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Low Complexity, Reconfigurable Digital Filters and Filter Banks for Channelization and Spectrum Sensing in Multi-Standard Wireless Communication Receivers

Presented by:
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A Word About NTU

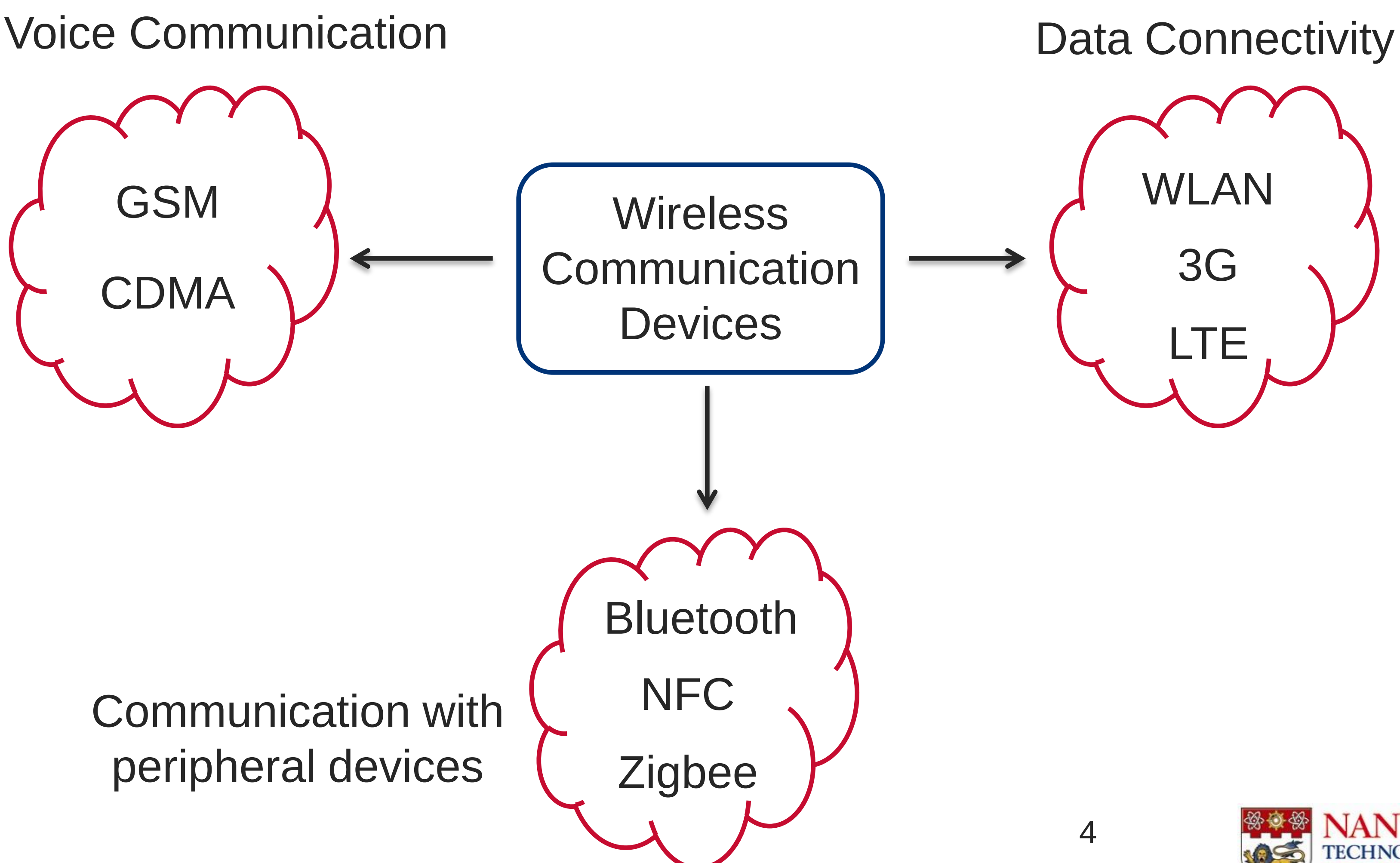
- NTU ranked 47th in the most prestigious Quacquarelli Symonds (QS) World University Rankings 2013.
- Ranked 2nd in the world among universities below the age of 50 by QS – 2012/2013.
- Ranked 8th in the world among universities below the age of 50 by Times Higher Education - 2013.
- World's Biggest Engineering University with 1100 faculty members in Engineering Schools alone.
- Rated as '5-star +' University under QS – Only 7 Universities in the world achieved this rating (NTU is the first and only Asian University in this league).
- Ranked as the 5th most-cited university with its research output ranked among the top three universities globally in Engineering by Essential Science Indicators of Thomson Reuters.

A fast rising young University (25 years old)

Outline of today's presentation

- Overview of Software Defined Radio and Cognitive Radio
- Challenges and Motivations
- Our Research Contributions
- Conclusions

Introduction: Mobile Wireless Communication

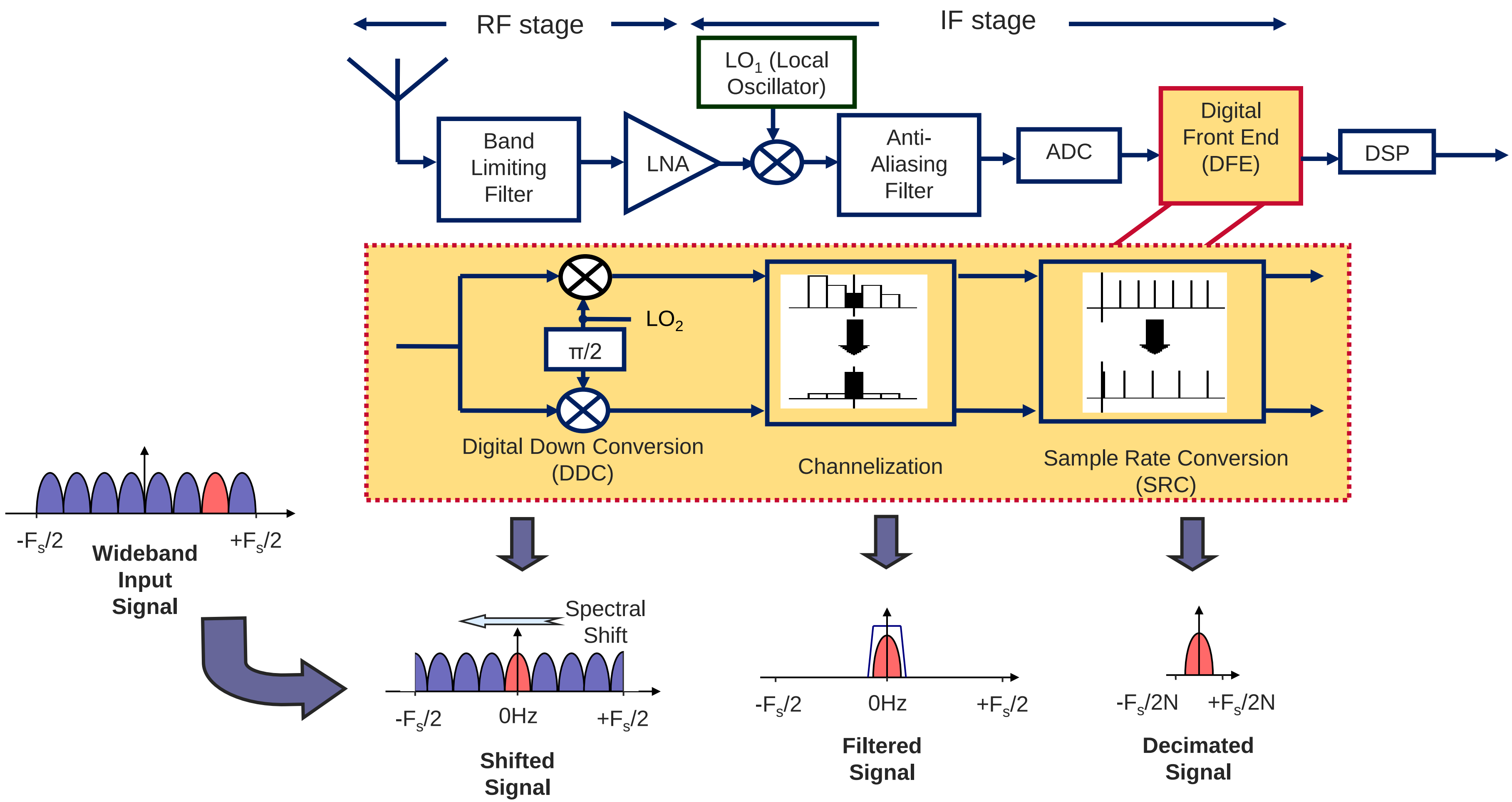


Introduction: Software Defined Radio

- Software defined radio (SDR) [1, 2] is a technology that has been proposed as a solution to seamlessly support the existing and upcoming wireless communication standards.
- Main characteristics:
  - Flexible transmitter and receiver (transceiver) architecture,
  - Digital Signal processing is able to replace, as much as possible, analog processing to realize programmable radio functionalities,
  - Transceiver where the frequency band and radio channel bandwidth can be defined by software.

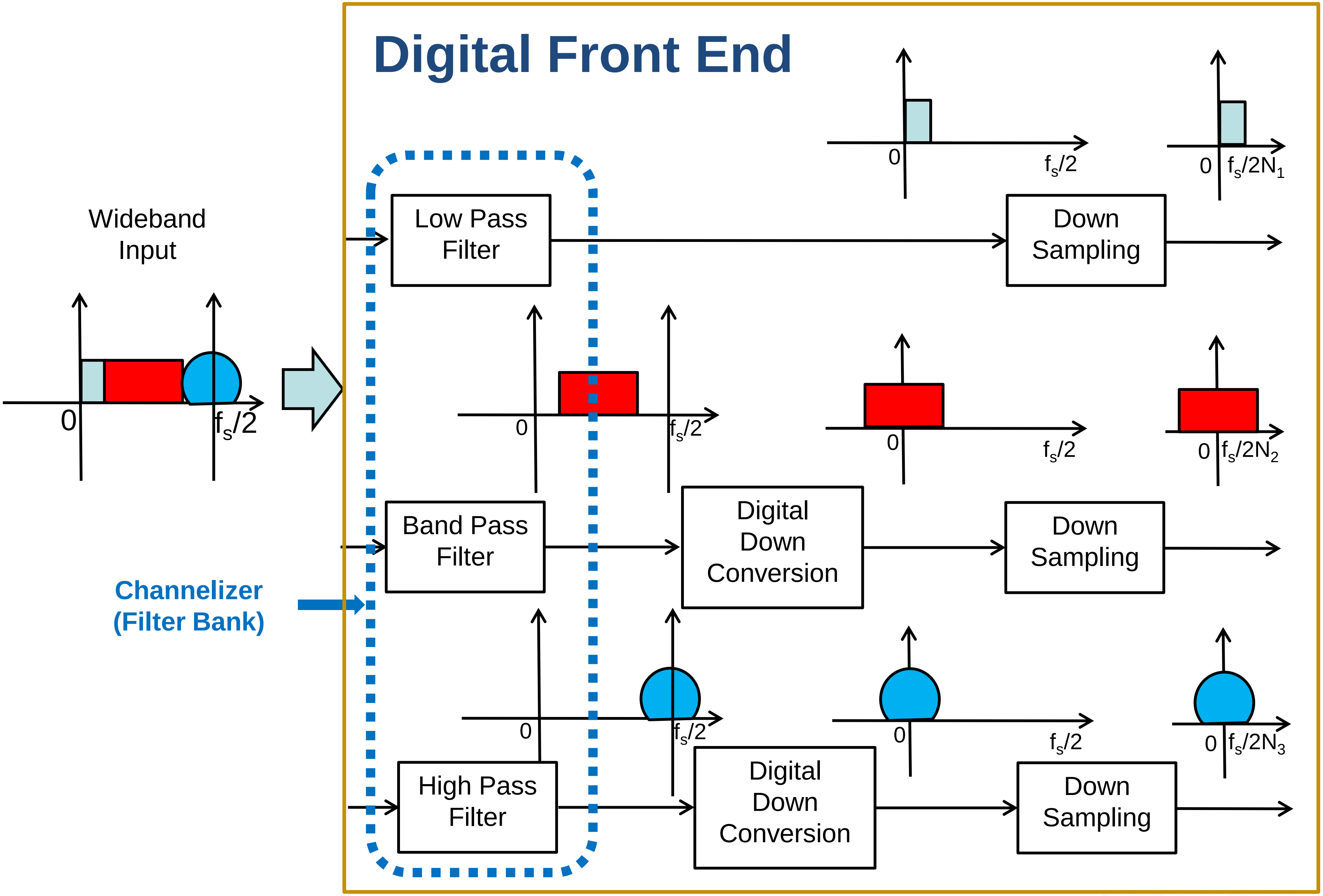
1. Mitola J., “The software radio architecture,” *IEEE Communications Magazine*, vol. 33, no. 5, pp. 26-38, May 1995.
2. Buracchini E., “The software radio concept,” *IEEE Communications Magazine*, vol. 38, no. 9, pp. 138-143, September 2000.

Introduction: SDR Receiver



3. Hentschel T., Henker M., Fettweis G., “The digital front-end of software radio terminals,” *IEEE Personal Communications*, vol. 6, no. 4, pp. 40-46, August 1999.

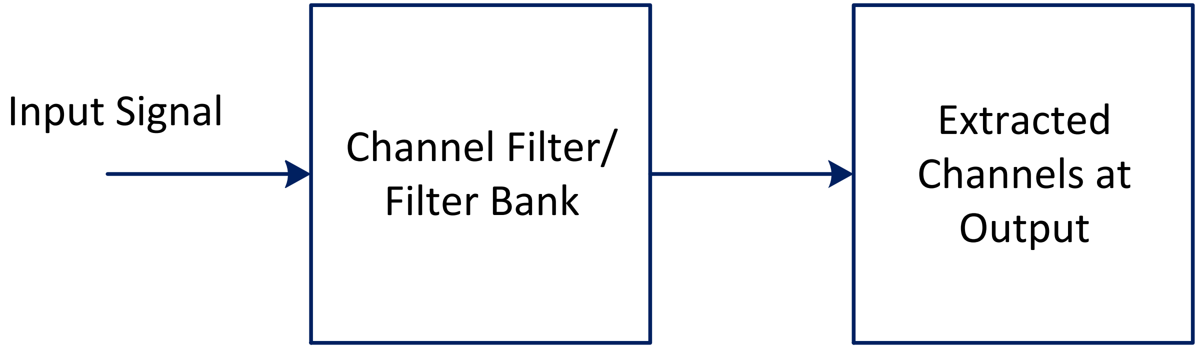
Digital Front End



3. Hentschel T., Henker M., Fettweis G., "The digital front-end of software radio terminals," *IEEE Personal Communications*, vol. 6, no. 4, pp. 40-46, August 1999.

Introduction: Channelization

- Channelization is the process of extraction of single or more than one channels (frequency bands) of interest from the wideband input signal [4, 5].



Block diagram of channelization in SDR receivers

It is the most computationally intensive block in the DFE – Operates at the highest sampling frequency.

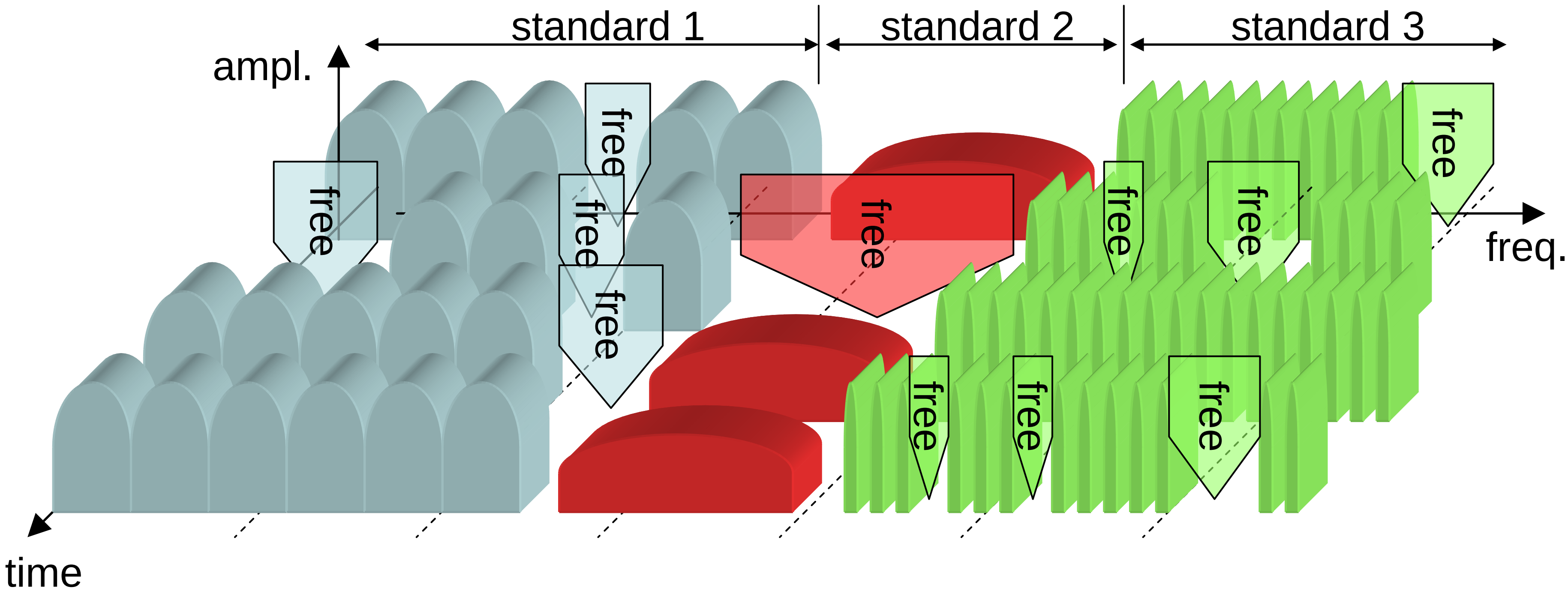
4. Lee Pucker, “Channelization techniques for software defined radio,” *in Proceedings of Spectrum Signal Processing Inc.*, Burnaby, B.C, Canada.
5. Hentschel T., “Channelization for software defined base stations,” *Annales des Telecommunications*, vol. 57, no. 5-6, pp. 386-420, March 2002.

Cognitive Radios - Opportunistic Spectrum Utilization

- SDR based cognitive radio (CR) targets the opportunistic usage of the radio frequency spectrum.
- Proposed to solve 'spectrum scarcity' due to existing static spectrum allocation scheme.
- CRs have the ability to sense and detect the current spectrum utilization, and change their behavioral and transmission characteristics dynamically so as to achieve efficient spectrum access.

6. Mitola J., Maguire G. Q., "Cognitive radio: Making software radios more personal," *IEEE Personal Commununications*, vol. 6, no. 4, pp. 13–18, August 1999.
7. Mitola J., "Cognitive radio for flexible mobile multimedia communications," *IEEE International Workshop on Mobile Multimedia Communications, MoMuC 1999*, pp. 3-10, San Diego, USA, 15-17 November 1999.
8. Haykin S., "Cognitive radio: Brain-empowered wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 2, pp. 201- 220, February 2005.

Spectrum Opportunities for cognitive radios – Time-varying spectral scenario



Cognitive radios (secondary users/unlicensed users) utilize free bands (vacant bands /white spaces/holes) for communication in an opportunistic fashion when primary users (licensed users) are not using those bands.

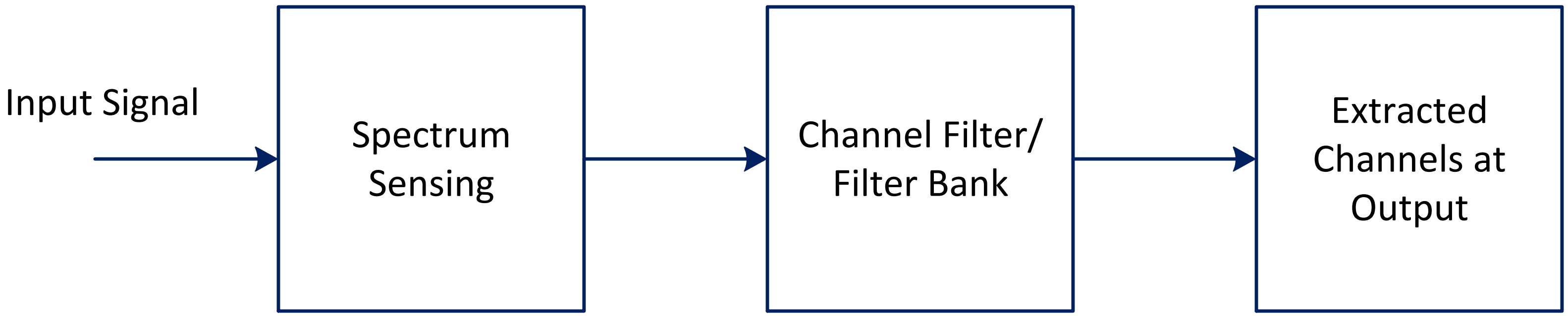
Spectrum Sensing

- Spectrum sensing in CRs - the presence and (or) absence of signals of licensed users (called primary users) is detected in the wideband input frequency range in order to allow opportunistic access of the vacant frequency bands to the unlicensed users (called secondary users or cognitive radio users) [9].

9. Ghasemi A., Sousa E.S., “Spectrum sensing in cognitive radio networks: requirements, challenges and design trade-offs,” *IEEE Communications Magazine*, vol. 46, no. 4, pp. 32-39, April 2008.

Introduction: Channelization and Spectrum Sensing in CRs

- Spectrum sensing is often done prior to channelization.



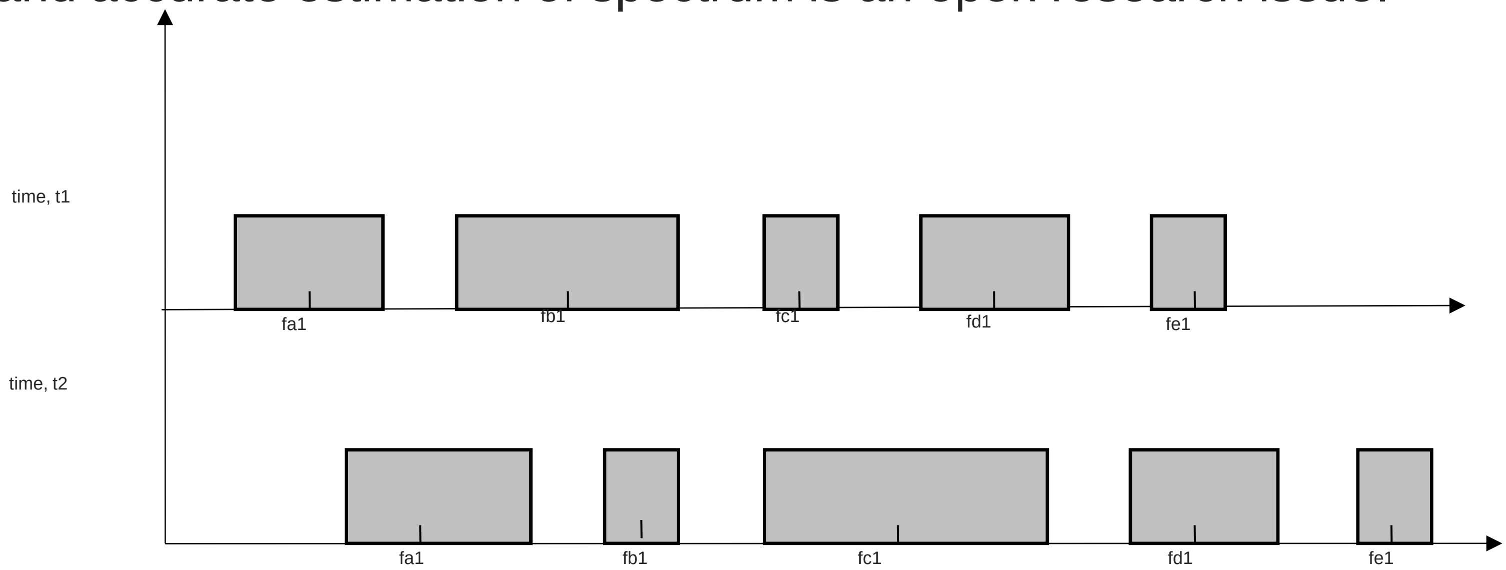
Block diagram of channelization and spectrum sensing in cognitive radios

- Digital filters and filter banks have potential applications in spectrum sensing and channelization. [10, 11].

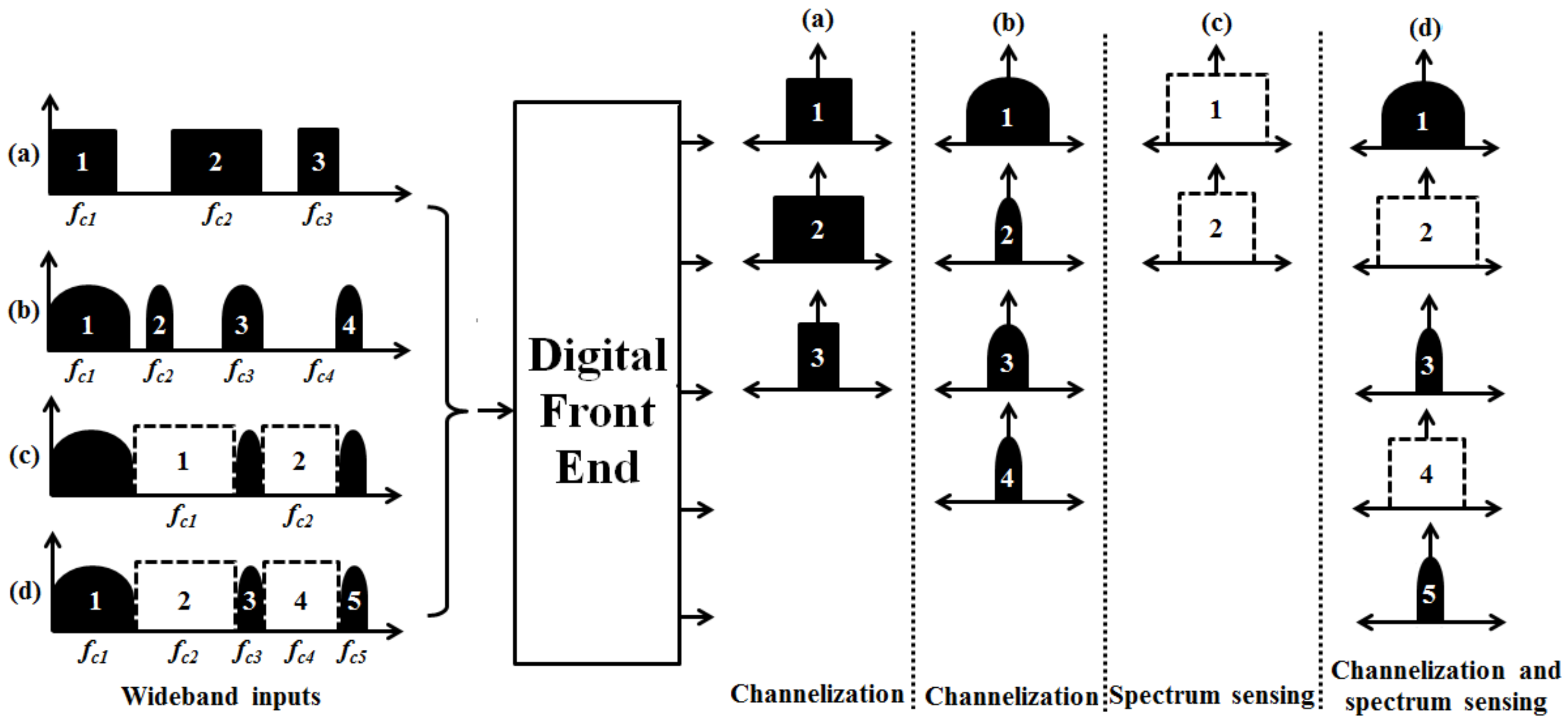
10. Yucek T., Arslan H., "A survey of spectrum sensing algorithms for cognitive radio applications," *IEEE Communications Surveys & Tutorials*, vol. 11, no. 1, pp. 116-130, First Quarter 2009.
11. Farhang-Boroujeny B., "Filter bank spectrum sensing for cognitive radios," *IEEE Transactions on Signal Processing*, vol. 56, no. 5, pp. 1801-1811, May 2008.

Spectrum Sensing and Channelization in Military Radio

- In military communications, the wideband signal will have time-varying frequency bands scattered across the spectrum. The locations of channels and channel bandwidths will change dynamically.
- The channelizer must be dynamically reconfigured to continue reception. Therefore, the center frequencies of the bandpass filter should be dynamically tuned to the new center frequencies with minimum computational overhead (low power) and high speed.
- This problem is not adequately addressed in the literature. Also real-time and accurate estimation of spectrum is an open research issue.



Introduction: Channelization and Spectrum Sensing in CRs



Channelization and Spectrum sensing in CRs

Filter banks for Spectrum Sensing & Channelization

Filter Bank	Complexity	Group Delay	Non-uniform bandwidth subbands	Control over bandwidth and location of each subband
Per Channel approach	Very high	Low	Yes	Yes
DFTFB [12]	Low	Low	No	No
MPRFB [13]	High	Low	Yes	No
FFB [14]	Very low	Very high	No	No

- DFTFB: Discrete Fourier transform (DFT) based filter bank.
- MPRFB: Modulated perfect reconstruction filter bank.
- FFB: Fast filter bank.

12. Vaidyanathan P. P., "Multirate digital filters, filter banks, polyphase networks, and applications: a tutorial," *Proceedings of the IEEE*, vol. 78, no. 1, pp. 56-93, January 1990.
13. Abu-Al-Saud W.A., Stuber G. L., "Efficient wideband channelizer for software radio systems using modulated PR filter banks," *IEEE Transactions on Signal Processing*, vol. 52, no. 10, pp. 2807–2820, October 2004.
14. Lim Y.C., Farhang-Boroujeny B., "Fast filter bank (FFB)," *IEEE Transactions on Circuits and Systems II: Analog and Digital Signal Processing*, vol. 39, no. 5, pp. 316-318, May 1992.

Challenges and Motivations

- Channelizer is the most computationally intensive part of the digital front-end in SDR/CR receivers.
- Channelizers in SDR/CR receivers have stringent area, power and cost specifications – Mobile handset constraints.
- In multi-standard scenarios, the conventional technique of switching the operation among distinct receivers for different standards is not an efficient approach.
- Reliable and fast spectrum sensing techniques with low implementation complexities are desired in CR receivers.

Our Selected Contributions

1. Coefficient Decimation Method (CDM) for Realizing Very Low Complexity Variable (Reconfigurable) Digital Filters

Coefficient Decimation Method (CDM)

Filter coefficients : h_0 h_1 h_2 h_3 h_4 h_5 h_6 h_7 $h_8 \ldots h_N$

CDM-I by M=2 : h_0 0 h_2 0 h_4 0 h_6 0 $h_8 \ldots h_N$

CDM-II by M=2 : h_0 h_2 h_4 h_6 $h_8 \ldots h_N$

•In CDM-I, if $H(e^{j\omega})$ denotes Fourier transform (FT) of the modal (prototype) filter coefficients, then FT of the modified filter coefficients is [16]

$$H'(e^{j\omega}) = \frac{1}{M}\sum_{k=0}^{M-1} H(e^{j\left(\omega - \frac{2\pi k}{M}\right)})$$

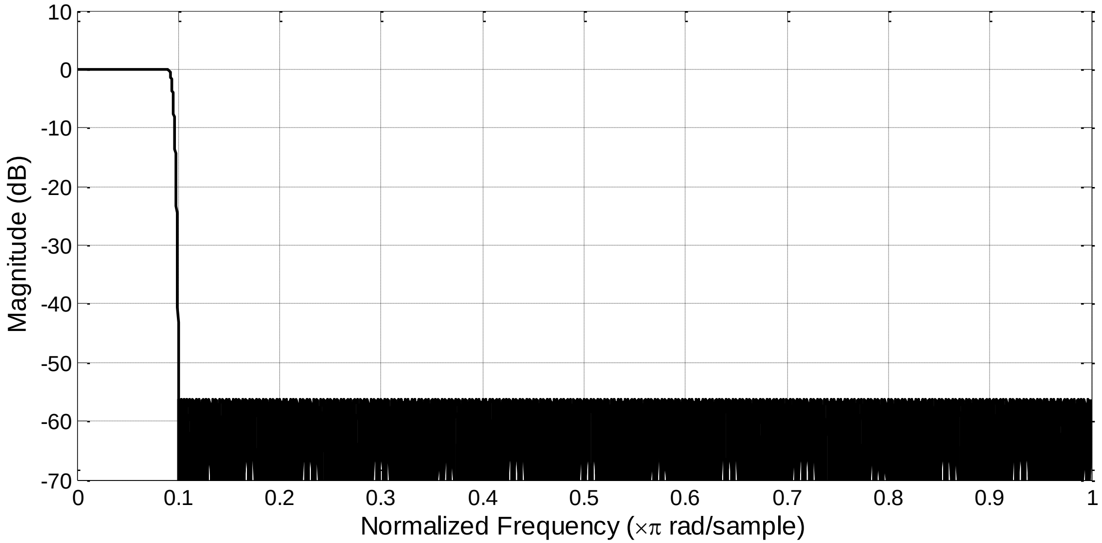
- Multi-band response with center frequencies at 2piK/M

16. R. Mahesh, A. P. Vinod, “Coefficient decimation approach for realizing reconfigurable finite impulse response filters,” *IEEE International Symposium on Circuits and Systems, ISCAS 2008*, pp. 81-84, Seattle, USA, 18-21 May 2008.

CDM: Illustrative Example

Filter coefficients: h_0 h_1 h_2 h_3 h_4 h_5 h_6 h_7 h_8 h_9 $h_{10} \ldots h_N$

Frequency response:



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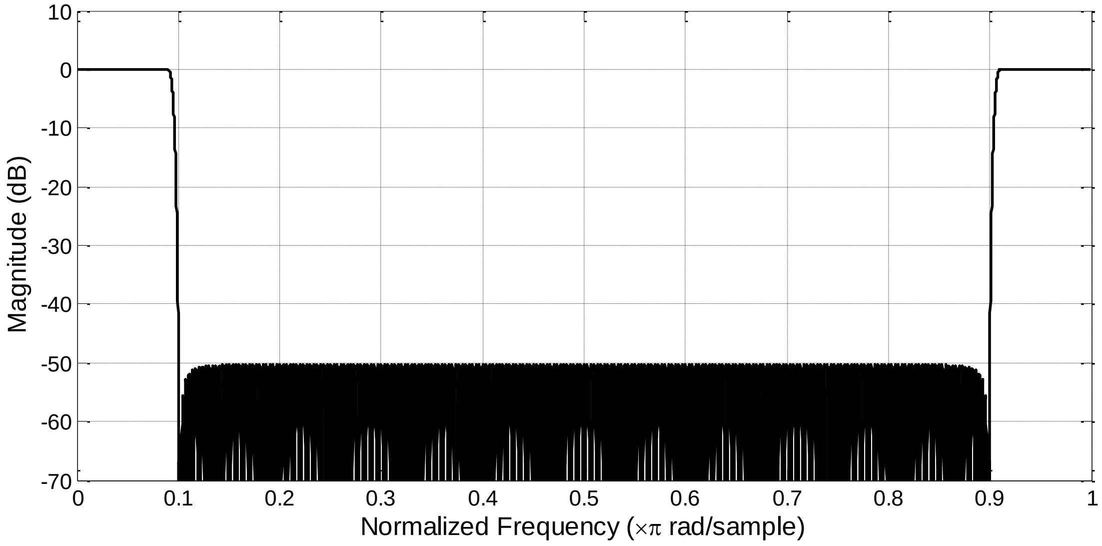
CDM: Illustrative Example

Filter coefficients: h_0 h_1 h_2 h_3 h_4 h_5 h_6 h_7 h_8 h_9 $h_{10} \ldots h_N$

CDM-I by *M*=2 : h_0 0 h_2 0 h_4 0 h_6 0 h_8 0 $h_{10} \ldots h_N$

Frequency response:



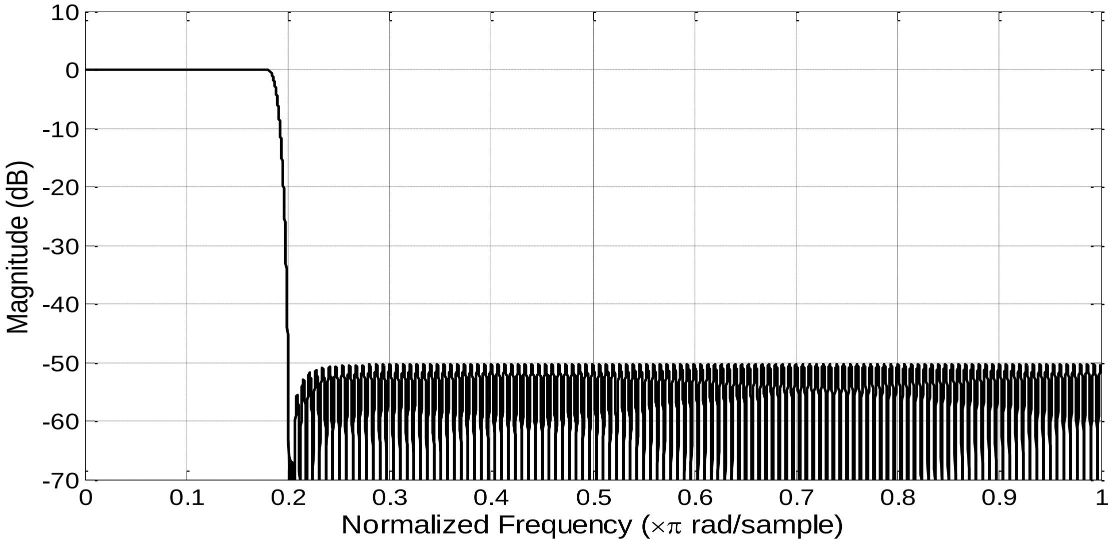
CDM: Illustrative Example

Filter coefficients: h_0 h_1 h_2 h_3 h_4 h_5 h_6 h_7 h_8 h_9 h_{10} … h_N

CDM-I by M=2 : h_0 0 h_2 0 h_4 0 h_6 0 h_8 0 h_{10} … h_N

CDM-II by M=2 : h_0 h_2 h_4 h_6 h_8 h_{10} … h_N

Frequency response:

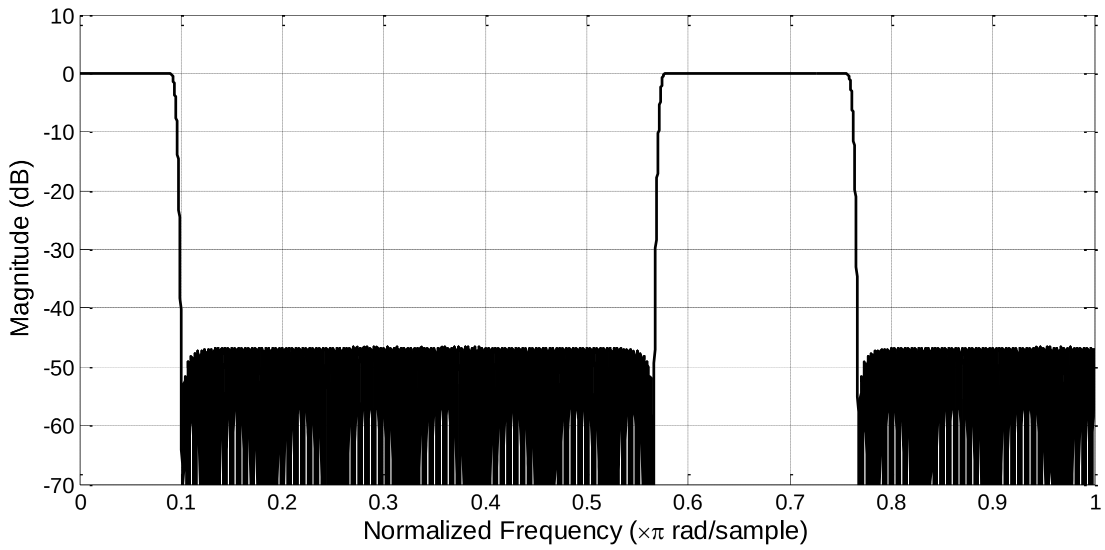


CDM: Illustrative Example

Filter coefficients: h_0 h_1 h_2 h_3 h_4 h_5 h_6 h_7 h_8 h_9 h_{10} … h_N

CDM-I by M=3 : h_0 0 0 h_3 0 0 h_6 0 0 h_9 0 … h_N

Frequency response:



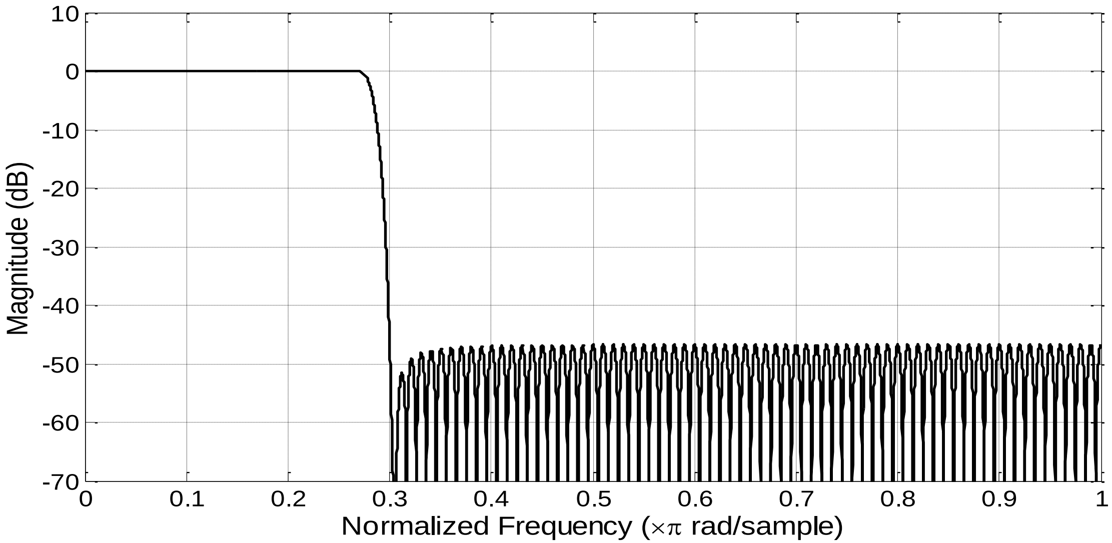
CDM: Illustrative Example

Filter coefficients: h_0 h_1 h_2 h_3 h_4 h_5 h_6 h_7 h_8 h_9 h_{10} … h_N

CDM-I by M=3 : h_0 0 0 h_3 0 0 h_6 0 0 h_9 0 … h_N

CDM-II by M=3 : h_0 h_3 h_6 h_9 … h_N

Frequency response:

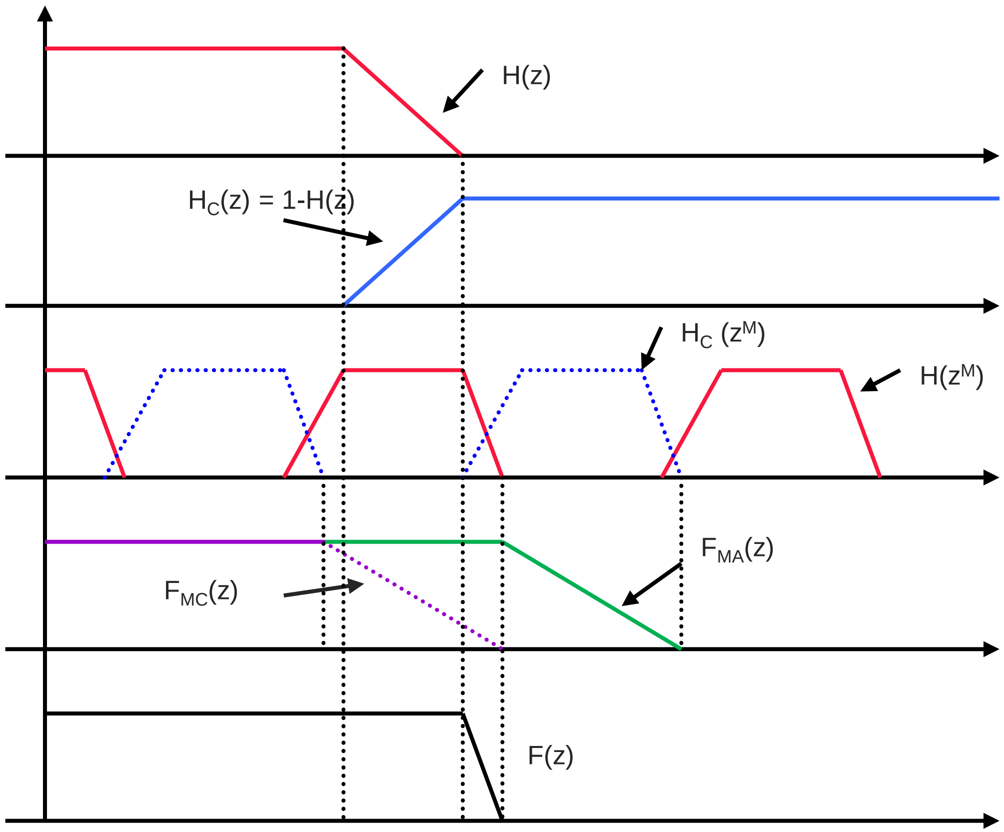


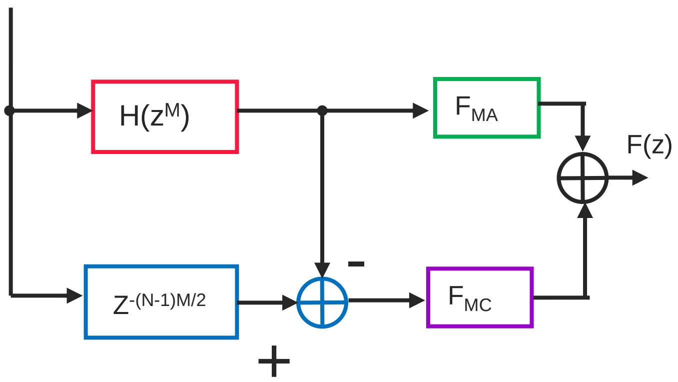
We can obtain multi-band (uniform bandwidth) magnitude responses as well as variable bandwidth frequency responses from a single fixed-coefficient LPF using CDM I and II respectively.

Contributions

2. CDM based Filter Bank (CDFB)

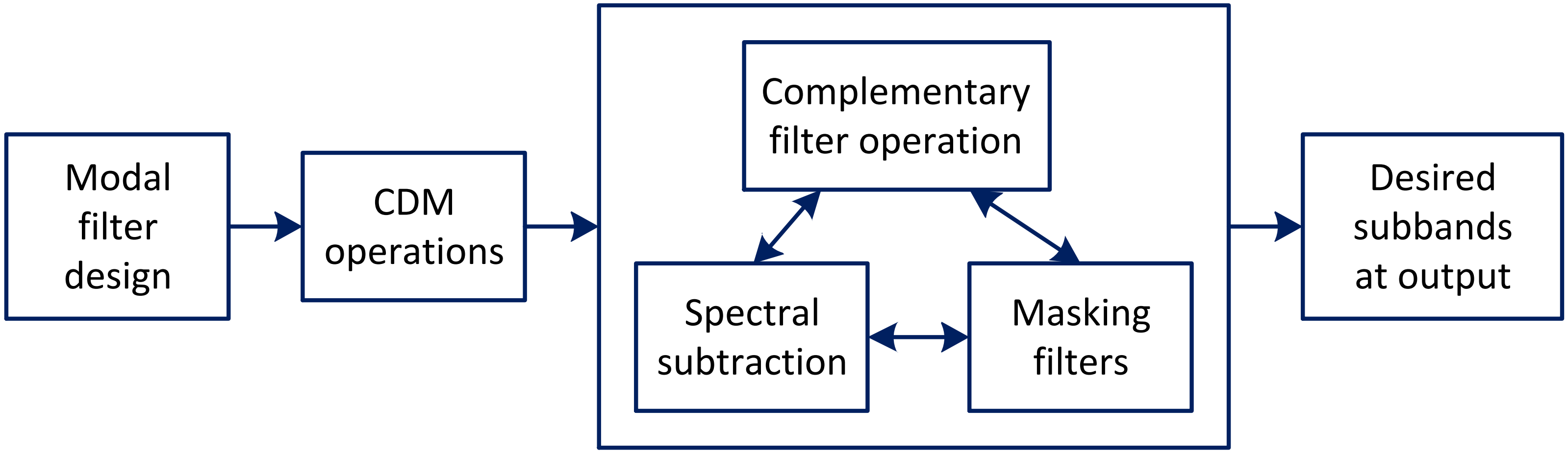
Frequency Response Masking (FRM) for Designing Filters with sharp cut-off





15. Lim Y.C., “Frequency-response masking approach for the synthesis of sharp linear phase digital filters,” *IEEE Transactions on Circuits and Systems*, vol. 33, no. 4, pp. 357- 364, April 1986.

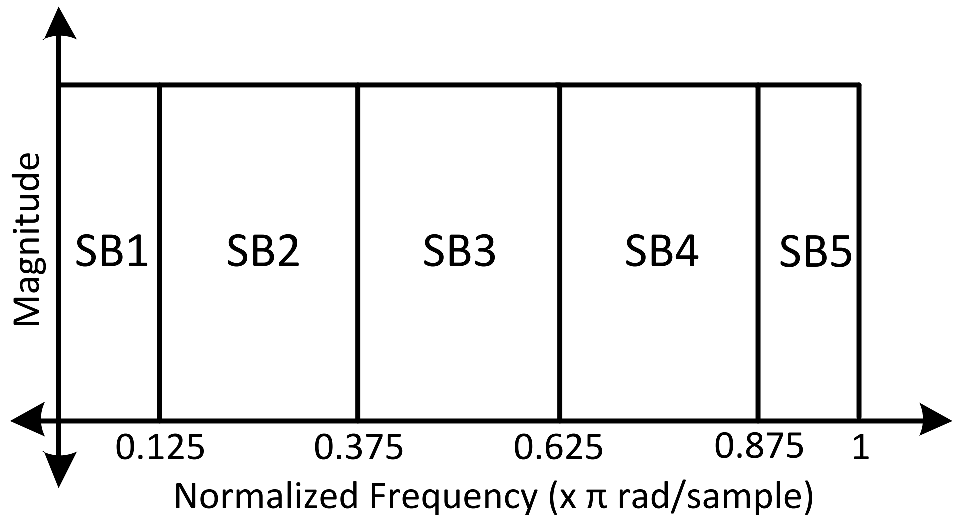
CDM based Filter Bank (CDFB)



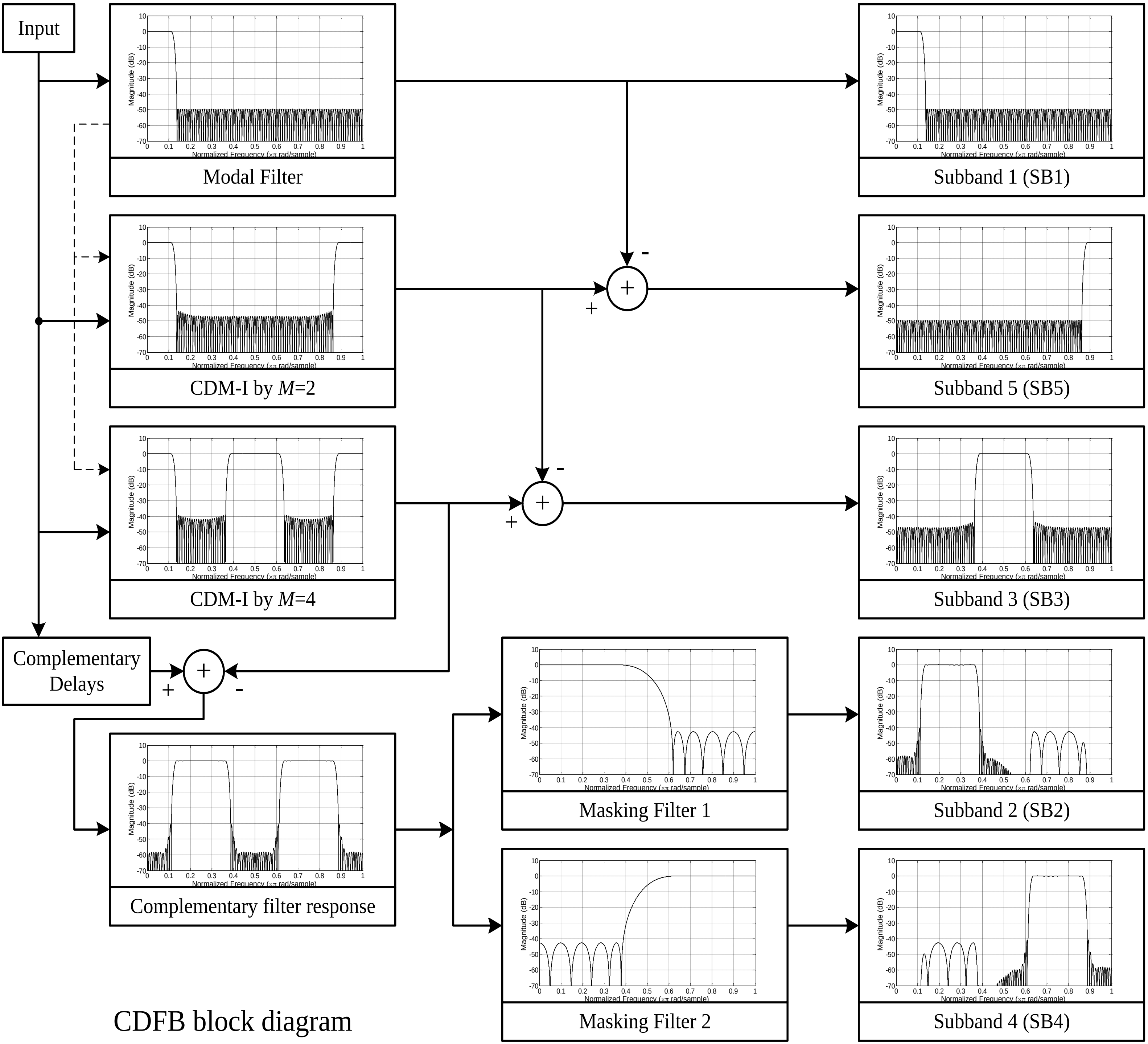
CDFB design procedure

17. R. Mahesh, A. P. Vinod, "Low complexity flexible filter banks for uniform and non-uniform channelisation in software radios using coefficient decimation," *IET Circuits, Devices & Systems*, vol. 5, no. 3, pp. 232-242, May 2011.

CDFB: Design Example



Desired subband distribution from 0 to $f_{samp}/2$



CDFB block diagram

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CDFB vs DFTFB (Xilinx XC40150XV)

Design	DFTFB		CDFB	
	Area (CLBs)	Delay	**Area (CLBs)**	**Delay**
FIR filter bank	2352/5184	32.7	**1755/5184**	**20.5**
DFT	2350/5184	53.8	**0/5184**	**0**
Full Design	4321/5184	51.6	**2200/5184**	**25.4**

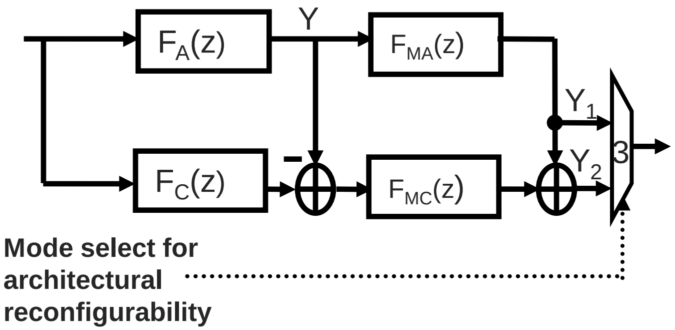
- CDFB offers area reduction of **49.09%** and speed improvement of **50.78%** over DFTFB.

Contributions

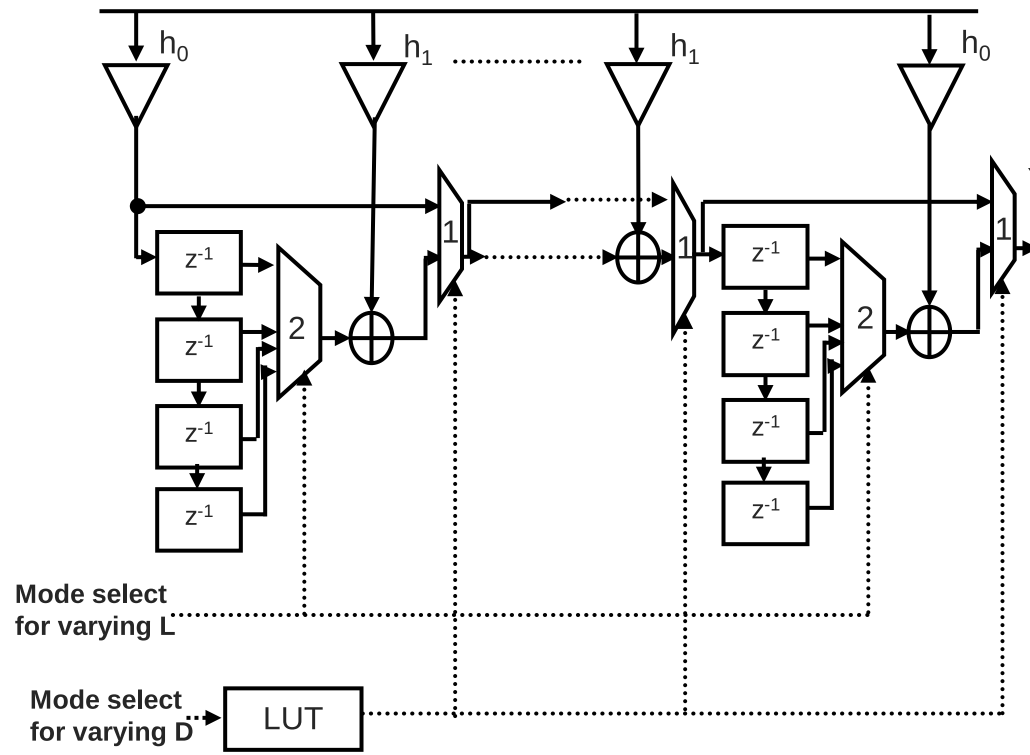
3. Decimation-Interpolation and Masking (DIM) based Channel Filter:

Exploiting two degrees of freedom for enhancing filter programmability

DIM based Channel Filter



The reconfigurable channel filter.



Architecture of modal filter.

- Filter level reconfigurability: by changing *I* and *D* of the modal filter, to obtain *D*I* different subbands. (*I*=interpolation factor, *D*=decimation factor for CDM-II)
- Architectural level reconfigurability: by selecting outputs Y_1 and Y_2 using Mux-3.
- By exploiting both, we are able to obtain **[*D.I* + (*I*+2)] distinct subbands** [18].

18. Smitha K. G., A. P. Vinod, "A new low power reconfigurable decimation-interpolation and masking based filter architecture for channel adaptation in cognitive radio handsets," *Physical Communication, Elsevier*, vol. 2, no. 1–2, pp. 47-57, March–June 2009.

DIM based Channel Filter: Design Example

	I	D	f_p	f_s	$[f_{mp}, f_{ms}]$ of masking filter	N_{mask}
1	1	1	0.1	0.125	[0.1,0.5]	7
2	1	2	0.2	0.25	[0.2,0.5]	10
3	1	3	0.3	0.375	[0.3,0.5]	15
4	1	4	0.4	0.5	[0.4,0.5]	32
5	2	1	0.05	0.0625	[0.05, 0.4375]	8
6	2	2	0.1	0.125	[0.1,0.5]	7
7	2	3	0.15	0.1875	[0.15,0.3125]	19
8	2	4	0.2	0.25	[0.2,0.5]	10
9	3	1	0.033	0.0416	[0.033,0.2917]	12
10	3	2	0.066	0.0833	[0.066,0.25]	17
11	3	3	0.1	0.125	[0.1,0.5]	7
12	3	4	0.133	0.166	[0.133 0.166]	99
13	4	1	0.025	0.0313	[0.025,0.2188]	16
14	4	2	0.05	0.0625	[0.05, 0.4375	8
15	4	3	0.075	0.0938	[0.075,0.3125]	13
16	4	4	0.1	0.125	[0.1,0.5]	6

Filter level reconfigurability

- Specifications of modal filter: passband edge f_p = 0.1 and stopband edge f_s = 0.125.
- Following Nyquist criterion, we can note that the maximum value of D is 4, for normalized frequency range 0 to 0.5, where 0.5 = $f_{samp}/2$.
- I = 4 for illustration.

	I	D	f_p	f_s	$[f_{mp}, f_{ms}]$ of masking filter	$[f_{mcp}, f_{mcs}]$ of complementary masking filter
1	3	1	0.366	0.375	[0.366,0.5]	[0.3,0.375]
2	3	2	0.4	0.417	[0.4, 0.5]	[0.266, 0.418]
3	3	3	0.433	0.4583	[0.433,0.5]	[0.233,0.458]
4	4	1	0.275	0.281	[0.275,0.468]	[0.225,0.281]
5	4	2	0.3	0.3125	[0.3,0.438]	[0.2,0.3125]
6	4	3	0.325	0.344	[0.325,0.4062]	[0.175,0.344]

Architectural level reconfigurability

DIM based Channel Filter: Design Example

Implementation Results

	Per Channel approach	DIM based channel filter
Gate count	533,451	**476,636**
Total power (mW)	421.3	**396.5**
Total delay (ns)	16.71	**17.035**

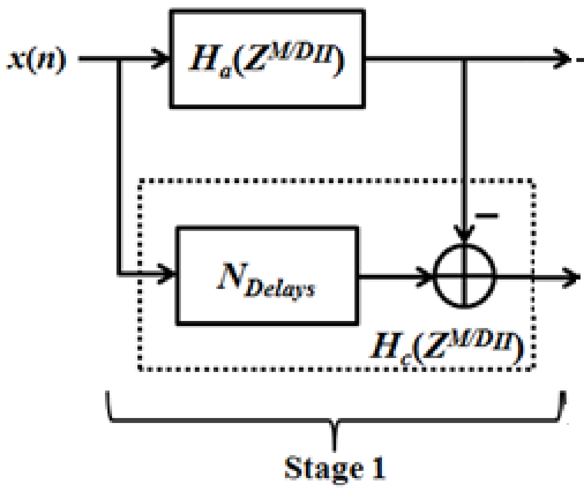
- The decimation-interpolation and masking based channel filter offers gate count reduction of 10.65% and power reduction of 5.89% over the PC approach architecture. **The real advantage is in it's high frequency response flexibility!**

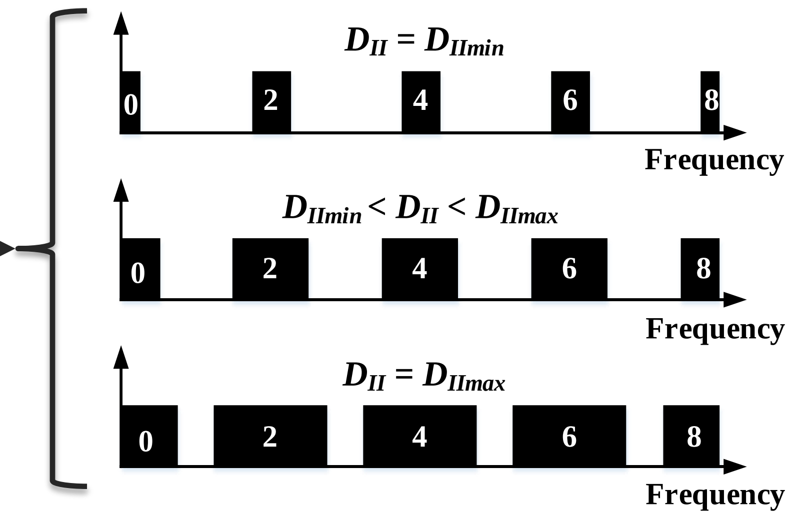
Contributions

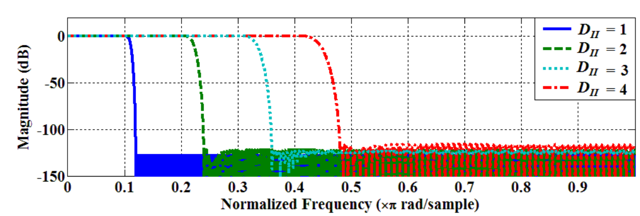
4. CDM-FRM based Filter Bank (CDM-FRM FB)

CDM-FRM FB: Stage 1

- **Stage 1** consists of prototype filter H_a and complementary filter H_c.
- The CDM-II decimation factor D_{II} for prototype filter is varied from D_{IImin} to D_{IImax}.
- Interpolation factor M is fixed.



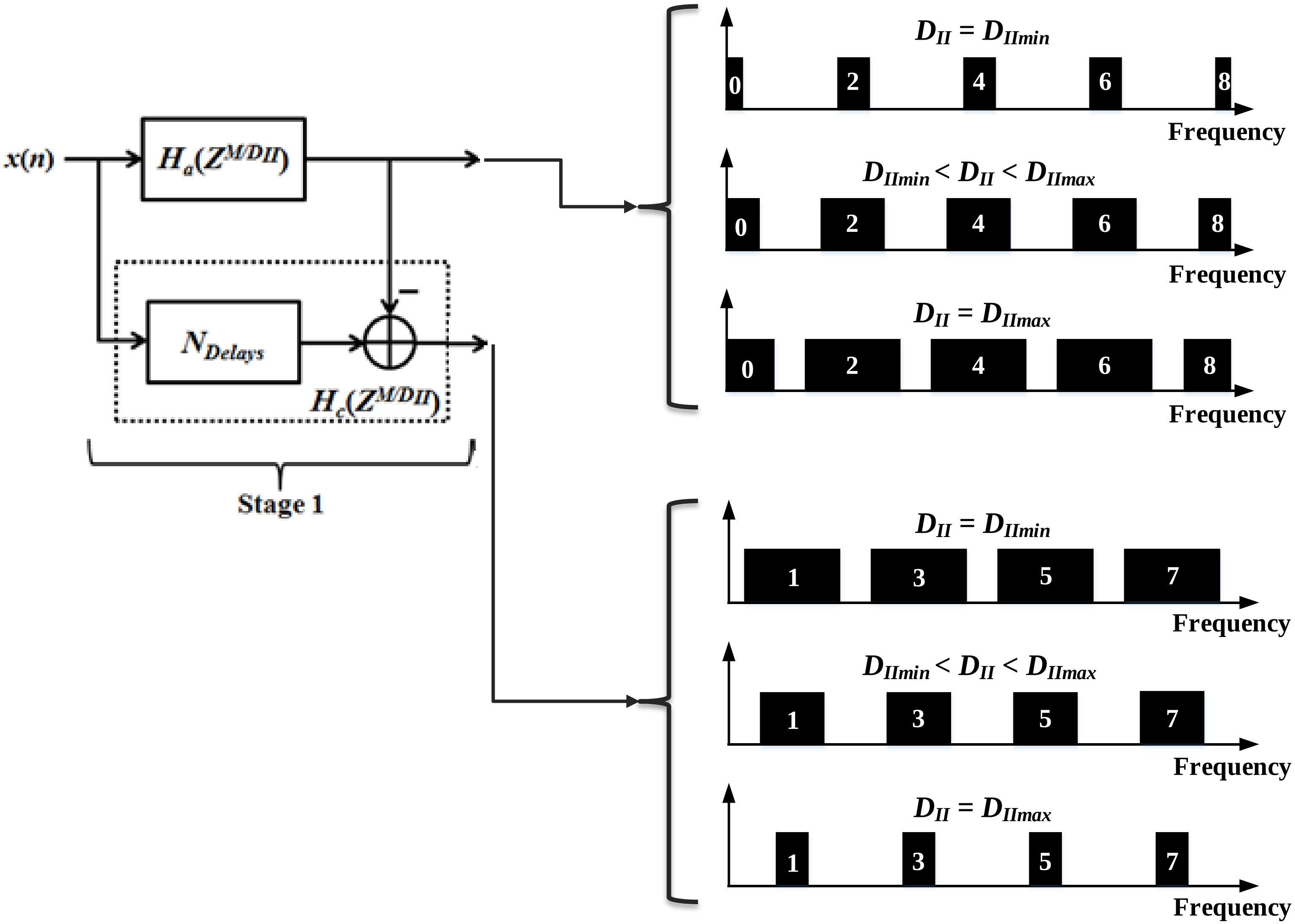




CDM-II

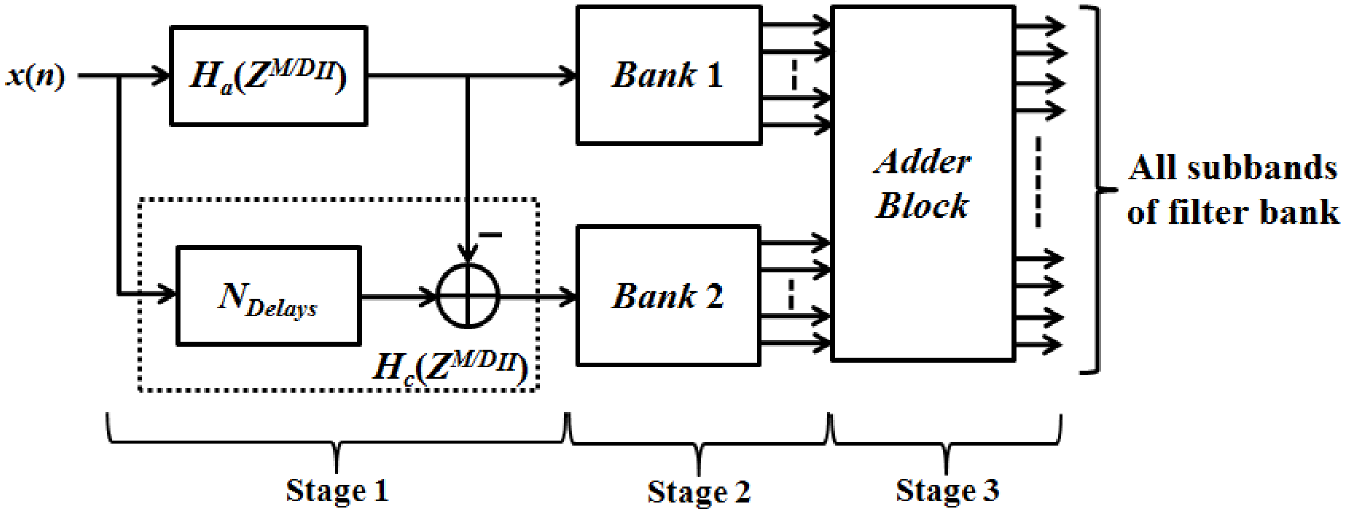
19. S. J. Darak, A. P. Vinod and E. M-K. Lai, “A low complexity reconfigurable non-uniform filter bank for channelization in multi-standard wireless communication receivers,” *Journal of Signal Processing Systems, Springer*, vol. 68, no. 1, pp. 95-111, July 2012.

CDM-FRM FB: Stage 1



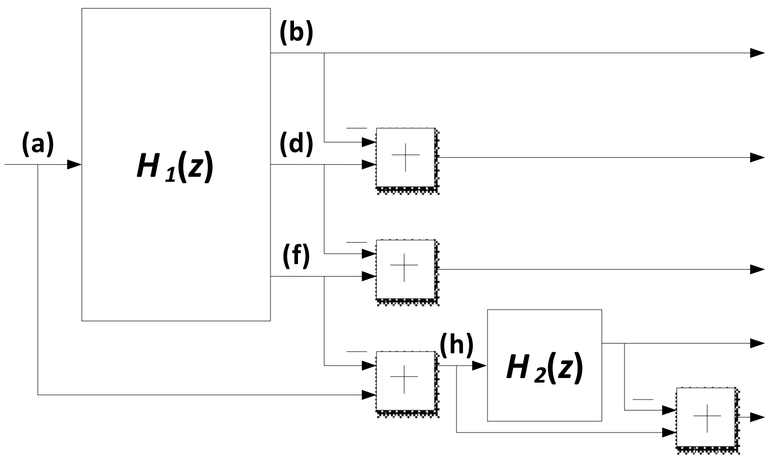
CDM-FRM FB: Stage 2

- **Stage 2** consists of two banks of fixed-coefficient masking filters, Bank 1 and Bank 2.
- Masking filters extract the desired subband by masking the other subbands.
- The number of masking filters are optimized using CDM-I.



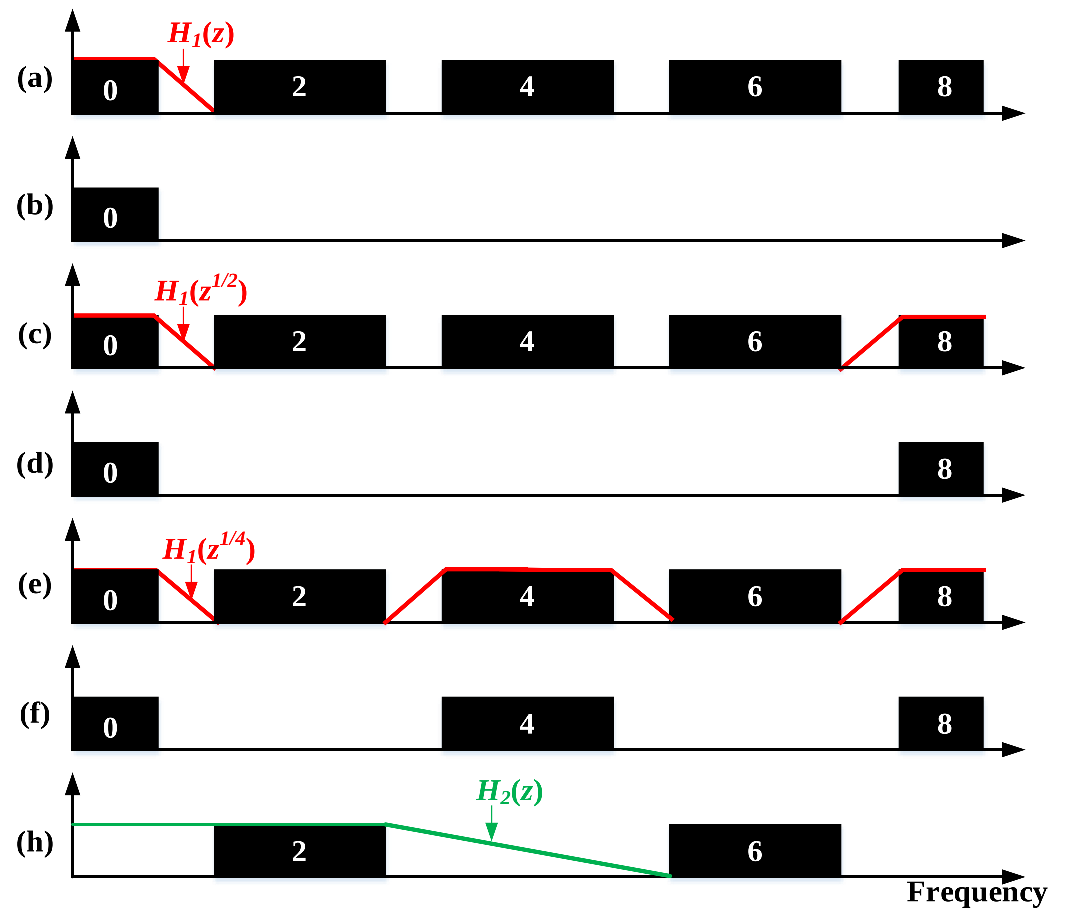
CDM-FRM FB

CDM-FRM FB: Stage 2



Stage 2 - Bank 1

- Single fixed-coefficient masking filter is used to extract bands 0, 4 and 8 as shown in figure.
- Similarly , masking filters $H_3(z)$ and $H_4(z)$ are used to extract subbands from the complementary response.



Frequency responses of Stage 2 - Bank 1

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CDM-FRM FB: Implementation Results

	Per Channel approach	DFTFB	CDM-FRM FB
Number of occupied slices	14334	11865	**10157**
Power (mW)	1473	709	**690**
Post-PAR minimum period (ns)	11.533	26.549	**30.12**

- Number of slices occupied by the CDM-FRM FB is **29.14%** lower than that of the PC approach and **14.4%** lower than that of the DFTFB.
- Power consumption of the CDM-FRM FB is **53.16%** lower than that of the PC approach and **2.68%** lower than that of the DFTFB.

Contributions

5. Improved Coefficient Decimation Method (ICDM) for variable filters and filter banks with enhanced flexibility

Recap: Coefficient Decimation Method (CDM)

Filter coefficients : $h_0 \quad h_1 \quad h_2 \quad h_3 \quad h_4 \quad h_5 \quad h_6 \quad h_7 \quad h_8 \ldots h_N$

CDM-I by M=2 : $h_0 \quad 0 \quad h_2 \quad 0 \quad h_4 \quad 0 \quad h_6 \quad 0 \quad h_8 \ldots h_N$

CDM-II by M=2 : $h_0 \quad h_2 \quad h_4 \quad h_6 \quad h_8 \ldots h_N$

•In CDM-I, if $H(e^{j\omega})$ denotes Fourier transform (FT) of the modal (prototype) filter coefficients, then FT of the modified filter coefficients is

$$H'(e^{j\omega}) = \frac{1}{M} \sum_{k=0}^{M-1} H(e^{j\left(\omega - \frac{2\pi k}{M}\right)})$$

16. R. Mahesh, A. P. Vinod, “Coefficient decimation approach for realizing reconfigurable finite impulse response filters,” *IEEE International Symposium on Circuits and Systems, ISCAS 2008*, pp. 81-84, Seattle, USA, 18-21 May 2008.

Modified Coefficient Decimation Method (MCDM)

Filter coefficients : h_0 h_1 h_2 h_3 h_4 h_5 h_6 h_7 $h_8 \ldots h_N$

MCDM-I by M=2 : h_0 0 $-h_2$ 0 h_4 0 $-h_6$ 0 $h_8 \ldots h_N$

MCDM-II by M=2 : h_0 $-h_2$ h_4 $-h_6$ $h_8 \ldots h_N$

•In MCDM-I, if $H(e^{j\omega})$ denotes FT of the modal filter coefficients, then FT of the modified filter coefficients is [23]

$$H'(e^{j\omega}) = \frac{1}{M}\sum_{k=0}^{M-1} H(e^{j\left(\omega - \frac{\pi(2k+1)}{M}\right)})$$

23. Abhishek Ambede, Smitha K. G., A. P. Vinod, "A modified coefficient decimation method to realize low complexity FIR filters with enhanced frequency response flexibility and passband resolution," *2012 35th International Conference on Telecommunications and Signal Processing, TSP 2012*, pp. 658-661, Prague, Czech Republic, 3-4 July 2012.

Improved Coefficient Decimation Method (ICDM): CDM + MCDM

Filter coefficients	:	$h_0 \; h_1 \; h_2 \; h_3 \; h_4 \; h_5 \; h_6 \; h_7 \; h_8 \ldots h_N$
CDM-I by M=2	:	$h_0 \; 0 \; h_2 \; 0 \; h_4 \; 0 \; h_6 \; 0 \; h_8 \ldots h_N$
CDM-II by M=2	:	$h_0 \; h_2 \; h_4 \; h_6 \; h_8 \ldots h_N$
MCDM-I by M=2	:	$h_0 \; 0 \; -h_2 \; 0 \; h_4 \; 0 \; -h_6 \; 0 \; h_8 \ldots h_N$
MCDM-II by M=2	:	$h_0 \; -h_2 \; h_4 \; -h_6 \; h_8 \ldots h_N$

24. Abhishek Ambede, Smitha K. G., A. P. Vinod, “An improved coefficient decimation based reconfigurable low complexity FIR channel filter for cognitive radios,” *2012 12th International Symposium on Communications and Information Technologies, ISCIT 2012*, pp.22-27, Gold Coast, Australia, 2-5 October 2012

ICDM

- ICDM = CDM + MCDM

- ICDM-I = CDM-I + MCDM-I
  - Different multi-band frequency responses with a center frequency resolution of π/M can be obtained, where M = decimation factor.

- ICDM-II = CDM-II + MCDM-II
  - Variable lowpass and highpass frequency responses can be obtained.

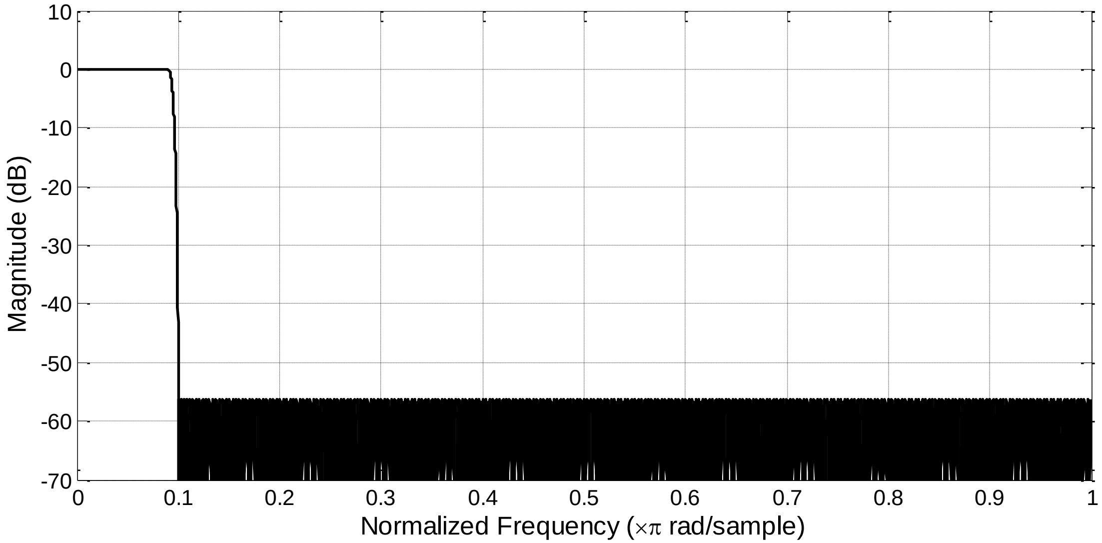
Contributions

6. ICDM-I based Channel Filter

ICDM-I: Illustrative Example

Filter coefficients: h_0 h_1 h_2 h_3 h_4 h_5 h_6 h_7 h_8 h_9 $h_{10} \ldots h_N$

Frequency response:

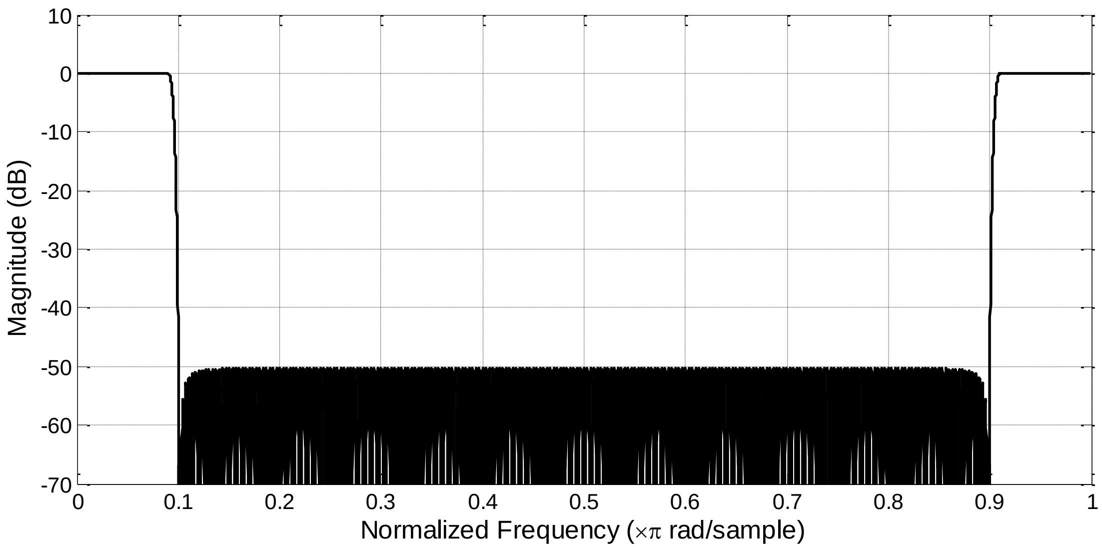


ICDM-I: Illustrative Example

Filter coefficients: h_0 h_1 h_2 h_3 h_4 h_5 h_6 h_7 h_8 h_9 $h_{10} \ldots h_N$

CDM-I by *M*=2 : h_0 0 h_2 0 h_4 0 h_6 0 h_8 0 $h_{10} \ldots h_N$

Frequency response:



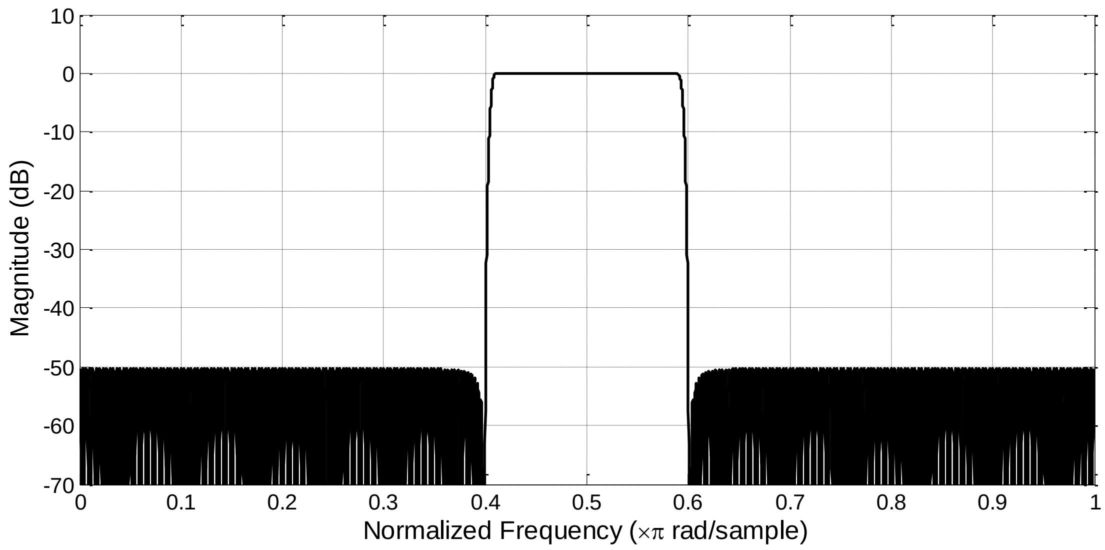
ICDM-I: Illustrative Example

Filter coefficients: h_0 h_1 h_2 h_3 h_4 h_5 h_6 h_7 h_8 h_9 h_{10} … h_N

CDM-I by M=2 : h_0 0 h_2 0 h_4 0 h_6 0 h_8 0 h_{10} … h_N

MCDM-I by M=2 : h_0 0 $-h_2$ 0 h_4 0 $-h_6$ 0 h_8 0 $-h_{10}$ … h_N

Frequency response:



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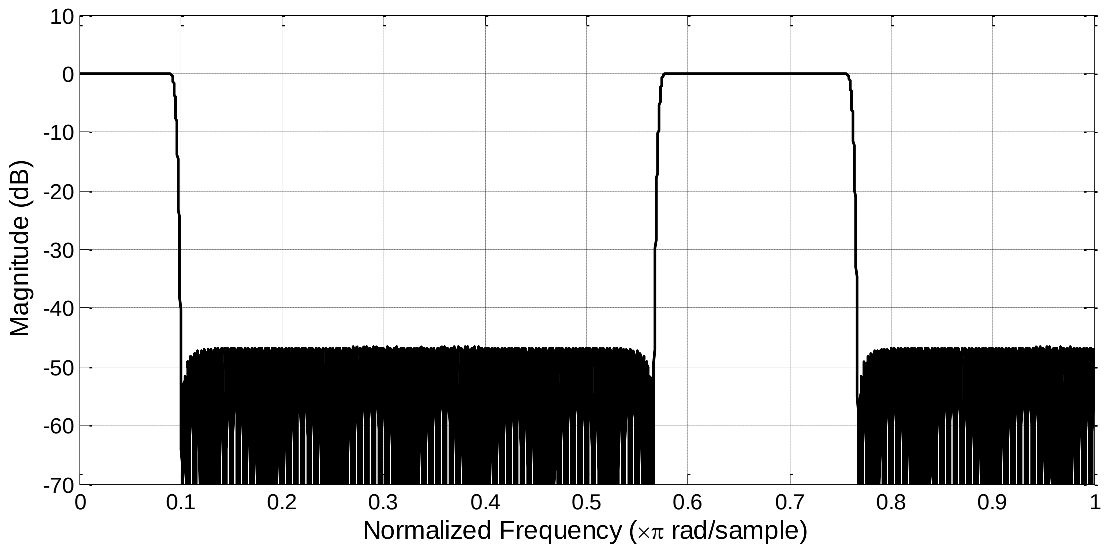
ICDM-I: Illustrative Example

Filter coefficients: h_0 h_1 h_2 h_3 h_4 h_5 h_6 h_7 h_8 h_9 h_{10} … h_N

CDM-I by M=3 : h_0 0 0 h_3 0 0 h_6 0 0 h_9 0 … h_N

Frequency response:



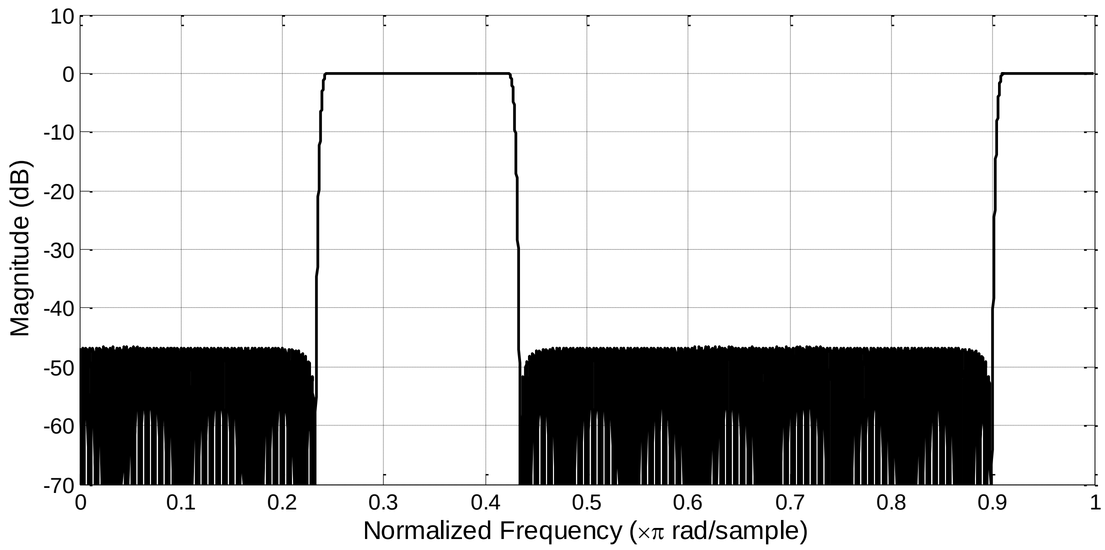
ICDM-I: Illustrative Example

Filter coefficients: $h_0 \quad h_1 \quad h_2 \quad h_3 \quad h_4 \quad h_5 \quad h_6 \quad h_7 \quad h_8 \quad h_9 \quad h_{10} \ldots h_N$

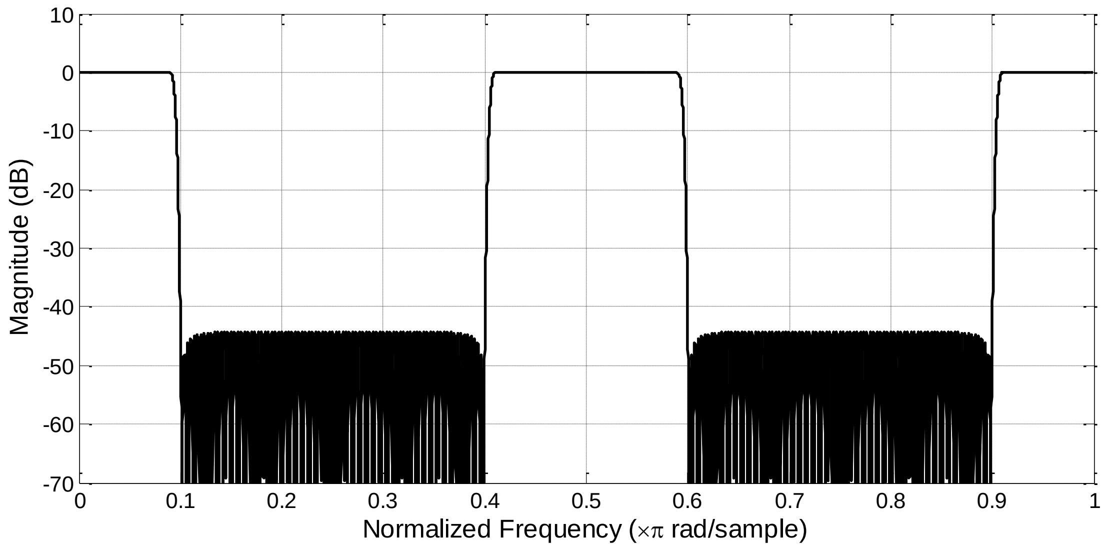
CDM-I by M=3 : $h_0 \quad 0 \quad 0 \quad h_3 \quad 0 \quad 0 \quad h_6 \quad 0 \quad 0 \quad h_9 \quad 0 \quad \ldots h_N$

MCDM-I by M=3 : $h_0 \quad 0 \quad 0 \quad -h_3 \quad 0 \quad 0 \quad h_6 \quad 0 \quad 0 \quad -h_9 \quad 0 \quad \ldots h_N$

Frequency response:

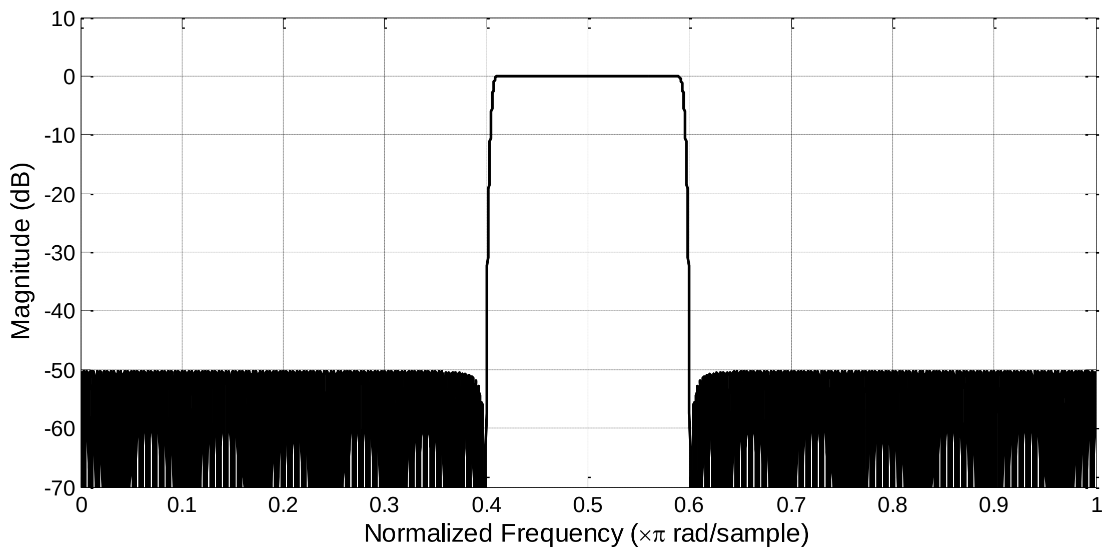


ICDM-I: Illustrative Example



CDM-I by

M=4



MCDM-I by

M=2

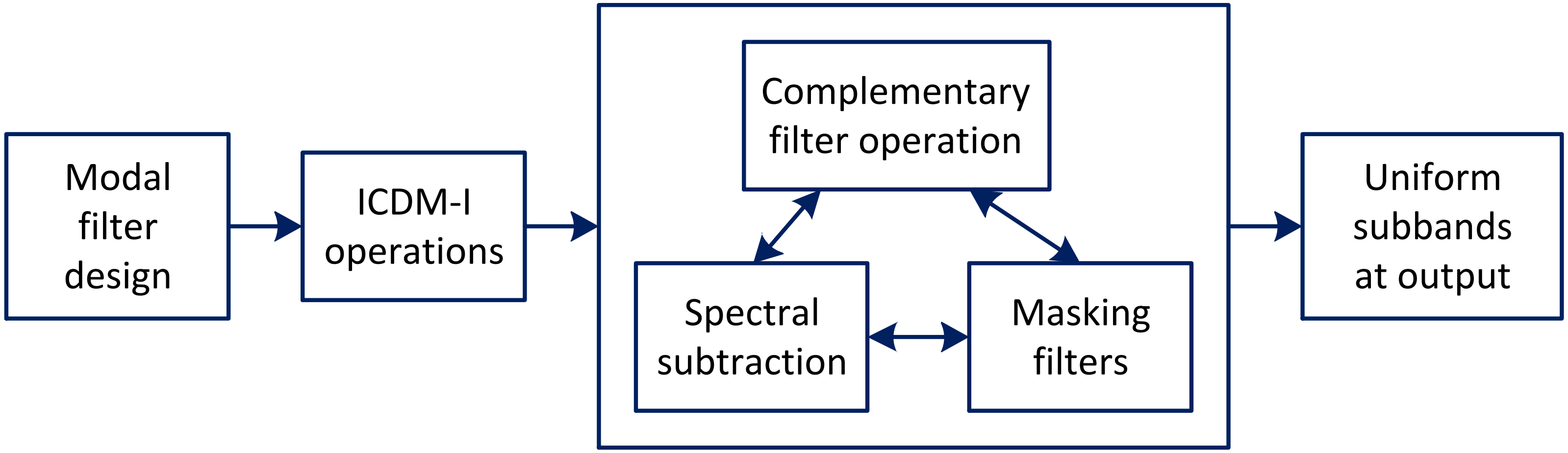
ICDM-I vs CDM-I

	CDM-I	ICDM-I
Modal filter order required	Higher	**Lower**
No. of coefficient multiplications (Implementation complexity)	Higher	**Lower**
Center frequency resolution of subbands (flexibility)	$2\pi/M$	**π/M**
Stopband attenuation performance (for same order modal filter)	Lower SA	**Greater SA**

Contributions

7. ICDM-I based FB

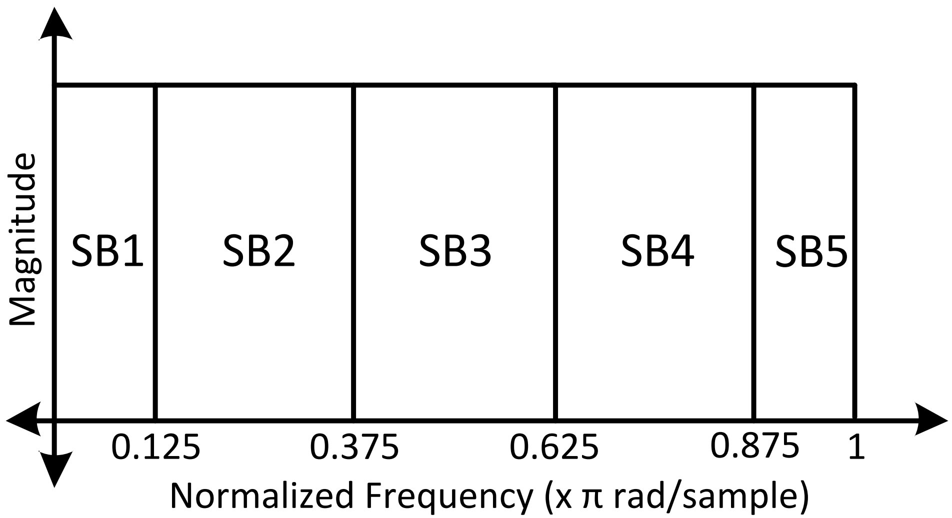
ICDM-I based FB



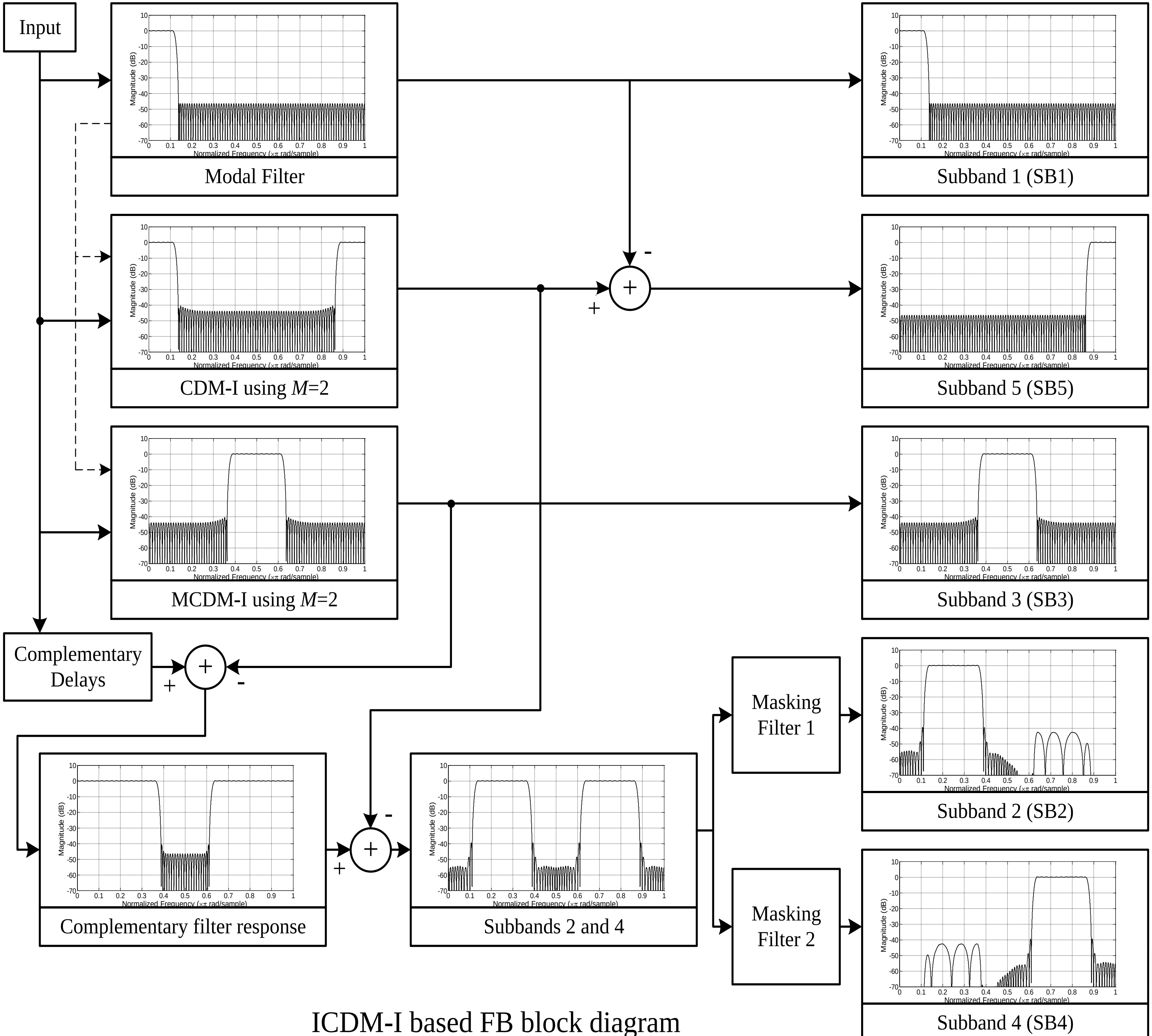
ICDM-I based FB design procedure

25. Abhishek Ambede, Smitha K. G., A. P. Vinod, “A New Low Complexity Uniform Filter Bank based on the Improved Coefficient Decimation Method,” *Radioengineering Journal*, vol. 22, no. 1, pp. 34-43, April 2013.

ICDM-I based FB: Design Example



Desired subband distribution from 0 to $f_{samp}/2$



ICDM-I based FB block diagram

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ICDM-I based FB: Implementation Results

	DFTFB	CDFB	ICDM-I based FB
Number of occupied slices	20433	7032	**5943**
Power (mW)	499	268	**206**
Post-PAR minimum period (ns)	4.344	16.172	**15.617**

- Number of slices occupied by the proposed ICDM-I based FB is **70.92%** lower than that of the DFTFB and **15.49%** lower than that of the CDFB.
- Power consumption of the proposed ICDM-I based FB is **58.72%** lower than that of the DFTFB and **23.13%** lower than that of the CDFB.

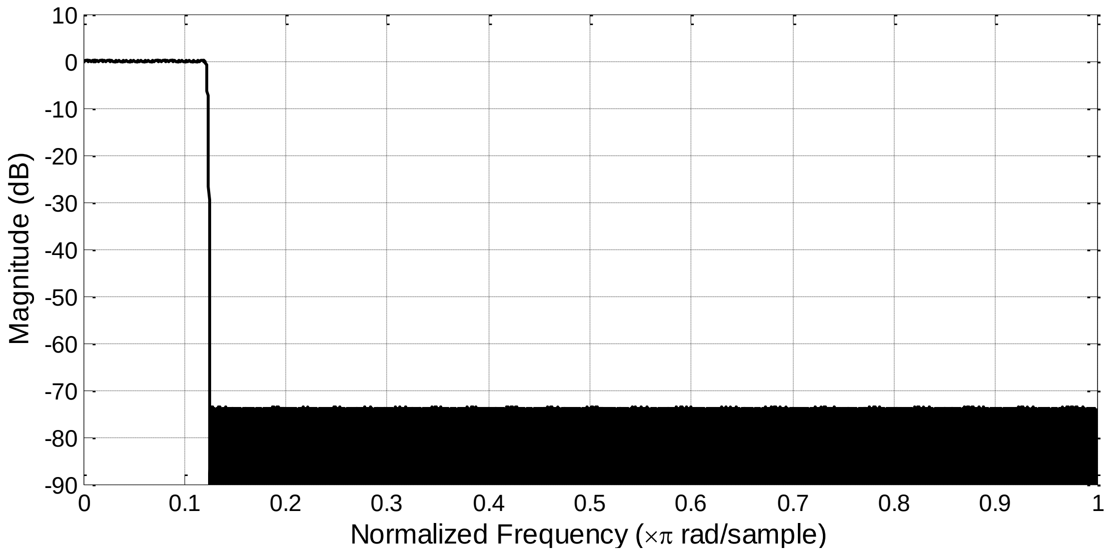
Contributions

8. ICDM-II based Channel Filter and FB

ICDM-II: Illustrative Example

Filter coefficients: h_0 h_1 h_2 h_3 h_4 h_5 h_6 h_7 h_8 h_9 h_{10} … h_N

Frequency response:



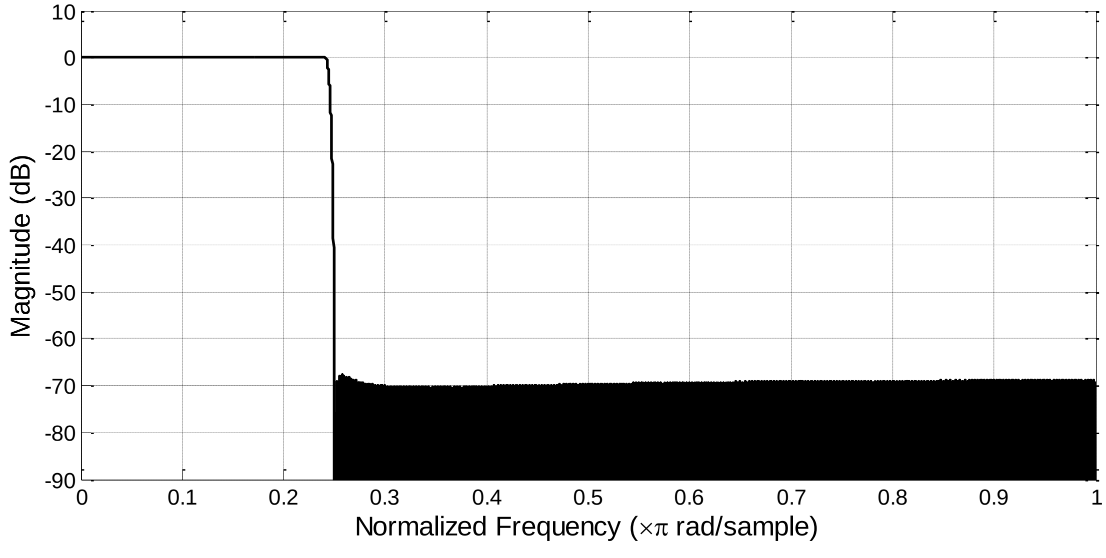
ICDM-II: Illustrative Example

Filter coefficients: h_0 h_1 h_2 h_3 h_4 h_5 h_6 h_7 h_8 h_9 $h_{10} \ldots h_N$

CDM-I by M=2 : h_0 0 h_2 0 h_4 0 h_6 0 h_8 0 $h_{10} \ldots h_N$

CDM-II by M=2 : h_0 h_2 h_4 h_6 h_8 $h_{10} \ldots h_N$

Frequency response:



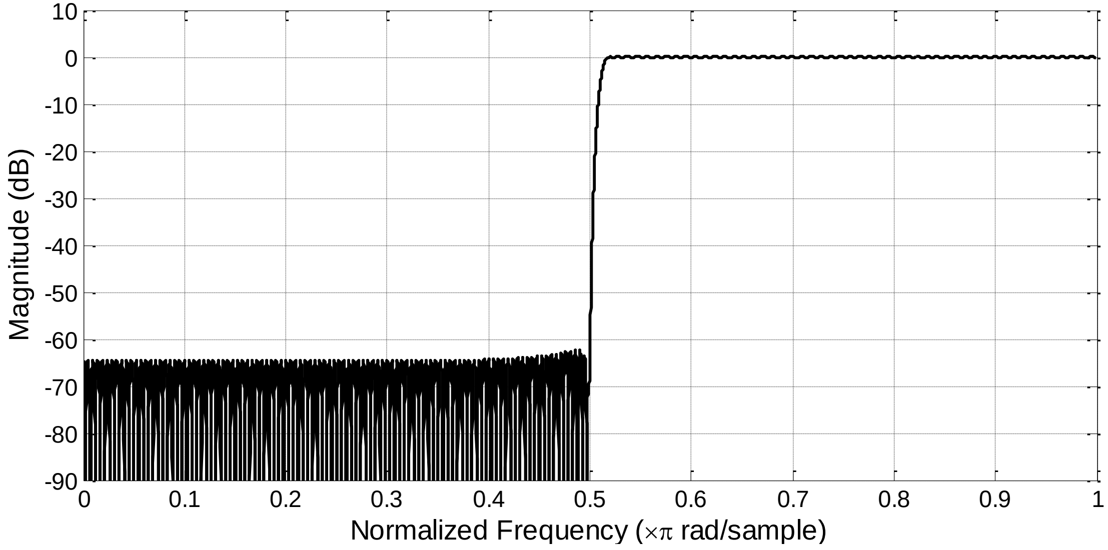
ICDM-II: Illustrative Example

Filter coefficients: h_0 h_1 h_2 h_3 h_4 h_5 h_6 h_7 h_8 h_9 h_{10} … h_N

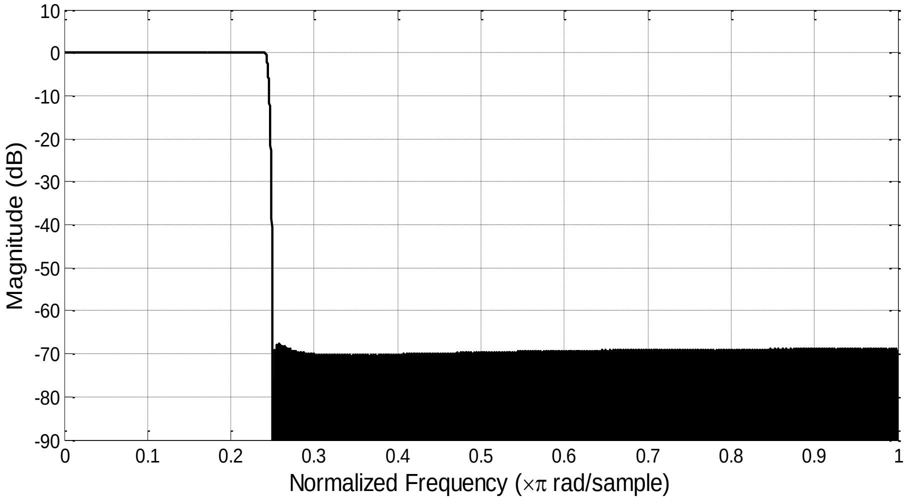
MCDM-I by M=4 : h_0 0 0 0 $-h_4$ 0 0 0 h_8 0 0 … h_N

MCDM-II by M=4: h_0 $-h_4$ h_8 … h_N

Frequency response:

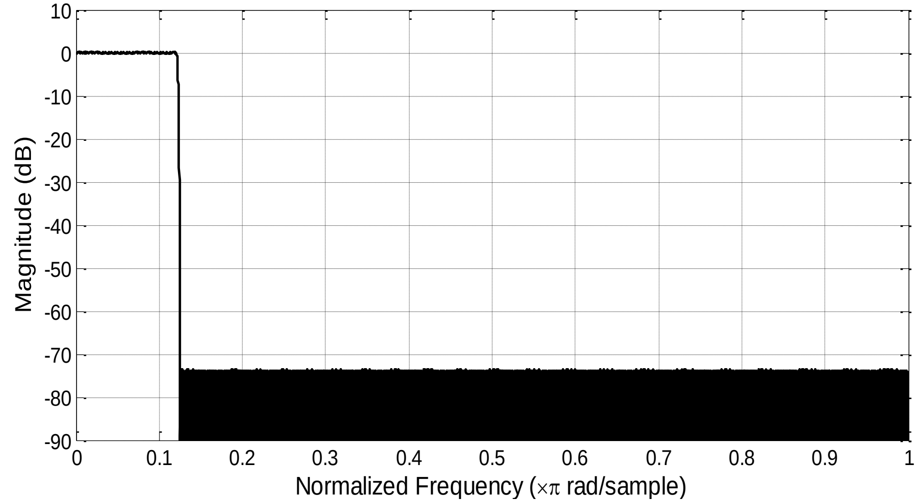


ICDM-II: Spectral Subtraction

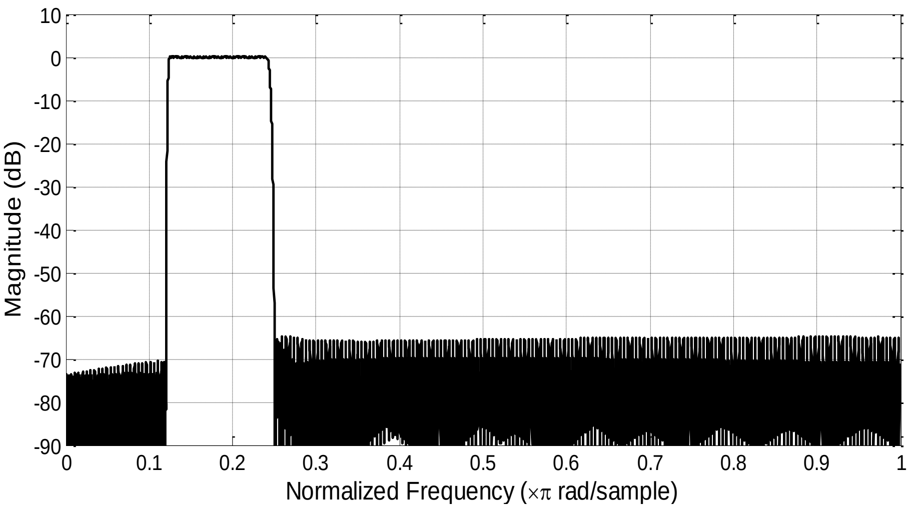


(a) Frequency response after CDM-II by M=2

−

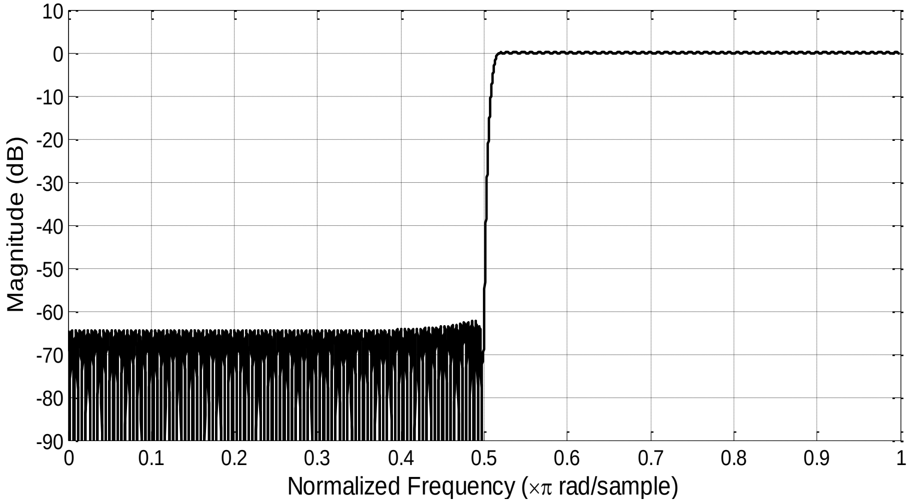


(b) Frequency response of modal filter



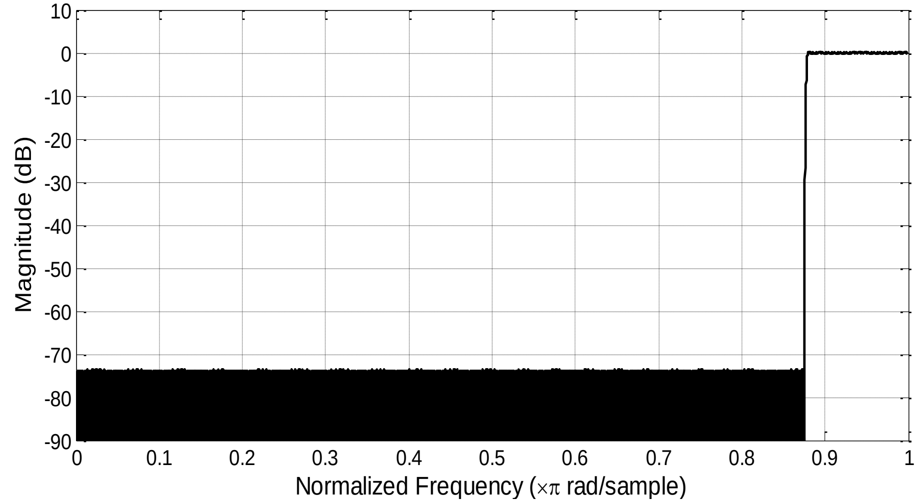
Resultant frequency response **[(a) - (b)]**

ICDM-II: Spectral Subtraction

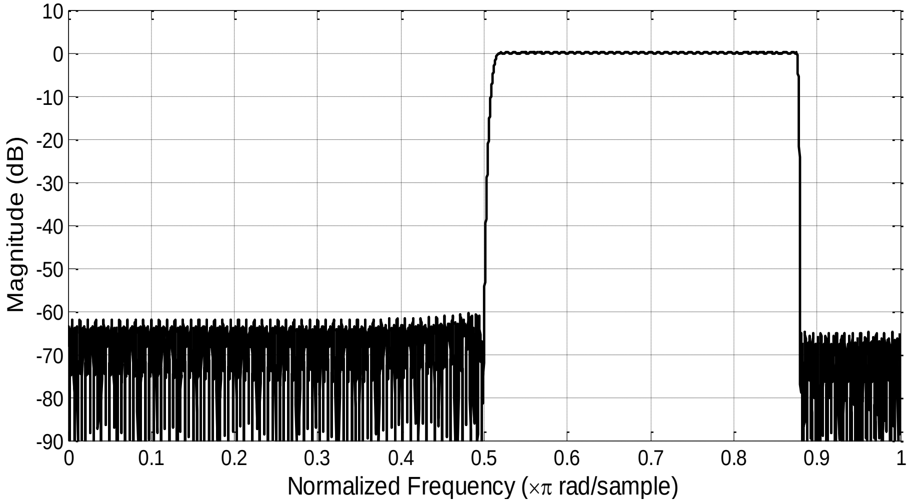


(c) Frequency response after MCDM-II by *M*=4

—

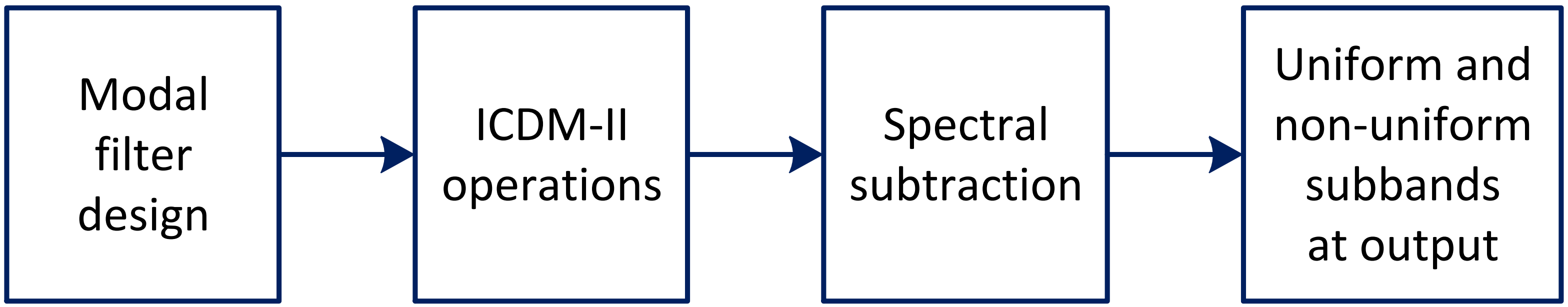


(d) Frequency response after MCDM-II by *M*=1



Resultant frequency response **[(c) - (d)]**

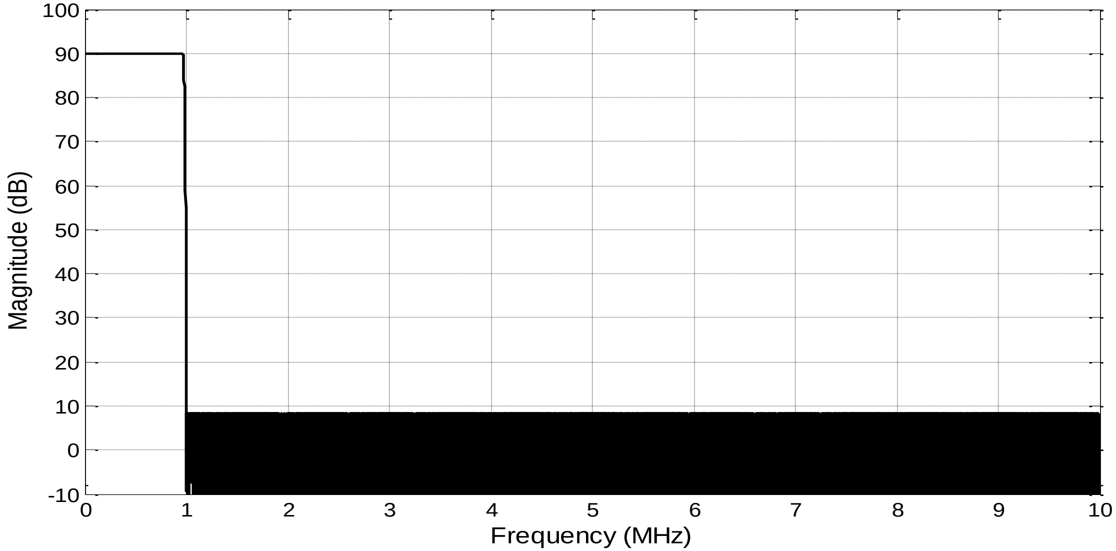
ICDM-II based Channel Filter and FB



ICDM-II based channel filter/ FB design procedure

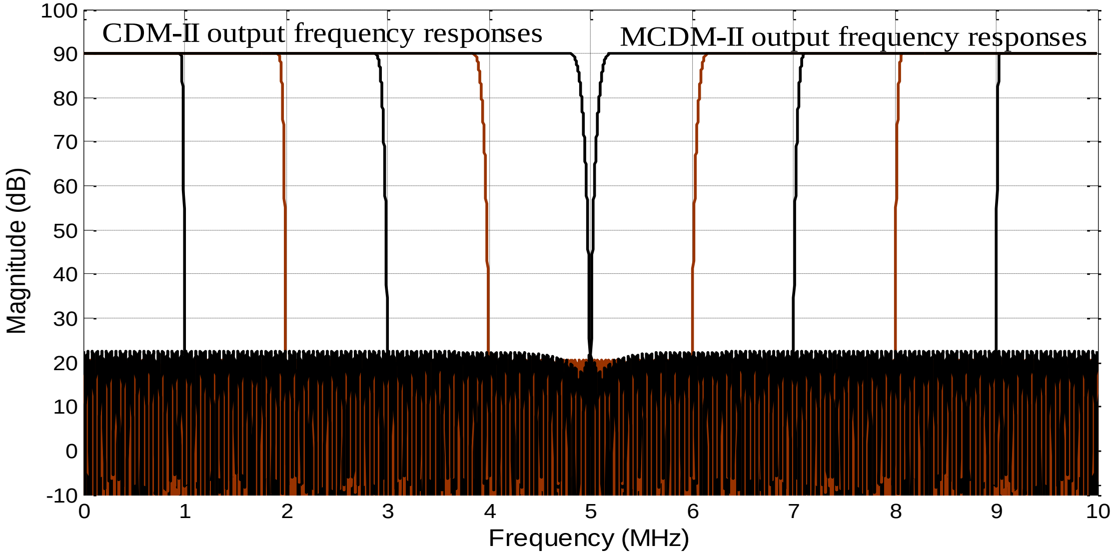
26. Abhishek Ambede, Smitha K. G., A. P. Vinod, "A low complexity uniform and non-uniform digital filter bank based on an improved coefficient decimation method for multi-standard communication channelizers," *Circuits, Systems, and Signal Processing (CSSP), Springer*, DOI: 10.1007/s00034-012-9532-9, Published online in December 2012.

ICDM-II based Channel Filter: Design Example



Modal

Filter



ICDM-II by

M=1 to M=5

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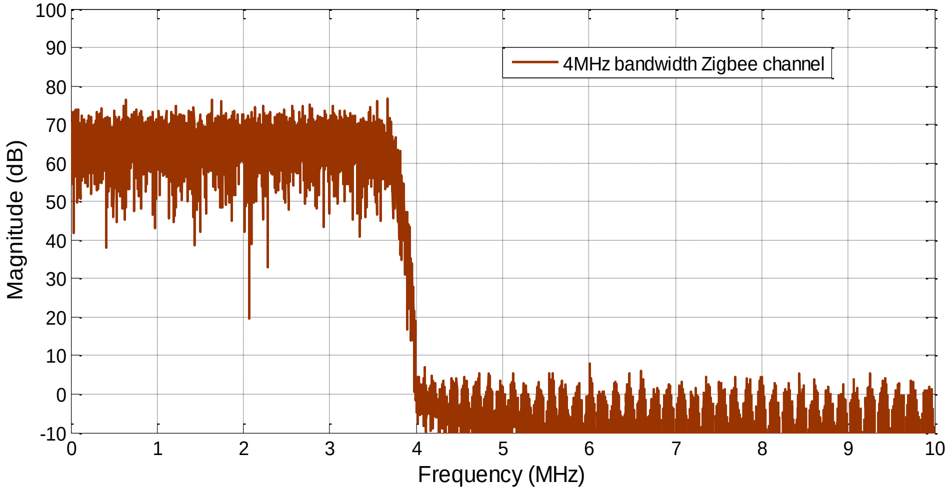
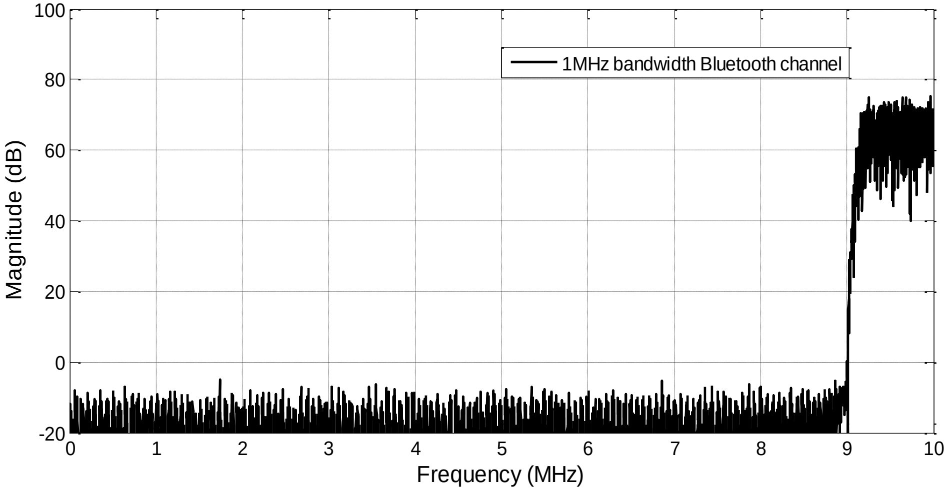
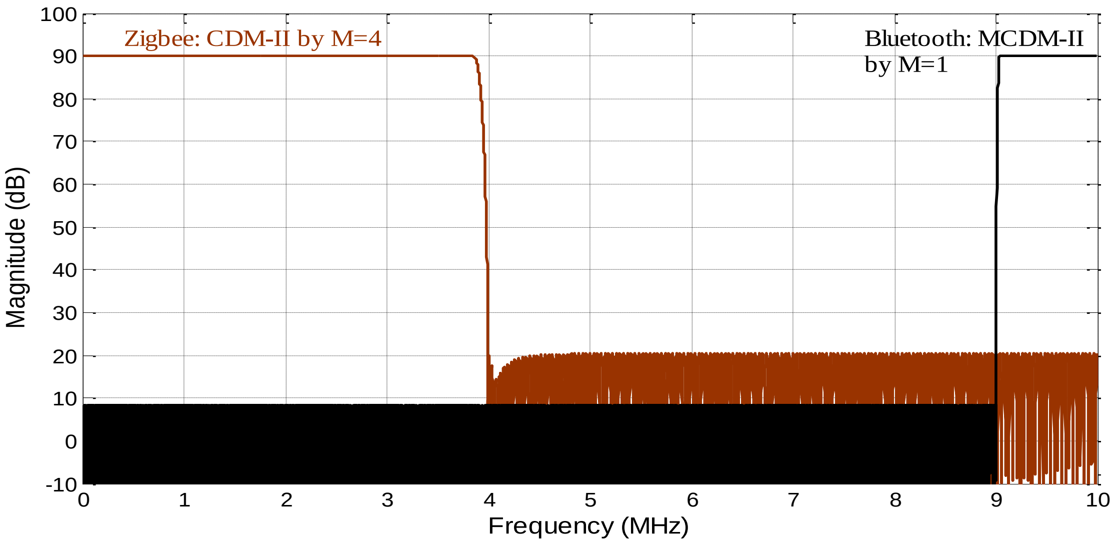
ICDM-II based Channel Filter: Design Example



Input signal during time interval $t_1 - t_2$



Input signal during time interval $t_2 - t_3$



ICDM-II frequency responses required to extract above channels

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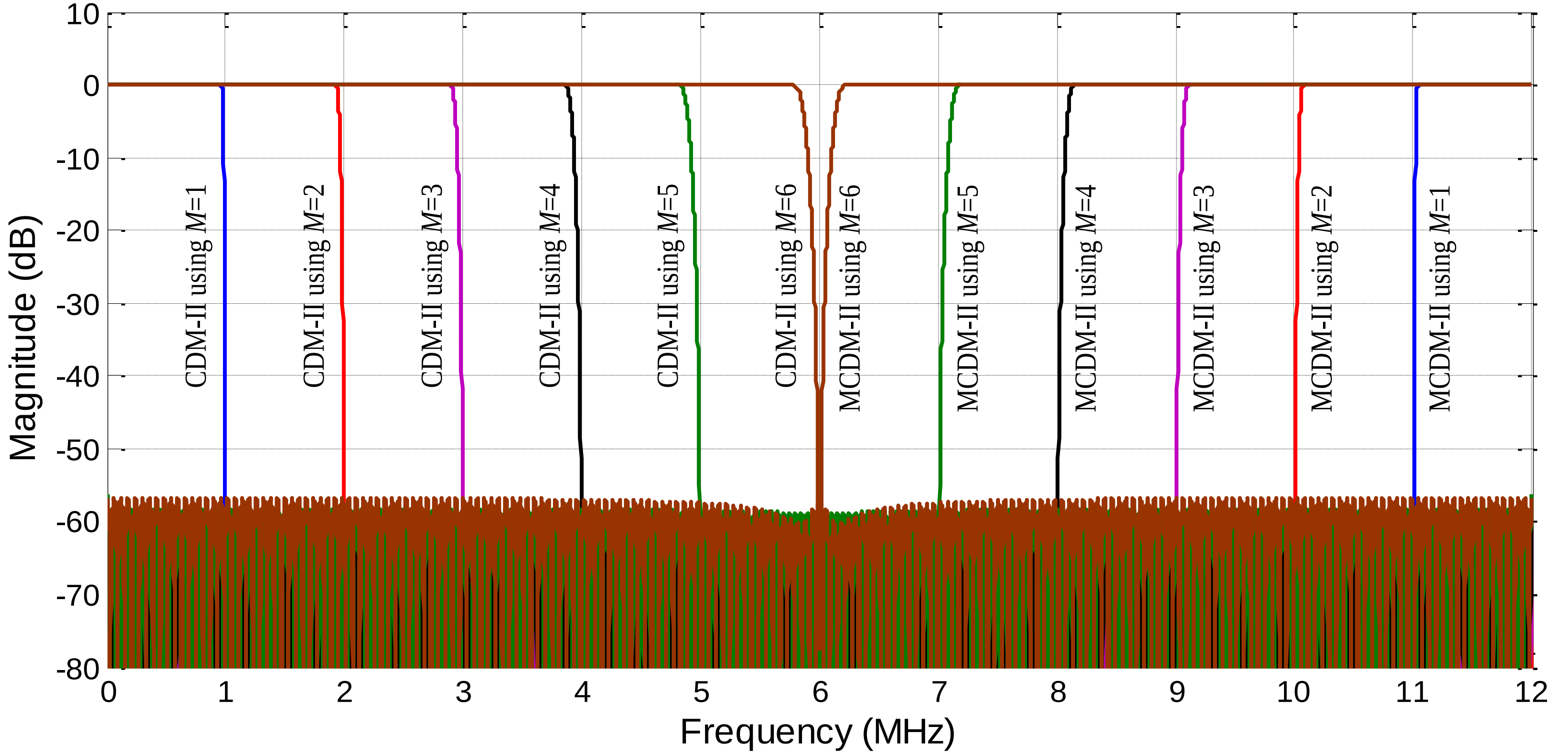
ICDM-II based Channel Filter: Design Example

	CDM-II based channel filter	ICDM-II based channel filter
Largest decimation factor required M_{max}	10	**5**
Worst case TBW increment	10 times that of the modal filter's TBW	**5 times that of the modal filter's TBW**
Worst case SA reduction	10 times that of modal filter's SA	**5 times that of modal filter's SA**

- The order of the modal filter in the proposed ICDM-II based channel filter is **57.14%** lower than that of the modal filter in the CDM-II based channel filter.

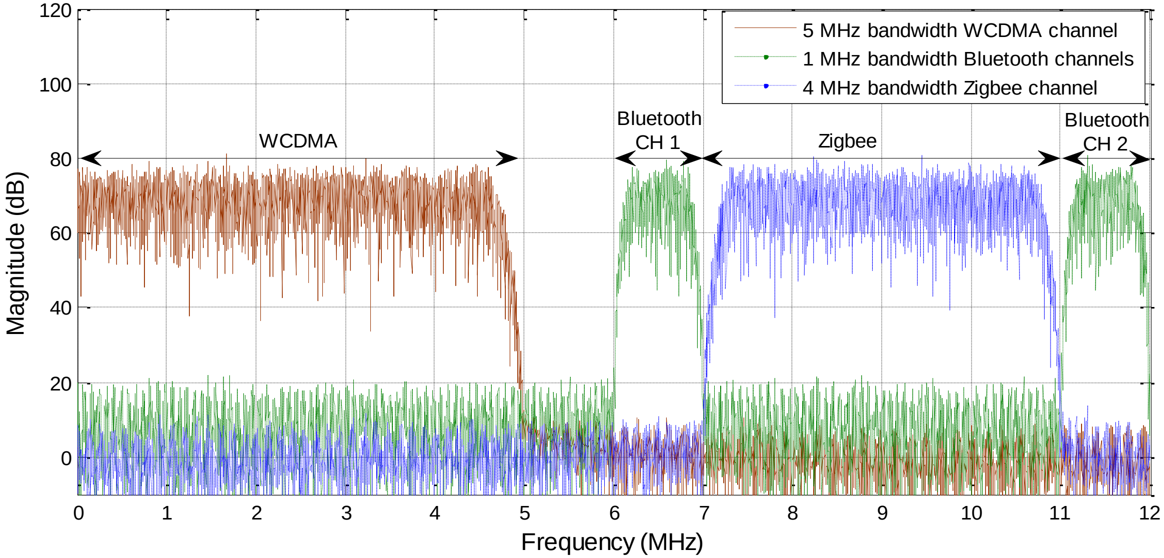
24. Abhishek Ambede, Smitha K. G., A. P. Vinod, "An improved coefficient decimation based reconfigurable low complexity FIR channel filter for cognitive radios," *2012 12th International Symposium on Communications and Information Technologies, ISCIT 2012*, pp.22-27, Gold Coast, Australia, 2-5 October 2012

ICDM-II based FB: Design Example

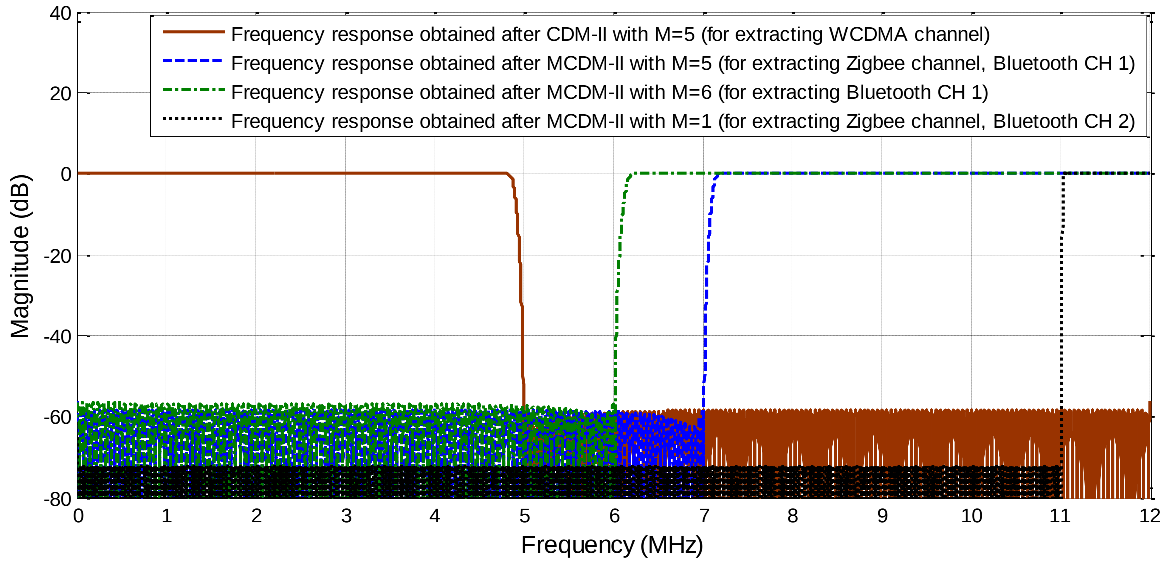


Frequency responses obtained by performing ICDM-II using *M*=1 to *M*=6

ICDM-II based FB: Design Example



Input signal containing WCDMA, Zigbee and Bluetooth channels



ICDM-II frequency responses required to extract above channels

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ICDM-II based FB: Design Example

	PDFB [27]	ICDM-II based FB
Largest decimation factor required M_{max}	12	**6**
Worst case TBW increment	12 times that of the modal filter's TBW	**6 times that of the modal filter's TBW**
Worst case SA reduction	12 times that of modal filter's SA	**6 times that of modal filter's SA**

- The order of the modal filter in the proposed ICDM-II based FB is **95.67%** lower than that of the modal filter in the CDM-II based PDFB.

27. Mengda Lin, A. P. Vinod, Chong Meng Samson See, "Progressive decimation filter banks for variable resolution spectrum sensing in cognitive radios," *IEEE 17th International Conference on Telecommunications, ICT 2010*, pp. 857-863, Doha, Qatar, 4-7 April 2010.

Conclusions

- A coefficient decimation method (CDM) and an improved coefficient decimation method (ICDM) to obtain different lowpass, highpass and multiband frequency responses using a single lowpass prototype filter have been proposed.
- Low complexity channel filters and filter banks (FBs) based on FRM, CDM and ICDM have been proposed for uniform as well as non-uniform multi-standard channelization.

Conclusions

- The proposed techniques are characterized by low complexities and high flexibilities when compared with the other methods in literature.
- Proposed filter banks also have potential applications in spectrum sensing and other areas (example: biomedical signal processing).

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Thank you