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Reconfigurable Filter Bank Design Techniques for Hearing Aid Performance Improvement

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Abstract: ***Hearing is one of the most crucial sense for human beings as it connects them to external world. Hearing loss impairs communication which is an essential human function. Hearing disability has massive negative impact on life, work, physical and emotional well-being as well as relationships and is rated as the third most common health problem affecting relations and quality of life. Hearing aid devices can selectively intensify sound signals in order to suit the hearing characteristics of the patients and is a boon for people with hearing misfortune. However, there is a huge gap between the potential and actual hearing aid users. This work provides a critical look into the various challenges posed by hearing aid users, the comparative of the existing state-of-art hearing devices and throws light on bottlenecks in hearing aid design and performance. Filter bank, being the holy grail of Digital Hearing aid, needs special attention for improving the hearing aid performance. Reconfigurability is the need of the hour for providing flexible and tailormade hearing aids that can suit individual hearing requirements. The paper discusses and gives an in-depth insight into the techniques for reconfigurable Filter bank design for performance augmentationin terms of parameters like Signal quality, Auditory compensation, Computational and Hardware complexity, area, speed, power, etc.***

Keywords:Frequency Response Masking, Hearing aid, Non-uniform Filterbank,Reconfigurable Filter, Variable bandwidth filter

I. INTRODUCTION

Hearing loss which impairs communication- an essential human function, is a leading cause of disability especially among older people and is rated as the third most common health problem affecting relations and quality of life. People with hearing loss above 40 decibels (dB) in the better hearing ear in adults and greater than 30 dB in the better hearing ear in children are considered having disabling hearing loss[50]. WHO report says- "Over 5% of the world's population (466 million people) has disabling hearing loss including 432 million adults and 34 million children[50]. This has increased from 360 million people five years ago[13].

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These eye-opening statistics furtherenvisages an enormous increase in the count of hearing-impaired subjects.

These 'Hard of Hearing' people can take advantage from hearing aids. However, current production of hearing aids meets less than 10% of global need and less than 3% of developing countries' needs. It is also estimated by WHO that by 2050 over 900 million people or one in every ten people will have disabling hearing loss [50]. Lack of treatment to this disorder might lead to Alzheimer's disease or hearing-impaired people might develop Dementia. The unaddressed hearing loss even costs countries an estimated US$ 750 billion annually in direct health costs and loss of productivity [50]. Though hearing aids can easily compensate for the majority of hearing losses, they are widely available only in the most highly developed countries. In United States, out of thehardly 16% of hearing impaired(aged between 20–69 years) and 30% of hearing-disabled (above 70 years) who can be benefittedusing hearing aids actually wears it [51]. The alarming growth rate of the hearing impaired and terrifying human tribulations associated with it indicates the dire need to address the research in augmenting the performance of existing hearing aids to ensure that it overcomes the bottlenecks which restricts the hearing impaired from using hearing aids and thus minimize the gap between the potential and actual hearing aid users leading to betterment of community.

Rest of the paper is organized as follows: Section II givesan overview of types of hearing loss, different auditory problems faced by hard-of-hearing people and how hearing aid plays a crucial role in overcoming this disheartening disability of hearing. This section also provides a comparative analysis of the state-of-the art hearing aids based on their features and performance. Section III elaborates about the crux of the hearing aid viz. filter bank and types of filter banks and comments of suitability of filter type for hearing aid application. Section IV presents a review of performance parameters to be considered for filter design and evaluation from the perspective of hearing instruments. Section V throws light on Reconfigurable filter bank which can enable hearing aids to become customized and tailor made as per the hearing profile of the patients and further scrutinizes the filter parameters that can be reconfigured in reconfigurable filter bank. Section VI presents a bird's eye view of the state-of-the-art Reconfigurable filter bank design techniques for hearing aid application. Section VIIelaborates the complete flow diagram of methodology of work. Section VIII presents results and puts forth few suggestions for performance improvement of hearing aids for discussion followed by concluding remarks.

II. HEARING LOSS AND ROLE OF HEARING AID

Sensorineural Hearing Loss (SNHL) is the most widely known hearing impairment. In SNHL, the cilia hairs present in cochlea in inner ear cannot distinguish cues of particular frequencies as expected. Hearing impeded individuals with SNHL also falls prey to the problem of Loudness recruitment. SNHL diminishes capacity to identify sound at a particular frequency in the presence of various existing frequencies.

The degree of hearing impairment of an individual can be gauged by taking their audiometry test. The audiogram obtained as a result of this hearing test highlights the hearing capability of patient over a varied range of frequencies by measuring patient's hearing threshold with respect to frequency. This auditory evaluation of hearing-weakened is done at each octave viz. 250Hz, 500Hz, 1kHz, 2kHz,4kHz and 8kHz owing to the fact that human ear responds to sounds in logarithmic manner and shows the mildest sound that the person can hear at different frequencies [6]. The audiogram provides a visual representation of hearing capacity of hearing challenged for varying frequencies andthus enables audiologist to interpret the hearing loss to be Mild Moderate, Severe orProfound depending on their hearing threshold as shown in Figure 1.

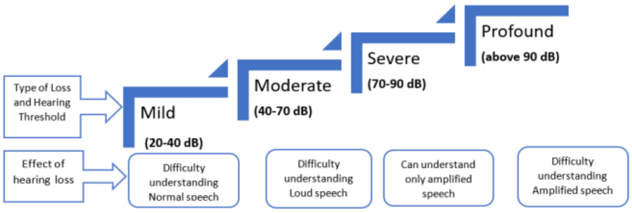

Fig. 1. Types of Hearing Loss with Hearing Threshold and their Effect

Hearing-impaired suffers from different types of auditory problems that diminishes their ability of understanding. If the hearing loss is below 45dB, then audibility is the main problem for hearing impaired whereas hearing loss beyond 45 dB indicates discrimination between cues to be a crucial challenge in hearing[39]. Also, hearing loss can be unilateral or bilateral. Hearing impaired subjects also experience reduced dynamic range and increased hearing threshold, reduced frequency resolution, reduced temporal resolutionand reduced spatial cues. These issues can critically affectspeech intelligibility of hearing-impaired[26]. Hearing aids have huge potential to enable hearing impaired with mild to severe hearing loss to listen and communicate in a better manner. Digital Hearing Aid compensates the reduced sensitivity of ear and thus improves hearing quality of patients with hearing misfortune. It is a well-established fact that when speech is heard and perceived at correct amplitude, it becomes more intelligible. In line with this, the fundamental role of hearing aid is to amplifyand process the input sound to provides best possible match to the audiogram of the patient and ameliorate their problems related to hearing impairment. The statistics published by World Intellectual Property Organization (WIPO) brings to the forefront the fact that significant amount of Research and inventions are being undertaken for hearing impaired for their hearing Restoration including Hearing aids as shown in Figure 2.

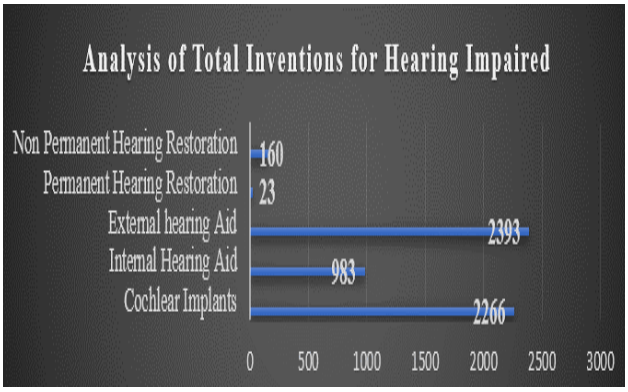

Fig. 2. Technical Categorization and Total Invention Count for the Assistive Devices and Technologies for Hearing Impaired Persons Technology Field [34]

Apart from design, verification and validation of Hearing aid is yet another crucial factor. Real-ear measurements (REM) is for verification of Hearing aid which is an objective measure of its performance. Verification provides clinician with confidence that they provide a quality hearing aid for greater benefit and satisfaction of hearing impaired[17]. However, literature suggests a wide number of audiologists(for Adults and Pediatricians) refrain from using REM during hearing aid fittings as shown statistically in Figure 3.

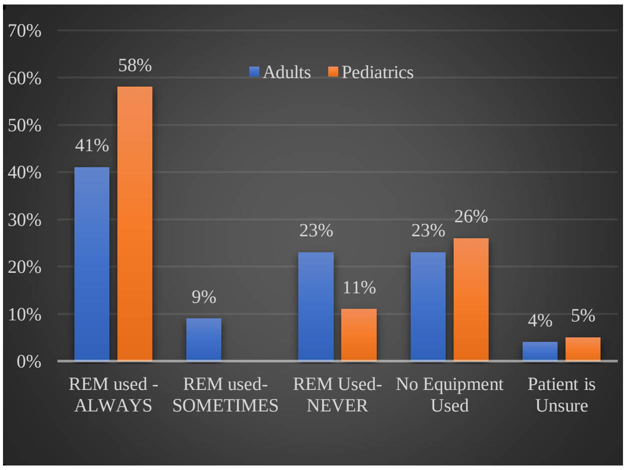

Fig. 3. Percentage of use of REM for Adults and Pediatric hearing aid fittings [3]

Today's modern digital hearing aids have variety of features being provided by manufacturers. Table I which provides a comparative scrutiny of state-of-the art hearing aids based on their features and technology used evidently indicates that the hearing aid industry has indeed travelled a long way from finding solution to some basic issues like problem of cocktail party to incorporating some of the most advanced features in latest hearing aid. However, the adoption rate of hearing aid is insignificant as compared to the rate at which advancements are happening in hearing aids. This is a clear indicator that people with hearing misfortune still faces a variety of problems which hampers the adoption of hearing aid.

Table- I: Overview of State-of-the art Hearing Aids with their Features and Technology used

Parameters	Oticon Opn S 1 miniRITE	Phonak Audeo B 312 B90	Starkey Halo2 i2400	ReSound LiNX 3D RIE 62 9	Widex BEYOND Fusion 2 440	Unitron Tempus MoxiTM Fit R	Signia Motion Nx 13 Nx
Adjustment Bands	16	20	24	9	15	20	20
Frequency Lowering	Speech Rescue™ LX	SoundRecover 2	Speech Shift	Sound Shaper (Frequency compression technology)	Audibility Extender (Linear frequency transposition for high frequency)	Frequency compression	Frequency compression
Environmental Adaptation	Yes	AutoSense OS	No	Environmental Classifier	Sound Class Technology: 9	No	3D Classifier
Noise Reduction	Maximum noise removal: 9 dB	Noise block-High resolution noise cancellation block	Acuity Voice: 4 options	Noise Tracker™ II (uses spectral subtraction technology)	Soft-level noise reduction	Yes	Sound Smoothing™: 3 Speech and noise management: 7
Listening Programs	4	5	-	Fully flexible programs: 4	5	-	6
Adaptive Adjustments	Yes	FlexControl	No	No	No	No	No
Automatic Acclimatization	Yes	Auto	No	No	No	No	No

The Key Open Challenges in hearing aid design for researchers include:

- Requirement of Sharp narrow transition bandwidth with reduced/less hardware complexity
- Reducing the noise requiring the need of high SNR in noisy environment
- Narrow bands with minimum possible overlap between bands for effective frequency selectivity
- Improvement in speech intelligibility and Speech Enhancement
- Reduced size of IC for aesthetic reasons
- Low power dissipation because of its portability
- Requirement of low-distortion output amplifier with high efficiency
- Improvement in sound quality with reduced THD and improved bass response [9]
- Handling increase power consumption and necessity for synchronization among gadgets owing to wireless data transmission facility introduced in hearing aids

III. FILTER BANKS IN HEARING AID

The list of key design challenges of hearing aid highlighted in Section II evidently shows that the hearing aid whichaims to benefit the masses with this sensory disturbance needs to be personalized in the sense that it is able to provide different decomposition schemes to serve the varying needs of different patients [23]. It should be more natural and humanized. Filter bank is the holy grail of Digital hearing aid. This inevitable part of hearing aid is a series of band-pass filters. It splits given sound signals in different sub-bands. After decomposing into differentbands, the selective gain is provided to each band to ensure better matching to audiogram. The filter banks broadly delineate input sound signal characteristics from perspective of different patients and thus ensure auditory compensation in Hearing aids. Normally frequencies ranging from 125 Hz to 8 KHz are considered to be the average normal hearing frequency and thus, in most cases, entire frequency range is divided upto 8KHz.The generic structure of filter bank is depicted in Figure 4.

Optimized performance of hearing aid greatly depends on the choosing the right type of filter bank. The filter types are categorized below as per their characteristics and critically analyzed with respect to their suitability for hearing aid application.

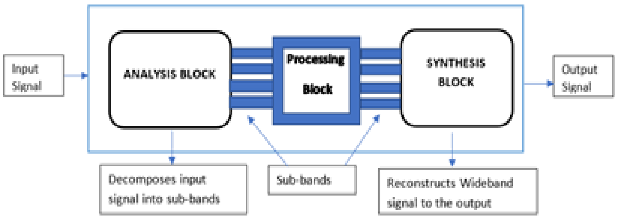

Fig. 4. Generic structure of Filter bank

Analog Vs. Digital Filter: Filter banks can be either analog or digital in nature. However, compared to analog counterpart, digital filters have advantage of flexibility, programmability, can exploit parallelism, provide higher accuracy, exact linear-phase, time-invariant performance and require relatively smaller silicon area[8]. These advantages, coupled with the advent of VLSI technology, has led to ubiquitous presence of digital filters in hearing aid design.

FIR vs.IIR Filter: In digital Filters,Finite Impulse Response (FIR) filter is more favorable for hearing aid application because of its stability, linear phase response with no phase distortion, symmetric coefficients and low coefficient sensitivity as against the popular nonlinear phase Infinite Impulse Response (IIR) Filter [25].This further aids in acoustic noise cancellation improvement and preserves phase cues in a better manner for binaural hearing where both hearing aids are worn together [33].

However, FIR filter poses high computational complexity and relatively high computational cost in addition to higher stop band attenuation in comparison to IIR filter.With the increasing order of FIR filter bank, the overhead also increases. As compared to IIR, FIR implementation is expensive with respect to hardware and power usage.This problem is further elevated when transition bandwidth of desired filter is very narrow [32]. To ensure linear phase and stability but at no additional complexity, FIR filters realized using transposed direct form can be utilized. It reduces implementation complexity and produces high output with no added complexity.

Uniform Vs. Non-Uniform Filter bank: FIR Filter banks can have Uniformly or Non-uniformlyspaced sub-bands. As Human perception can better be represented in logarithmic scale, the non-uniform filter better mimics the resolution characteristics of human hearing and results in better matching to patient's hearing profile [11]. Also, better sub-band distribution in non-uniform filter banks provides improved auditory compensation. Achieving same level of matching using uniform filter bank requires greater count of sub-bands. This further adds to hardware complexity and cost. Also, uniform filter bank doesn't take into consideration the unique auditory characteristics of hearing as well as fails to consider auditory features of different hearing loss patients. Hence use of uniform filter bank doesn't give satisfactory performance in terms of audiogram fitting. Owing to this, non-uniform filter gained lots of attention from researchers and are considered as a better choice for hearing aids.

Fixed (Number of bands)- Non uniform Filter bank vs. Variable band filter: If filter bank possesses fixed number of bands either uniform or non-uniform, then it limits the flexibility of audiogram matching and fitting of hearing loss with steeply sloping audiograms, further inhibiting improvement in auditory compensation[24]. However, if the number of bandsincreases, then it increases the power consumption and cost. Thus, there is need for filter-bank with a reducedcount of sub-bands that can be effortlesslytailored with least possible modification in parameters. Today hearing aids with more than 32 bands are already available in the zest to improvise matching error. However, it directly affects power and computational aspects. Literature suggests Variable Bandwidth filter provides better matching to audiogram as compared to fixed, non-uniform filter bank.

Figure 5 shows the tree like hierarchy paving path (the suitable type at each level is highlighted in red color) towards suitability of filter bank type for Hearing instrument.

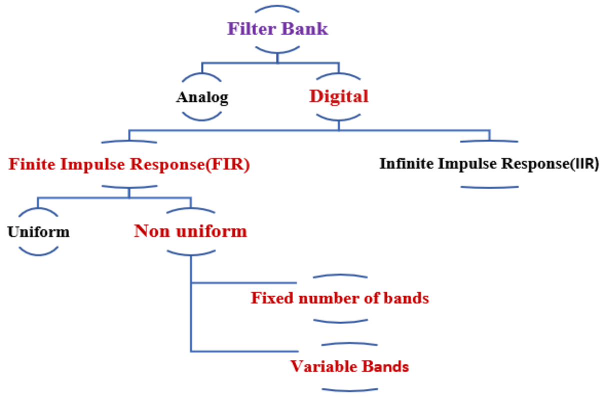

Fig. 5. Roadmap towards suitable choice of filter bank type for Hearing Aid

Thus, the comprehensive comparison of filter bank types in this section suggests that Digital FIR Non-Uniform filter banks with variable number of sub bands and bandwidth is an apt choice for digital hearing aid application.

IV. REVIEW OF PERFORMANCE PARAMETERS FOR FILTER DESIGN AND EVALUATION

There are various performance parameters which are very critical from the perspective of hearing aid users. Thus, these parameters can be chosen a criterionto design and evaluate performance of filter banks in hearing aid application.

- **Matching error**: It is difference between hearing loss curve and matching curve in audiogram. This matching error helps to measure the quality of filter design. Reduced matching error ensures better auditory compensation which is achieved by adjusting gains of filter bank based on patients individual hearing profile. Matching error up to± 3 dB is acceptable [1].
- **Flexibility:** High flexibility is needed for more accurate fitting, so as to improve the clarity of wearer.
- **Power consumption and dissipation**: Digital hearing aid is a portable wearable device. Hence, there is severe need to limit power consumption, as increased power can result in heating up of device and may have negative impact on health of ear. Increased power dissipation also affects battery life. So, power consumption and dissipationneed to be low to prolong battery life time.
- **Hardware complexity**: In order to reduce power dissipation, we need low hardware complexity. Reducing the no. of multipliers helps to achieve reduced hardware complexity.
- **Computational complexity**: Needs low or at least acceptable computational complexity. Filtering operation is very computationally intense and requires huge power. Hence designing hardware efficient filter bank is a major challenge.
- **Size**: Hearing aid, being a portable and wearable device, aesthetics is also very important factor. The use of hearing aid brings with it the societal stigma. Hence, hearing aid with minimum possible size is also a major requirement of hearing-impaired subjects.

- Thus, small IC/chip area is also an important design parameter to be taken care of.
- **Delay**: Though non uniform filter is better compared to uniform filter, design using non uniform filter bank has large delay[36]. The maximum tolerable delay is 20 ns for appropriate synchronization with lip movements. Latency of more than 20 ns may affect the lip reading. Hence delay is also an important parameter under consideration.
- **Quality of signal**: Improved signal quality is one of the most sought requirement of hearing hindered patients.
- **Higher stop band attenuation**: It should be at least 60 dB or more is required for the filter channels. A higher stop band can provide more gain before start of feedback and may give improved magnitude response programmability.

V. RECONFIGURABLE FILTER BANK

New demands dawn with advancements in hearing aid technology. At the forefront is the demand for Flexibility. Reconfigurability in hearing aid can be brought in by chipping in the reconfigurability capability in it's most important component i.e. filter bank.

This indicates the dire need for making filter bank, which is the holy grail of hearing aid, adjustable or in words reconfigurable in nature so as to suit the varying characteristics of patient's hearing loss.Generic diagramof reconfigurable filter bank is presented in Figure 6.

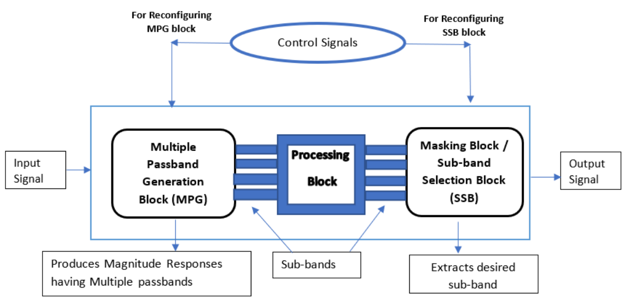

Fig.6. Generic diagram of Reconfigurable filter bank

Thus, the focus is on providing the same hearing aid with the capability to meet varying requirements of patients with different hearing loss types and changing hearing profiles.The filter bank needs to be such that the hearing-impaired subject should be able to adjust hearing aid by appropriately selecting frequency regionwith reduced hearing sensitivity. After bringing to the forefront the concept of reconfigurability and presenting how reconfigurable filter bank design can act as a perfect stepping stone towards the design of customized and tailor-made hearing instruments, now the section opens up to the researchers' various design challenges, consideration and constraints in reconfigurable filter design

A. Design Challenges in Reconfigurable Filter Bank Design

There are five major challenges identified towards the design of reconfigurable filter bank which are enlisted as follows:

1. **Adjustable multiple band spectral decomposition schemes:** Hearing device amplifiesinput signals for increased hearing threshold of the patient. However, if gain is applied to entire frequency region, intensities of few signals post amplification might increase above the discomfort threshold of the hearing impaired resulting in hearing pain[28]. So,complete frequency band needs to be separated into many sub bands and every sub band must possess its own amplification coefficient. Thus, reconfigurable filter bank should provide multiple band spectral decomposition schemes such that only the frequency range where gain is required can be configured and appropriate gain be provided to compensate for increased hearing threshold.

2. **High tuning flexibilitywith minimum change in parameters:**In reconfigurable filter bank, controlling frequency parameters should be possible without the need for hardware reimplementation. If filter bank possesses fixed/uniform bands, then it limits the flexibility of audiogram matching and fitting, further inhibiting improvement in auditory compensation. However, increasing number of bands for better auditory compensation,increases the power consumption and cost. Thus, designers need to come up with reconfigurable filter design with a lesser bandthat can be need-based tailored with least possible modifications in filter parameters.

3. **Narrow Sharp transition bandwidth:** Transitional bandwidth has direct impact on computational cost of overall filter [39]. Thus, achieving sharp transition bandwidth requires filter with large value of N. This results in elevatedpower, hardware complexity and cost.

4. **Optimum choice between flexibility and power consumption:**Filter banks should be ideally having low complexity as well as better auditory compensation. There are 2 major challenges in digital hearing aid viz. flexibility and power.More flexibility is needed for more accurate fitting, so as to improve the clarity of wearer. On the contrary, power consumptions need to be low to prolong battery life.

5. **Establishing equilibrium between complexity and performance:**Reconfigurable filter bank is more complex than its uniform and non-uniform counterparts.So, it is challenging under constraints to be used widely for hearing aid applications. The challenge for designers lies in finding equilibrium between complexity and performance.

B. Design Considerations and Constraints for Sub-Band Distribution in Filter Bank

Human ear has higher hearing resolution and hence better hearing in low frequency as compared to high frequency range.

Also, owing to propagation of sound waves from base towards apex of cochlea, major damage of hair cells and partitions within basiliar membrane occurs near the base compared to apex. Thus, sub-band distribution needs to be such that more subbands are allocated in lower and higher frequency range compared to middle frequency range [39]. This can lead to better auditory compensation. Also, if sub-bands in higher frequency range and lower frequency range are symmetric, better frequency resolution can be achieved and can be better suited for hearing impaired with severe loss in high frequencies.

C. Filter Parameters to be reconfigured for Reconfigurable filter bank design

Reconfigurable filter bank mainly deals with ability to change three major parameters of filter as per varying needs of patients hearing profile viz. Filter coefficients, Filter type and Modefor Sub-band decomposition schemeselection.

Extensive literature survey highlights the following ways by which attempt has been made to bring in reconfigurability in filter banks of hearing aid:

1. Design of variable bandwidth filter (VBF) where bandwidth can be varied dynamically [12]. Here, the bandwidths can be reduced or enhanced without changing filter order or filter coefficient. It can be achieved simply by changing the sampling frequency[12]
2. Selecting different sets of bandwidths and spectral shifting of selected sub-bands to provide better matching to the same audiogram [11]
3. The filter coefficients can be changed during execution using Distributed arithmetic-based FIR filter.
4. The location and number of sub bands can be altered by varying the control signals. [40]
5. Sub bands are movable depending on value of control parameters without modifying structure of filter bank.
6. Altering the transfer function of filter bank by modifying control signals, thus providing different sound decomposition schemes [16]
7. Bandwidth can be changed by changing sampling frequency
8. Number and bandwidths of sub bands can be made adjustable with optimum selection of various bands according to one’s needs.
9. Sub band schemes can be altered using control signals without changing filter bank configuration. Later, gain of sub bands can be optimized using suitable optimization algorithm.
10. DesigningLow, High and Band pass filter with varying cut off frequency [8]
11. Obtaining different sub band distribution schemes based on control signals without modification in Filtercoefficients or structure.
12. Flexibility to control filter bank central frequencies and bandwidth to attain better compensation performance [22]
13. Modifying interpolation factor(M) in same channel and usingextra pair of masking filter in different channels to FRM based reconfigurability[46]

Thus, implementing reconfigurable non uniform filter bank can be an effective way to include reconfigurability in hearing aid to provide an efficient solution to the problems of millions of hearing impaired.

VI. STATE-OF-THE-ART TECHNIQUES FOR RECONFIGURABLE FILTER DESIGN

This Section presents a bird’s eye view of the stat-of-the-art techniques for design of Reconfigurable filters. A few of them are highlighted as under:

- Distributed arithmetic based design[27]
- Variable bandwidth filter-based design [15]
- Coefficient decimation-based approach [20]
- Frequency response masking based design[32] [41]
- Fractional Interpolation based design[2][40]
- Filter design based on Interpolation, decimation and masking filter [38][7]
- Interpolated FIR based Filter [6]
- Variable Bandwidth Filter based on Farrow structure[11]
- Design using Cosine modulated uniform FB and non-linear transformation [14]
- Fractional Fourier Transform based design [16]

A. Filter Designs Based on Distributed Arithmetic Approach:

Multiplier is a computationally complex, area consuming and power greedy block in FIR filter. Hearing aid requires reconfigurable filters which requires low power and area and gives high throughput. Distributed arithmetic (DA) method which substitutes multiplications and additions with a look up table and shifter accumulator can be a great solution for above mentioned requirement [28]. To achieve reconfigurability in FIR filter, Bhagya Lakshmi. N. et.al. [5] proposed an optimized DA based FIR filter where filter coefficients can be changed during runtime. To improvise the area-delay product, power and performance, Naik et. al. [53] suggested modified DA method where Carry Look Ahead based adder tree (multiplexer-based structure) allows reuse of MAC blocks for memory locations reduction and better area-delay product. A high speed and low power FIR filter is presented in [52] where author proposed offset-binary code (OBC) DA for reconfigurable filter design with shared LUT updating method.

B. Variable Bandwidth (VBW)Filter Based Designs

In VBW based designs as presented in [11], filter sub-bands are extracted from a single variable bandwidth filter. Farrow structure based variable bandwidth filter can be a good choice for multiplier- less based hearing instruments. In [12], Parks–McClellan algorithm is used for filter design for a set of evenly spaced bandwidths within the tunable bandwidth.Reconfigurability is attained is updating the adjustable parametersdependent on bandwidth. In [10],author presented a Variable bandwidth filter using Sample rate conversion-based technique where Bandwidth can be changed by altering bandwidth ratio.

C. Coefficient Decimation Based Approach

Kowsick Prasad et. al [20] appliedcoefficient decimation method to warped filters for complexity reduction. In [53], Mahesh et. al. proposed a reconfigurable FIR filter in which every M^{th} filter coefficient remains same while all remaining coefficients are substituted by zero. This results in generation of multiple frequency bands generation and proves to be computationally efficient with low complexity.

D. Frequency Response Masking (FRM) Based Design

FRM design is apt where sharp narrow transition band with less computational complexity is the major filter bank requirement. FRM strategy guarantee the extraordinary decrease in the multiplier and adder count in straight stage FIR channel[29].Ying Wei et. al. [39] proposed computationally efficient, low-power, small chip area 16-band nonuniformly spaced digital filter bankfor hearing aid applications using FRM with multiple band-edge shaping filters. In[41],[54], filter bank with two half-band filters as prototype filters with symmetric sub-bands at mid frequency point is propose for reduced computational cost owing to increased filter length with audiogram matching within +/-5dB. A unified FRM-based complex modulated filter bank structure is proposed by Wenxu et. al. [42]where even-orodd-stacked, maximally or non-maximally decimated designsareachieved with reduced computational complexity.A non-uniform filter with less complexity is proposed by Sebastian et. al. [31] for hearing aid application based on FRM technique and half-band filter. In [37], author presented FRM based non-uniform filter with variable decomposition schemes with matching error within tolerable level.

E. Filter Based on Farrow Structure

In [11][12], author proposed a reconfigurable VBF tunable filter based on farrow structure since in Farrow structure, the overall response is weighted linear combination of fixed sub-filters allowing tunability of bandwidth. In[11], author furtherspecified coefficients in canonical signed digit (CSD) format and proper coefficient representation were selected based on optimization techniquesfor Farrow based filter for reduced complexity

Section V and VI presented a detailed view of the reconfigurable filter banks, along with their performance parameters, filter parameters that can be reconfigured and the state-of-the-art techniques for filter bank design.

VII. METHODOLOGY

Figure 6 elaborates the methodology of complete flow from filter specification, design, implementation to evaluation in the form of a flow diagram

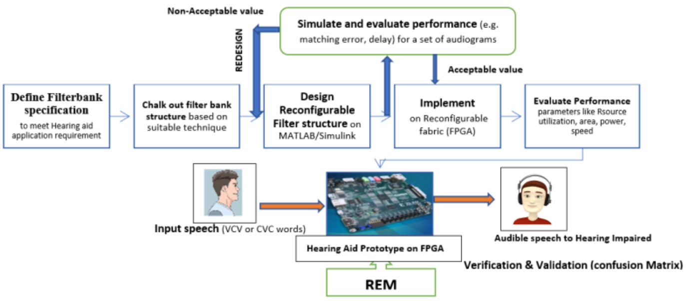

Fig. 6. Methodology for Filter bank design, implementation and evaluation

VIII. RESULTS AND DISCUSSION

This section presents results in terms of improvement in performance parameters through proposed design techniques and few suggestions for further improvementin performance of filter banks in hearing instruments are put forth for further discussion.Table II tabulates the results in terms of percentage improvement or savings in the performance parameters in filter bank design techniques for hearing aid.

Few suggestions for further performance improvement in terms of area and power includes replacing multipliers with adders or use of multiplier less filters like cascaded integrator comb (CIC), replacing adders with 4:2 compressors in FIR filter design for improved are and speed[19], reducing the effective word length of filter channels coefficients, adopting Multi-rate architecture and usage of approximate multipliers for filter. Variable Bandwidth Filters with farrow structure, FIR filter realized using transposed direct form, adopting Canonical signed digit space [4] and Distributed Arithmetic based FIR filter can be good techniques for complexity reduction and speed improvement.Further, applying signal processing algorithms like Multiband compression, Speech enhancement, Prescription-fitting for reduced inter-band interference[35] can surely result in improved speech intelligibility.Apart from above mentioned techniques forimprovement, it has been observed that existing devices for people with hearing misfortune mainly focusses on either of the three arenas of Hearing viz. Hearing Restoration, Enhancement or Assistance. However, research can be taken ahead combining the advantages of two or all three of these arenas as shown in Figure 7.

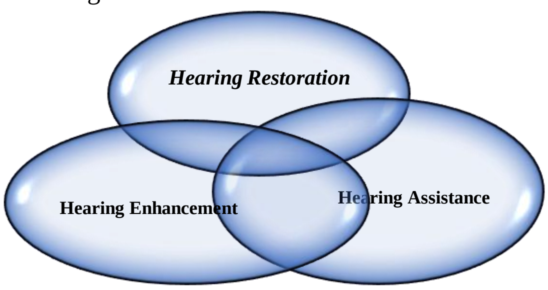

Fig.7. Amalgamation of Domains of Hearing Restoration, Enhancement or Assistance

Table II: Percentage Improvement in Performance parameters of Filter Bank for hearing Aid through given design techniques

Sr. No	Design Technique	Compared with	% Improvement/ Savings in Parameter mentioned					
		* Mild loss in high frequency ** Mild loss at all frequencies	Max. Matching error (MME)		Complexity (multiplier count per band)			
1.	Reconfigurable filter bank based on Interpolation, Decimation and FRM [38]	Uniform Filter bank (Direct)	24.57% *	54.44% **	68%			
		Non-uniform filter-bank	49.8% *	26.45% **	45.5%			
		* Mild loss in high frequency ** Mild loss at all frequencies	Matching error					
2.	Interpolated FIR (IFIR) based Non-uniform filter bank [6]	Fixed Uniform Filter-bank	40.22% *		45.9% **			
		Fixed Non-uniform filter-bank	60.25% *		12.67 % **			
			Area		Power			
3.	Approximate Method for Filter-bank Design[47]	Exact Method for filter bank design	20%		14%			
			Area	Power	Delay			
4.	Frequency Response Masking (FRM)[46]	Per-channel (PC) based	85%	45.2%	56.63%			
		Discrete Fourier transform filter bank (DFTB) based	67.33%	25.5%	42.44%			
		*Compared to separate FIR filters as Masking Filters for each channel)	Number of Multipliers (Evaluation of Hardware Complexity)		Trade-off between Hardware and Switching Complexity			
5.	Method for Masking filter design for Reconfigurable FRM [43]	Variable bandwidth (VBW) - based Farrow Filters	16% *		Comparatively less switching complexity			
		Interpolation-based farrow Filters	23% *		Reduced hardware complexity but increases switching complexity			
			Power Dissipation (µW @ 1.1V,1/024MHz)					
6.	Bank of Multiplexers and Adders (BMA) for Multiplication in FIR filter	Conventional Multiplier (based on Carry-save adders)	50% reduction in power ** excluding power dissipated by RAM					
			Area	Number of gates		Memory		
7.	Approximately linear phase IIR half-band filter for FRM based Uniform Filter bank [44]	linear phase FIR half-band filter for FRM based Uniform Filter bank	22.7 %	23.8%		20 %		
			Power	Delay	Memory	Adder Count		
8.	Sub-band coding-based FIR filter based onFloating-pointarithmetic [45]	Analysis bandpass FIR Filter	9%	21.26%	44.5%	14.8%		
		* Mild loss in high frequency ** Mild loss in all frequencies	Matching Error		Delay		No. of Multipliers	
			*	**	*	**	*	**
9.	Fractional Interpolation based Reconfigurable filter bank[1]	Non-Uniform FIR filter bank [21]	70.45%	58.92%	17% (Rise)	3% (Rise)	6% (Rise)	6% (Rise)
		Reconfigurable FB based on Interpolation, decimation and FRM [38]	41.1%	43.07%	45.69%	53.62%	25.5%	25.5%
		Reconfigurable FB based on Non-Linear Transformation [33]	24.26%	11.2%	60.6% (Rise)	60.6% (Rise)	64.2%	64.2%
			Area (Number of transistors)		Power Dissipation			
10.	Multiply-Accumulate(MAC) unit for Filter-bank with Modified GDI(Gate Diffusion Input) Logic [48]	Filter bank based on CMOS Logic	77%		95.55%			
		Filter bank based on GDI Logic	35.55%		47.81%			

IX. CONCLUSION

This paper presented the techniques for reconfigurable filter banks design for hearing instruments. The motive behind this work was to identify the major bottlenecks in design and use of hearing aid and thus develop a strategic roadmap towards further performanceimprovement of hearing instruments to minimize the hugegap between potential and actual hearing aid users. Fromthis work, it can be concluded that Non-Uniform Finite Impulse Response filter with varying or fixed number of bands is an apt choice for hearing aid design.Reconfigurability is the dire need in today's hearing aid to suit the varying characteristics of hearing loss of different patients.This can be achieved by making filter bank,the holy grail of Hearing aid, reconfigurable in nature.Reconfigurability in filter bank gives flexibility to control and modify the filter parameterslike number of sub bands, their bandwidths, central frequencies, location of sub-bands and sub-band decomposition schemes simply by changing control parameters or varying the transfer function without the need for hardware reimplementation while ensuring that performance ofhearing aid be optimized or further improved in terms of major performance factors like auditory compensation, power, latency (delay), computation and hardware complexity and speed.

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