area, speed, power, computational and hardware complexity, and auditory compensation. FRM-based reconfigurable filters can optimize audiograms by up to 60% and reduce delay by 20 to 40% with distributed sub-band schemes. Overall, reconfigurable filter banks provide flexibility, customization, and optimized performance while minimizing complexity and power consumption.
To overcome challenges in conventional hearing aids, such as delay, error, and power issues, a narrow bandwidth, high tuning flexibility, and configurable multiple-band spectral decomposition are required. Hearing aids raise the hearing threshold to improve hearing, but if gain is increased across all frequencies it results in discomfort and stress [26]. To avoid this, frequency range is divided into sub-bands, each with distinct amplification. Reconfigurable filter banks achieve this by adjusting gain only for necessary frequencies through multiple-band spectral decomposition.
Reconfigurable filter banks allow adjusting of frequency parameters without changing hardware. Fixed or uniform filter banks lack flexibility for audiogram fitting, and increasing the number of bands for better auditory adjustments raises cost and power consumption. Thus, designers should focus on reconfigurable filter banks with minimal modifications, fewer sub-bands, and narrow transition bandwidths. The ideal filter banks balances complexity with high auditory compensation. Digital hearing aids face challenges in flexibility and power. Enhanced flexibility improves fit and audibility, while reduced power consumption extends battery life [6]. Reconfigurable filter banks address these challenges, but careful optimization is required to manage performance and design complexity [6].

Techniques used for the design of reconfigurable filter in a digital hearing aid

Each bank in the digital hearing aids' filter bank structure uses the FIR filter. Selecting the optimized FIR filter architecture for filter bank structure is crucial for achieving best performance. From literature, it is identified that Reconfigurable-digital FIR filter is preferred for the filter bank structure of digital hearing aids. Techniques used to design a reconfigurable filter in a digital hearing aid are as shown in Table 1.

Discussion

The proposed reconfigurable, adjustable, hardware-efficient, and parallel processing filter bank architecture of the hearing aid device is obtained by optimising each individual bank's FIR filter. For this optimisation, each bank uses the FP-CSHM [43] and CSM techniques-based FIR filter. The FIR filter architecture proposed for each bank with FP-CSHM and CSM techniques are as shown in Figure 7. In FP-CSHM, redundant computations are eliminated by identifying common computations, known as alphabets. The partial products in this multiplication process are generated through addition and shifting, resulting in enhanced filtering performance with minimal register overhead. The detailed architecture for FP-CSHM is illustrated in Figure 8.

The CSM automation approach in FIR filters skips multiplication at coefficient indexes when the coefficient value is zero or matches any previous coefficient values. This method rearranges the FIR structure and selects sub-band frequencies based on hearing loss. For an 8-tap FIR-CSM, multiplication is bypassed at coefficient indexes 4, 5, 6, and 7. A symmetric FIR-CSM filter ensures at least a 50% reduction in the number of multiplications. Consequently, CSM and FP-CSHM provide a reconfigurable, hardware-efficient, parallel computation architecture for FIR filters, forming the filter bank structure in hearing aid devices. The algorithmic procedure for implementing the CSM mechanism is depicted in Figure 9.

Figure 10 shows the proposed filter bank structure for digital hearing aids using the FIR-CSM filter. According to published data, current hearing aid filter banks consume nearly half of their hardware costs. Designing a more efficient filter bank structure can significantly reduce this. FIR-CSM offers several advantages: it halves hardware costs by removing redundant multiplications and increases system speed. FP-CSHM further reduces computation time by replacing multiplications with add-and-shift techniques and parallel processing. Together, CSM and FP-CSHM enable a more compact, efficient filter bank design that is compatible with existing hearing aid models, reduces complexity, saves power, and lowers manufacturing and maintenance costs without compromising performance.

Conclusion

The objective of this review is to introduce an innovative filter bank structure for hearing aid devices, which accounts for reduction in hardware cost and computation speed. An in-depth survey was carried out relating to hearing loss, types of existing hearing aids, design alternatives, and filter bank structure in order to propose a novel filter bank structure that lowers manufacturing costs with minimal usage of hardware resources and by modifying its band frequencies in accordance with the severity of hearing loss. The proposed filter bank structure for hearing aid device uses Coefficient Scanning Mechanism (CSM) and Floating Point-Computation Sharing High-speed Mechanism (FP-CSHM) mechanism in FIR filter which is present in each bank of the filter bank structure. CSM algorithm automatically takes coefficients of each bank as its input, rearranges the Finite Impulse Respons (FIR) structure with reduced hardware and reconfigures the band frequencies based on the hearing loss rate. This algorithm guarantees a minimum reduction in multiplication count equal to half of the filter length, regardless of the filter specification. This approach, therefore, reduces the hardware need of the FIR filter by half when compared to alternative approaches. The FP-CSHM algorithm increases the speed of the computation by removing redundant computation and replaces multiplication operation with add and shift technique. Hence, a reconfigurable, simplified hardware efficient and cost-effective hearing aid device is possible with the proposed FIR-CSM filter bank structure.

Ethical Considerations

Funding

There are no funding sources for our work.

Authors' contributions

RK: Design study, literature work, and drafting the manuscript; US: Reviewing the literature survey, revision of the manuscript and finding novel architecture to overcome the gap of previous research; NB: Statistical guidelines, manuscript orientation and revision of the manuscript.

Conflict of interest

There is no conflict of interest.

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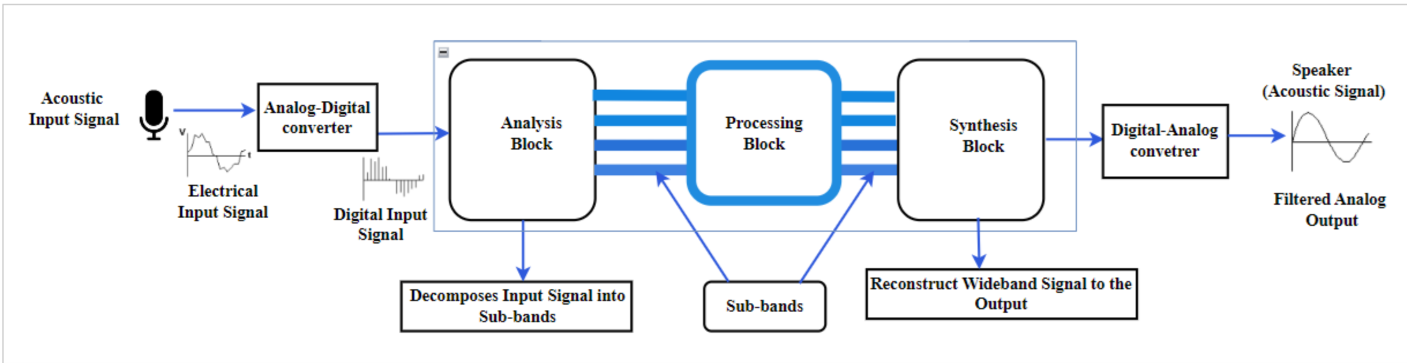

Figure 1. General structure of hearing aid device

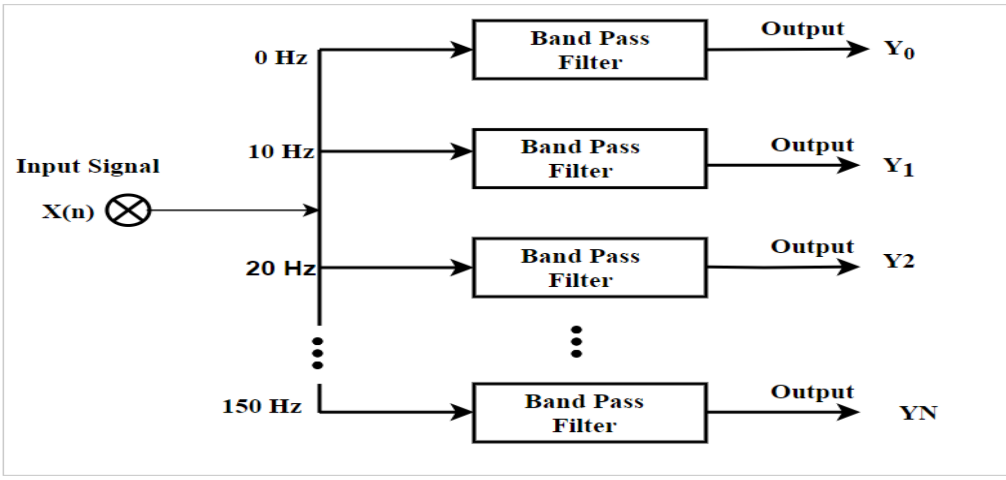

Figure 2. General structure of filter bank

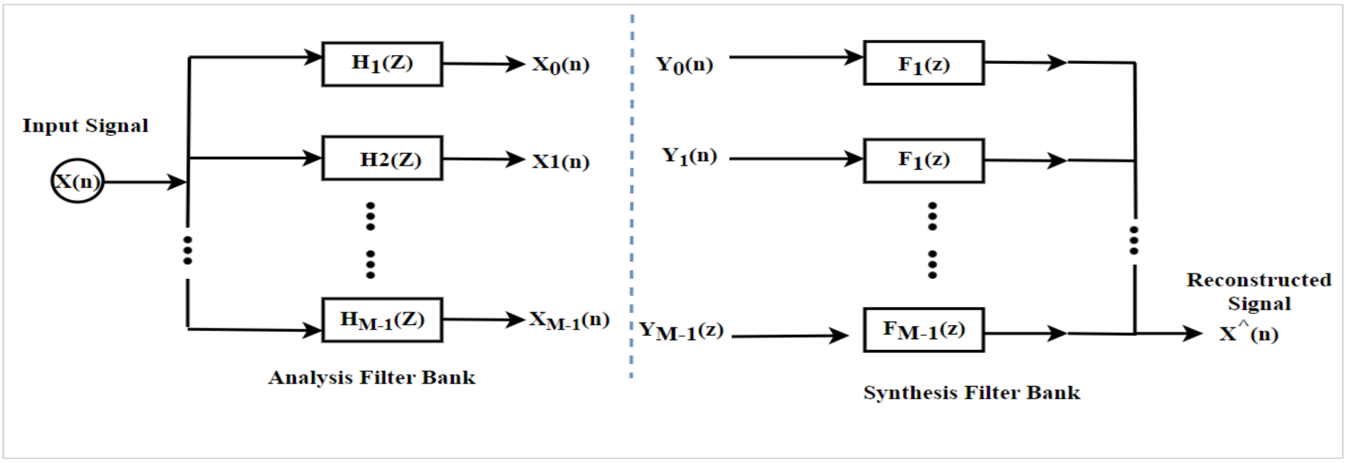

Figure 3. Analysis and synthesis filter bank

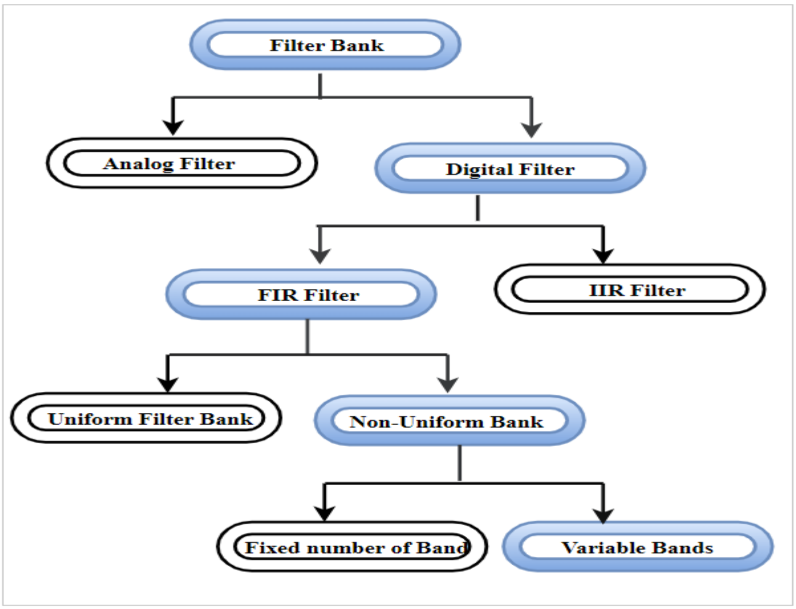

Figure 4. Types of filters in hearing aid devices

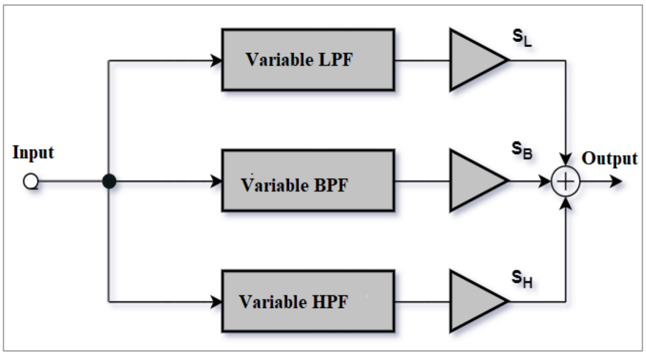

Figure 5. Variable filter-bank

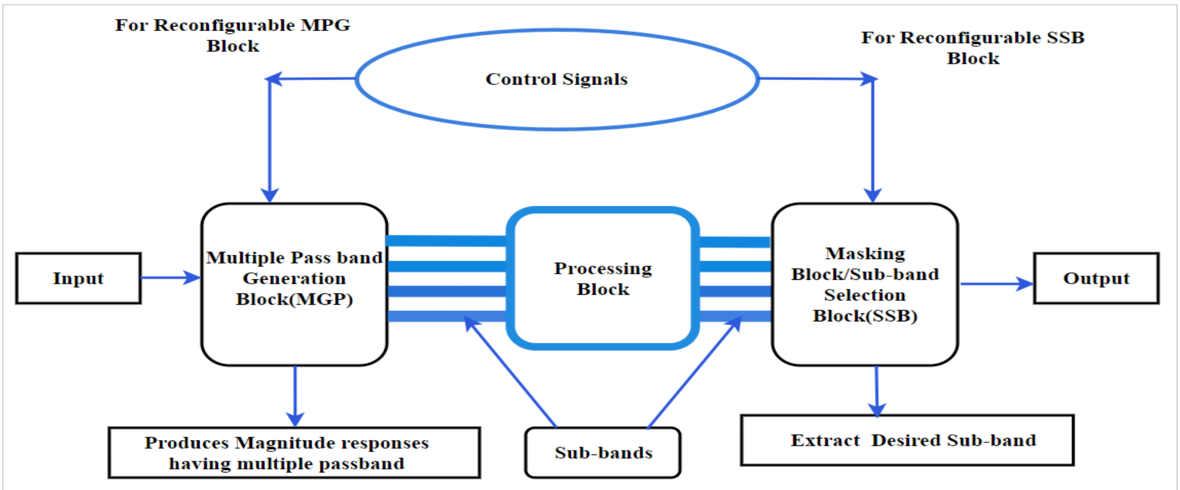

Figure 6. General structure of reconfigurable filter bank used in hearing aid device

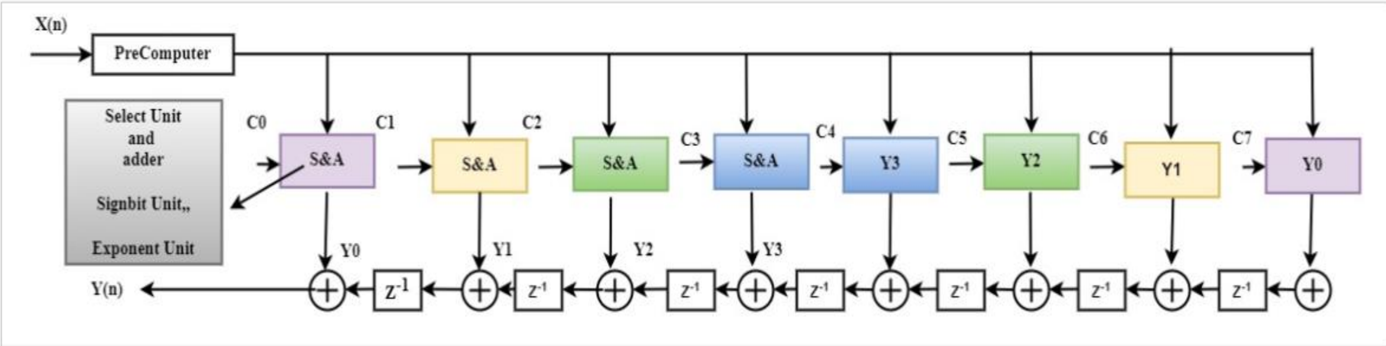

Figure 7. Proposed 8-tap finite impulse response filter design using floating point-computation sharing high speed multiplier and coefficient scanning mechanism

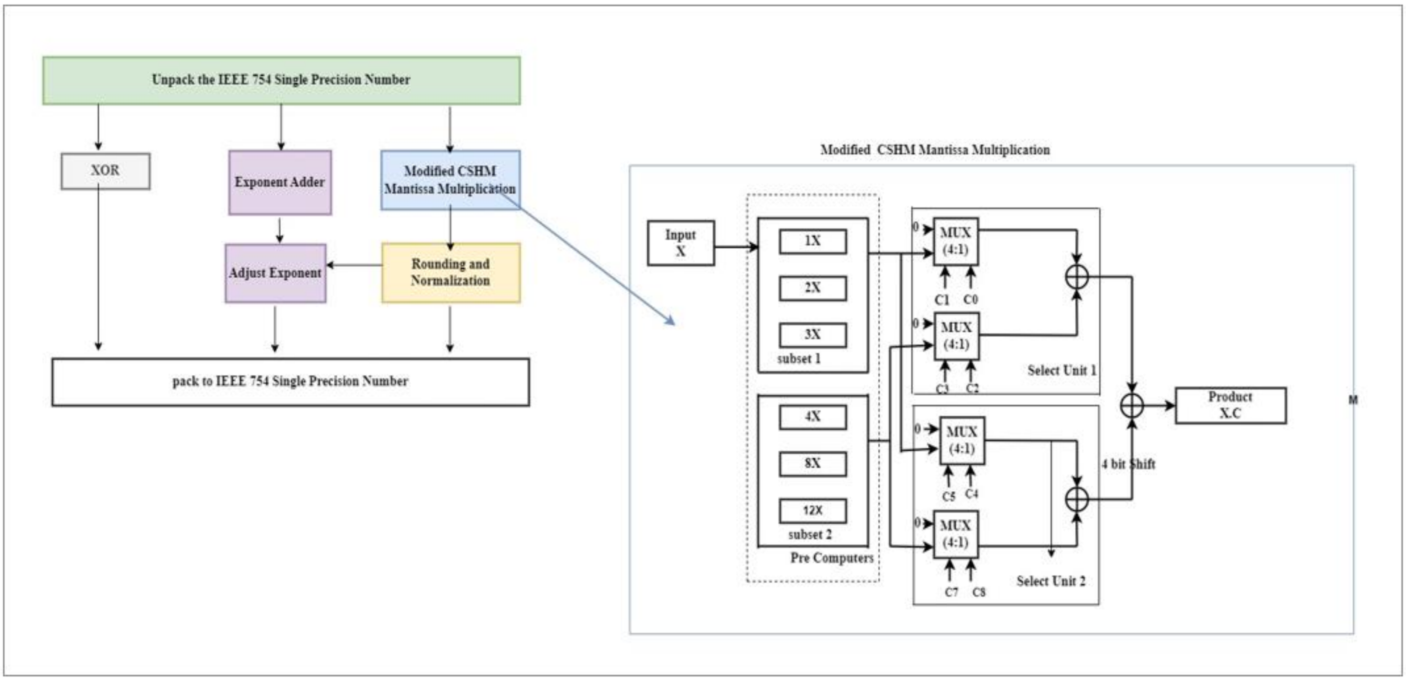

Figure 8. Floating point-computation sharing high speed multiplier architecture

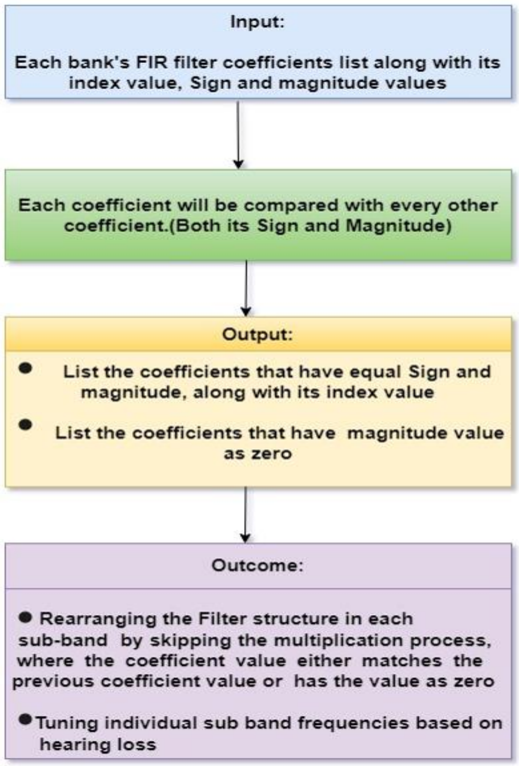

Figure 9. Automation algorithm used to implement coefficient scanning mechanism

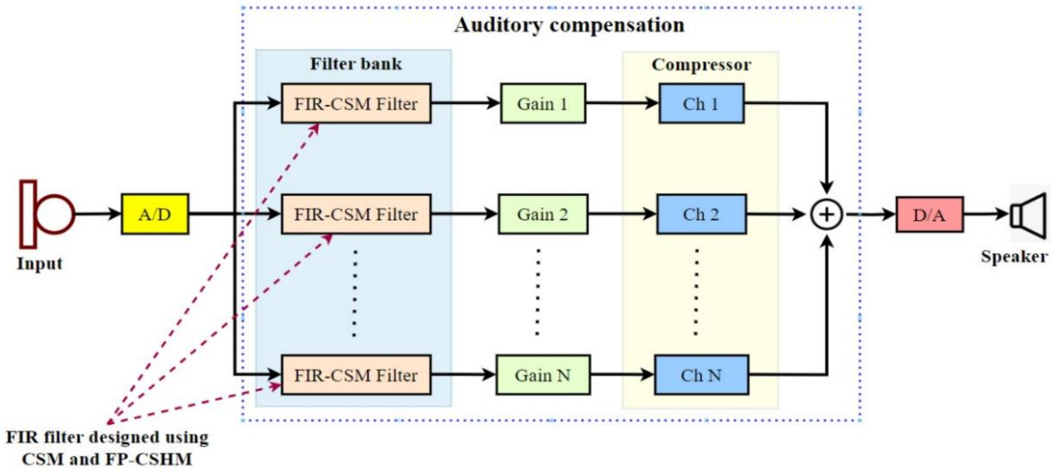

Figure 10. Proposed filter bank structure of hearing aid device using finite impulse response-coefficient scanning mechanism

Table 1. Techniques used for designing reconfigurable finite impluse response filter

Reconfigurable digital FIR filter design approach	**Description**	**Inferences**
Distributed LUT arithmetic multipliers [39]	1. To reduce the area and power consumption for each sub-filter inside the filter bank, the conventional multiplication approach has been substituted with memory-dependent DA multipliers based on dual-port LUT. 2. Implemented using CMOS gpdk45 nm technology file.	With the input sample size w=4, the LUT-DA-based filter bank design outperforms the conventional multiplier-based filter bank design in terms of area reduction (24%), power reduction (22%), and delay improvement (24%).
FRM (proposed I) and non-maximally decimated filter bank system (proposed II) reconfigurable architectures [40]	1. Appropriate for precise wideband channelizers 2. When several bandwidths are realized, these approaches are advantageous. 3. A considerable reduction in both multipliers and adders effectively contributes to the overall size reduction in hardware.	Compared to farrow structure-based filter bank 1. In the proposed method I, there is a reduction of 0.33% in the number of multipliers, while in the proposed method II, with a reduction of 4.87%, it is more significant. 2. The number of adders is significantly decreased in both proposed methods, with a reduction of 58.7% in method I and 49.3% in method II. 3. Both proposed methods yield substantial computational savings, with a 69% reduction in method I and a 67% reduction in method II.
CLS non-uniform dynamic filter bank and CDM [41]	1. The unweighted integral square error is the focus in constrained least square FIR filter design. 2. The coefficient decimation method , produces the original frequency response reduced to a decimal version.	Proposed filter bank structure requires only 74 multipliers and 73 adders per sample which is equivalent to 50% reduction in multiplication operation per sample.
Farrow structure-based design [17]	The farrow structure could be used to successfully implement a variable bandwidth filter, where the overall filter response depends on the weighted linear combination of individual FIR sub-filter.	The proposed design minimizes the hardware overhead associated with implementing non-uniform frequency bands.
Variable bandwidth filter based design [42]	1. The proposed variable bandwidth filter offers the flexibility to modify the filter's bandwidth without changing the filter's order or coefficients. 2. Bandwidth reduction or enhancement is achieved by changing the input signal's sampling frequency.	The proposed variable bandwidth FIR filter achieves a significant 70% reduction in transition bandwidth and a substantial 50% reduction in hardware complexity compared to existing filtering methods.

FIR; finite impulse respons, LUT; look-up table, DA; distributed arithmetic, CMOS; complemetary metal oxide semiconductor, FRM; frequency response matching, CLS; constrained least square, CDM; coefficient decimation method