Digital Filters in CMOS Technology: Design, Topology and Performance

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Content

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   - Findings and suggestions.

Introduction

It all started with analog . . .

- Ideally, electronic filter should infinitely attenuate the signals with frequencies from the unwanted range (stop-band), and pass, with no attenuation, the signals within desired frequencies (stop-band).
- Foster's early work on reactance networks and filtering theory is usually considered as the beginning of electronic filters research, [Fos24].
- In the same period, the image parameter method used in LC filters is introduced by Zobel, [Zob23].
- More advanced network synthesis techniques and rigorous mathematical procedures are developed by Darlington and Cauer, respectively [Dar39; Cau32].
- Bode covered the fundamental concepts of filter design and analysis in frequency domain [Bod45]

It all started with analog . . .

- Filters' transfer function synthesis and realization with passive networks have been given by Zverev [Zve67].
- Similar is done for the microwave range with the work of Matthaei, Young and Jones [MYJ64].
- Important theoretical work on linear-phase, sharp cutoff and high selectivity filters was done by Rakovich, Lazovich, Djurich, Popovich, Litovski and Milovanović [RL72; RL73; RD72; RP80; LM83].
- Late seventies and early eighties, brought the era of very large scale integration circuits (VLSI) and its' proliferation outside of the niche, military, realm into the consumer industry space.
- This enabled the affordable, solid-state, active blocks, e.g. operational amplifiers. This approach is systematized in the work of Valkenburg, Williams and Taylor [Val82; WT06].

Digital takes over . . .

- The groundbreaking work of Oppenheim and Schafer is considered as the foundation for discrete-time signal processing field, [OS75; OS10].
- Raibner and Gold gave the more elaborate, real-world, applications of the digital filters with emphasis on algorithms and the effects of filters' coefficients quantization [RG75].
- Hamming work on Finite Impulse Response (FIR) and Infinite Impulse Response (IIR) filters design covers practical trade-offs going beyond the purely mathematical, system level, perspective [Ham89].
- Concepts like optimization based FIR filters design, multi-rate and poly-phase filters were promoted by Parks, Burrs, Crochier and Raibner [MPR73; RC75; PB87; CR87].
- Wave digital filters, adaptive filters, Wiener/Kalman filters and filtering based on a statistical methods were established [Wid+75; Fet86; Hay96].

Digital takes over . . .

- The recent research in the DSP field introduced the domain specific techniques like sparse and graph filters [LH13; Shu+13].
- Research shifts towards the performance optimization of various hardware realizations, [JD23; NDB23].
- This is particularly true for VLSI realization where power and/or area are the prime minimization targets, [DR22; Zod+24].

→ The goal of this paper is to overview the process of digital filers design with emphasis on influence of filter's class and topology to performance of the filter assuming VLSI realization in 65nm CMOS technology.

- Finite Impulse Response (FIR)

$$y_{FIR}[n] = \sum_{k=0}^{M} c_k x[n-k]$$

  - Order of the filter, M[1], poorly related to selectivity.
  - Linear phase for $c_k = c_{M-k}$ or $c_k = -c_{M-k}$.
  - Stable by design.
- Infinite Impulse Response (IIR)

$$y_{IIR}[n] = \sum_{k=0}^{M} c_k x[n-k] - \sum_{k=1}^{M} d_k y[n-k]$$

  - No linear phase[2].
  - Order of the filter, M, strongly related to selectivity.
  - Feedback-system (susceptible to instability).

[1] $L = M + 1$ is usually referred as a filter's "length".

[2] Unless phase correction is used or analog linear phase prototype with appropriate transformation.

FIR and IIR Filters (Transfer Function)

$$H(\upsilon) = \frac{Y(\upsilon)}{X(\upsilon)},$$

where υ is the complex number defined as,

$$\upsilon = \begin{cases} z = re^{j\theta} & \text{, discrete time (digital)} \\ s = \sigma + j\omega & \text{, continuous time (analog),} \end{cases}$$

and z is the discrete-time complex exponential base, s is the complex (Laplace) frequency. The transfer functions of FIR and IIR filters are,

$$H_{FIR}(z) = \sum_{k=0}^{M} c_k z^{-k} \quad H_{IIR}(z) = \frac{\sum_{k=0}^{M} c_k z^{-k}}{1 + \sum_{k=1}^{M} d_k z^{-k}}.$$

FIR and IIR Filters (Transfer Function)

Definitions (Important Transfer Function Properties)

Magnitude:

$$|H(\upsilon)| = \sqrt{H(\upsilon)H(\upsilon^*)}$$

Phase:

$$\Phi(\upsilon) = \angle H(\upsilon) = \frac{1}{2j} \ln\left[\frac{H(\upsilon)}{H(\upsilon^*)}\right]$$

Group Delay:

$$t_d = -\frac{\mathrm{d}\Phi(\upsilon)}{\mathrm{d}\upsilon}$$

Attenuation:

$$a_{dB} = -20\log\left(|H(\upsilon)|\right)$$

Selectivity:

$$S = \frac{w_{pass}}{|w_{stop} - w_{pass}|}, w \in \{\omega, \theta\}$$

FIR and IIR Filters (Filter Synthesis)

- The synthesis of the filter transfer function can be performed in continuous (Laplace, s domain) or in discrete (z domain) time.
- FIR filters are synthesized directly in the z domain (windowing, optimization, etc.) [Har78; MPR73].
- Direct, z domain, synthesis of IIR is significantly harder than FIR (rational polynomial function), [LPT98; LH13; Tar+01]
- Traditionally, IIR transfer functions are synthesized by conformal mapping of the Laplace, s domain, analog prototype into the z domain.

Definitions

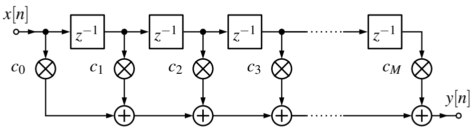
Bilinear: $s = \frac{2}{T}\frac{z-1}{z+1}$ Quadratic[3]: $s = \frac{1}{2T}\frac{3z^2 - 4z + 1}{z^2}$

[3] Proposed in [MPL14]

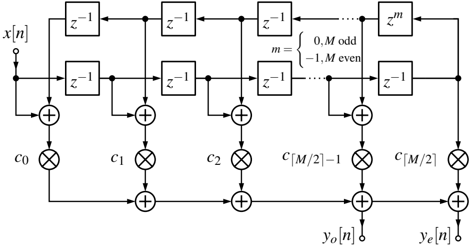
FIR and IIR Filters (Filter Topology)

$$y_{FIR}[n] = \sum_{k=0}^{M} c_k x[n-k]$$

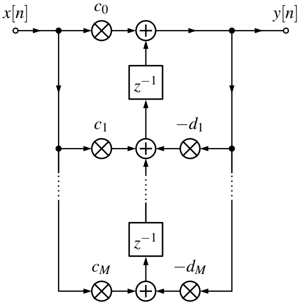
$$y_{IIR}[n] = \sum_{k=0}^{M} c_k x[n-k] - \sum_{k=1}^{M} d_k y[n-k]$$



(a): FIR: General



(b): FIR: Folded Delay Line



(c): IIR

Figure 1: Direct realization of digital filters

$$\frac{b_o}{s+a_o} \mapsto \begin{cases} \dfrac{c_{0,o} + c_{1,o} z^{-1}}{1 + d_{1,o} z^{-1}} & \text{, bilin.} \\ \dfrac{\sum_{k=0}^{2} c_{k,o} z^{-k}}{1 + \sum_{k=1}^{2} d_{k,o} z^{-k}} & \text{, quad.} \end{cases}$$

$$\frac{b_{1,i} s + b_{0,i}}{s^2 + a_{1,i} s + a_{0,i}} \mapsto \begin{cases} \dfrac{\sum_{k=0}^{2} c_{k,i} z^{-k}}{1 + \sum_{k=1}^{2} d_{k,i} z^{-k}} & \text{, bilin.} \\ \dfrac{\sum_{k=0}^{2} c_{k,i} z^{-k}}{1 + \sum_{k=1}^{4} d_{k,i} z^{-k}} & \text{, quad.} \end{cases}$$

S-domain:

Poles: $s_{p,o}, s_{p,i} = \sigma_i + j\omega_i$

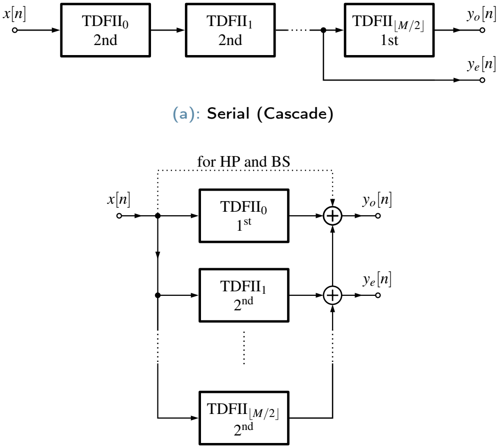
Residues: $s_{r.o}, s_{r,i} = \alpha_i + j\beta_i$

Nominator: $b_o = r_o, a_o = -p_o,$

$a_{1,i} = -2\sigma_i, a_{0,i} = |s_{p,i}|^2$

Denominator: $b_{1,i} = 2\alpha_i, b_{0,i} = -2(\alpha_i\sigma_i + \beta_i\omega_i)$

$i = 0, 1, \ldots, \lfloor M/2 \rfloor$



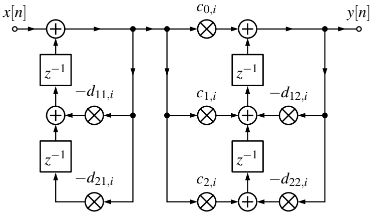
(b): Parallel (Cascode)

Figure 2: Distributed realization of IIR filters

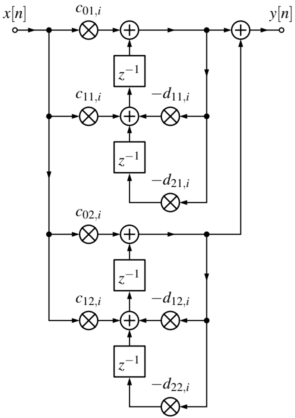
$$H_{ser,i}(z) = \frac{1}{1+\sum_{k=1}^{2} d_{k1,i} z^{-k}} \cdot \frac{\sum_{k=0}^{2} c_{k,i} z^{-k}}{1+\sum_{k=1}^{2} d_{k2,i} z^{-k}}$$

$$H_{par,i}(z) = \frac{c_{01,i} + c_{11,i} z^{-1}}{1+\sum_{k=1}^{2} d_{k1,i} z^{-k}} + \frac{c_{02,i} + c_{12,i} z^{-1}}{1+\sum_{k=1}^{2} d_{k2,i} z^{-k}}$$

$z_{p,i} = \lambda_i + j\eta_i$ (poles), $z_{r,i} = \rho_i + j\gamma_i$ (residues), $c_{0l,i} = 2\rho_i$, $c_{1l,i} = -(\lambda_i + \gamma_i \eta_i/\rho_i)$, $d_{1l,i} = -2\lambda_i$, $d_{2l,i} = |z_{p,i}|^2$, $l = 1, 2$.



(a): Serial (Cascade)



(b): Parallel (Cascode)

Figure 3: 4^{th} order $TDFII_i$ cell for quadratic s-to-z transform

Design Examples

Three filter realizations are considered

- FIR synthesized with Parks-McCllelan algorithm [MPR73]
- IIR synthesized with bilinear s-to-z transform (IIR bilinear) and
- IIR synthesized with quadratic s-to-z transform (IIR quadratic) [MPL14].

Specification:

- Notch (Band-Stop) filter with:
  - Central (notch) frequency, $f_0 = 5\text{MHz}$
  - 40% relative bandwidth, $f_{bwr} = f_{bw}/f_0 = 0.4 \Rightarrow f_{bw} = 2\text{MHz}$ $(Q = 1/\omega_{bwr} = 2.5)$
  - At least 60dB stop-band attenuation, $a_{dB,\text{stop}} \geq 60\text{dB}$.
  - Less than 1dB pass-band attenuation, $a_{dB,\text{pass}} \leq 1\text{dB}$.

Application:

- Multi-Standard Radio (MSR) with available sampling frequencies $f_s = k \times 61.44\text{MHz}, k = 1, 2$.

Design Examples

FIR design:

- Stop-band edges $\pm 3\%$ of central frequency, f_o ($[f_{stop,l}/f_o, f_{stop,h}/f_o] = [0.97, 1.03]$).
- Estimated order for a given constrains is $M = 170$, [Cen25]
- Sampling frequency: $f_{s,FIR} = 61.44\text{MHz}$.

IIR designs:

- LP $\rightarrow$ BS frequency translation, $s \mapsto \dfrac{\omega_{bw}}{\omega_o^2 + s^2} s$, [OT68]
- Pass-band edges obtained by solving, $f_o^2 = f_h f_l$, $f_{bw} = f_h - f_l$,

$$f_l = \frac{1}{2} f_{bw} \left(\sqrt{1 + 4\left(f_o/f_{bw}\right)^2} - 1 \right)$$

$$f_h = \frac{1}{2} f_{bw} \left(\sqrt{1 + 4\left(f_o/f_{bw}\right)^2} + 1 \right)$$

For a given BS filter parameters, $f_l = 4.099\text{MHz}$ and $f_h = 6.099\text{MHz}$ ($[f_l/f_o, f_h/f_o] = [0.82, 1.22]$).

IIR designs:

Table 1: Normalized Poles of LSM[4]LP Prototype and Translated BS Filter for IIR Biilinear

No.	LP	BS
1/2	$-0.2838434341 \pm j0.9265437853$	$-0.0487295044 \pm j0.8202217798$
3/4	$-0.6886065659 \pm j0.3750262747$	$-0.1961900822 \pm j0.8605934781$
5/6		$-0.2518125277 \pm j1.1045829462$
7/8		$-0.0721770666 \pm j1.2148944003$

Sampling frequency: $f_{s,IIR\ blin.} = 61.44\text{MHz}$.

Table 2: Normalized Poles of LSM LP Prototype and Translated BS Filter for IIR Quadratic

No.	LP	BS
1/2	$-0.4076505823 \pm j0.8728824408$	$-0.0715481706 \pm j0.8257686640$
3/4	$-0.7958988355 \pm j0.0$	$-0.2512882179 \pm j0.9679123057$
5/6		$-0.1041438339 \pm j1.2019694406$

Sampling frequency: $f_{s,IIR\ quad.} = 2 \times 61.44\text{MHz} = 122.88\text{MHz}$.

[2] Critical Monotonic Amplitude Characteristic prototypes up to 10^{th} order available in [TLAS15]

Design Examples

Quantization:

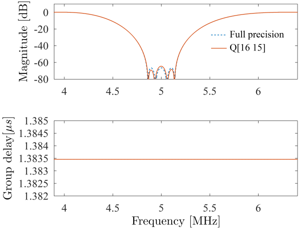
- Format $Q[N\ F]$, N (word length), $F = N - I$ (fractional part) and I integer part,

$$I = \left\lceil \log_2 \left(\left\lceil \max \left\{ |c_{k,i}|, |d_{l,i}| \right\} \right\rceil \right) \right\rceil ,$$

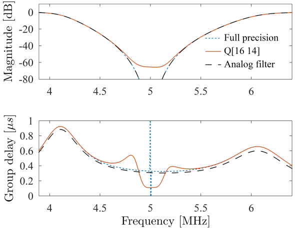
  where $i = 1, 2, \ldots, N_S$, $k = 0, 1, 2$, $l = 1, 2$ and N_S is the number of cells.

Front- & Back-End Tooling:

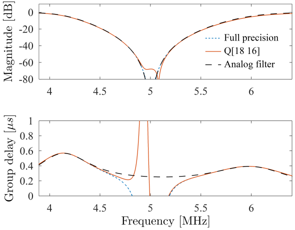
- Synthesis of transfer functions: MATLAB/GNU Octave.
- HDL language of choice: VHDL
- EDA language of choice: Tcl/Bash
- Simulation (NCsim), Synthesis (Genus) and Implementation (Innovus): Cadence Design System® (CDS) [SK24].
- Technology node: TSMC 65 LP/GP MS RF mini@sic



(a): BS FIR 170$^{\text{th}}$ order



(b): BS IIR bilienar, 8$^{\text{th}}$ order



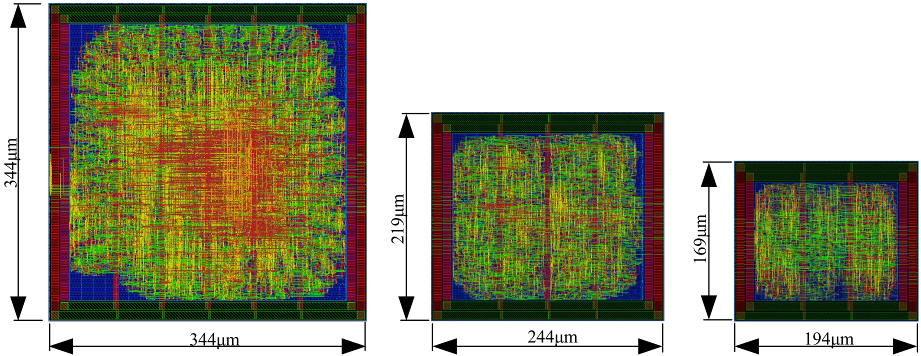
(c): BS IIR quadratic, 12$^{\text{th}}$ order

- Selectivities:

$$S_{FIR} = 5.52$$
$$S_{IIR,bilin} = 5.83$$
$$S_{IIR,quad} = 5.14$$

Figure 4: Magnitude and group delay

Design Examples



(a): FIR (b): IIR quadratic (c): IIR bilienar

Figure 5: Layouts of designed filters

Simulation Results

- Composite sinusoidal excitation,

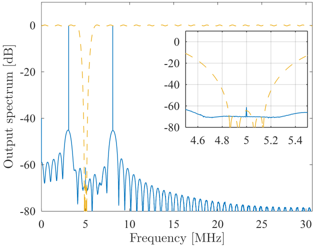
$$x[n] = \sum_{k=0}^{2} \sin\left(2\pi \boldsymbol{f_{in}}[k] n T_s\right), \;\; n = 0, 1, \ldots, N_{FFT} - 1$$

$\boldsymbol{f_{in}} = [3.090\text{MHz}, 4.995\text{MHz}, 8.085\text{MHz}],\; N_{FFT} = 16384\ (2^{14})$
$f_{res} = f_s / N_{FFT}$ (3.75kHz for FIR, IIR bilin. and 7.5kHz for IIR quad.)
Edge frequencies corresponds to relative bandwidth of one and middle to central frequency of the filter, f_o.

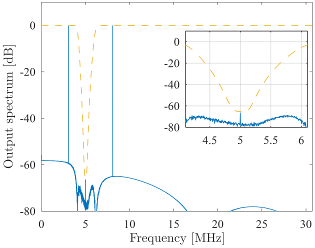
Table 3: Attenuation of RTL model at Input Frequencies

Realization / f_{in}	$f_{in}[0]$	$f_{in}[1]$	$f_{in}[2]$
FIR Parks-McCllelan	0.176dB	61.189dB	0.170dB
IIR bilienar	0.046dB	66.385dB	0.030dB
IIR quadratic	0.084dB	75.958dB	0.286dB

Simulation Results



(a): FIR



(b): IIR biliniear

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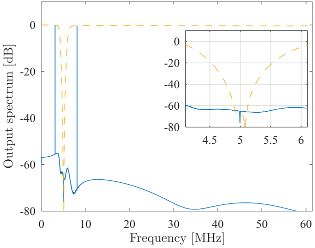

(c): IIR quadratic

Simulation Results

Table 4: Performances of The Designed Filters

Realization			Unit	FIR *Parks-McCllelan*	IIR *bilinear*	IIR *quadratic*
No. of Std. Cells			-	29979	6991	15499
No. of Metals			-	6	5	6
Wiring			µm	323168	51575	99739
Area			μm^2	118336	32786	53436
Price*			€	437	122	198
Savings ($\delta_€$)			%	-	72.08	54.70
Consumption	**WC** $V_{DD} =$ 1.08V $T =$ 125°C	P_{int}	mW	5.066	1.240	3.458
		P_{ext}	mW	2.042	0.502	2.004
		P_{leak}	µW	10.770	2.383	4.416
		P_{tot}	mW	7.119	1.763	5.467
		δ_P	%	-	75.24	23.21
		E_{tot}	µW/MHz	115.87	28.67	44.49
		δ_E	%	-	75.23	61.60
	BC $V_{DD} =$ 1.32V $T =$ 0°C	P_{int}	mW	8.024	1.969	5.456
		P_{ext}	mW	3.206	0.821	3.155
		P_{leak}	µW	22.88	4.69	8.12
		P_{tot}	mW	11.250	2.795	8.619
		δ_P	%	-	75.16	23.40
		E_{tot}	µW/MHz	183.105	45.491	70.141
		δ_E	%	-	75.15	61.70

* Only for silicon, no packaging, measurements, etc.

Prices for target, TSMC 65 LP/GP MS RF mini@sic, process run are available at [EUR25]. (3691€/mm^2 for Uni.)

Conclusion

- The chronological literature review, following the filters design field evolution, was given in introduction.
- An overview of the common digital filter hardware realizations is provided (direct/distributed).
- Quadratic s-to-z transform is proposed as an alternative to bilinear.
- The influence of filter class and topology choice on performance was examined by comparing the three VLSI realizations of band-stop notch filter: FIR, IIR bilinear and IIR quadratic.
- Key performance parameters namely, area, price and power consumption are observed assuming the TSMC 65nm GP/LP process node.
- Significant savings, up to 70%, can be achieved when choosing IIR over FIR class, at the price of phase linearity loss.

Thank You for Your Attention!

Open for questions ...

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