Design of Cascaded Integrator-Comb Decimation Filters for Direct-RF Sampling Receivers

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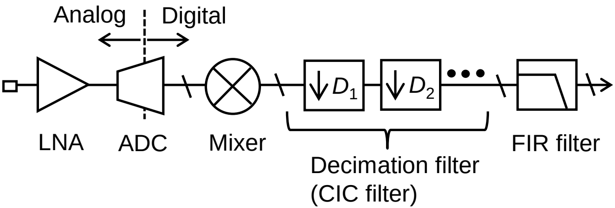
Outline

Background

Direct-RF sampling receivers:

- Downconvert and filter RF signals in digital domain.
- Suitable for nano-scale digital CMOS process.
- Reduce the design cost and time to market.



LNA: Low-noise amplifier, ADC: Analog-to-digital converter,

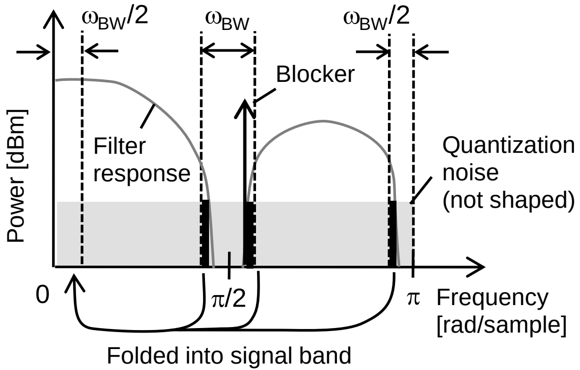
RFIC ’10 [1], A-SSCC ’11 [2], JSSC ’12 [3]

Decimation filters:

- Decrease GS/s rates of an ADC to MS/s rates.
- Consist of cascaded integrator-comb (CIC) filters.

Noise and Blockers Folded by Decimation

Quantization noise of the ADC and out-of-band blockers around the notch frequencies are folded into the signal band (ω_{BW}).

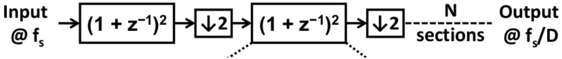


The CIC filter needs to reduce the folded noise and blockers to obtain the required output SNR (SNR_{out}).

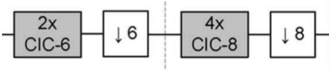
Objectives

Generally, CIC filters with some orders are cascaded (multistage) to achieve the desired sampling rate and required noise level.

- A-SSCC '11 [2]: Two 2nd-order CIC filters (D =16, D: total decimation factor).



- JSSC '12 [3]: 2nd- and 4th-order CIC filters (D =48).



A higher order:

- Provides more attenuation for the folded noise and blockers.
- Increases the power consumption and area (TCAS-II '01 [4]).

The order should be as small as possible for GS/s CIC filters.

We present a method to determine the lowest orders of CIC filters.

Required SNR_{out} of CIC Filter

- A RF-direct sampling receiver is assumed to comply with the Bluetooth Low Energy (BLE) specifications.

Block	Performance	Requirement
Receiver	Operating frequency, f_c	2400–2483.5 MHz
	Signal bandwidth, f_{BW}	~ 1.5 MHz
	Sensitivity	≤ -74 dBm
	Output SNR, $SNR_{out}{}^*$	≥ 14 dB
CIC filter	$SNR_{out}{}^*$	≥ 14 dB

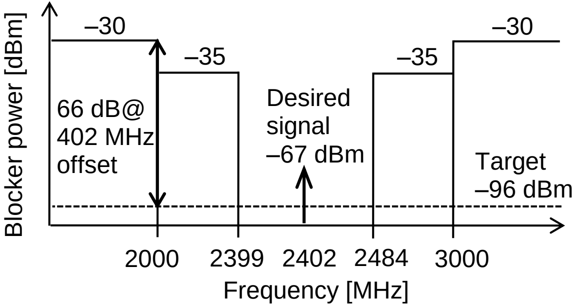
* Input (desired) power, $P_{des,RX} = -74$ dBm

- SNR_{out} is mainly determined from the quantization noise of the ADC.

The CIC filter needs to reduce the folded quantization noise to obtain $SNR_{out} = 14$ dB for $P_{des,RX} = -74$ dBm.

Required Blocker Rejection of CIC Filter

Out-of-band blocking requirements for BLE



- The CIC filter needs to attenuate the blockers to -96 dBm ($= -67$ dBm – 14 dB – 15 dB (margin)).

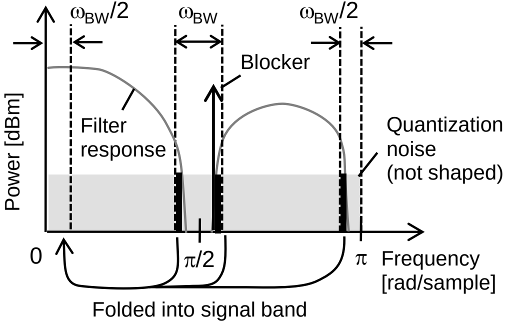
Block	Performance	Requirement
CIC filter	Blocker rejection@ 3–401 MHz offset ≥402 MHz offset	 61 dB 66 dB

Analysis of Folded Quantization Noise

Quantization noise is folded around the notch frequency,

$$\omega_k = 2k\pi/D \ (k = \pm 1, \ \cdots, \ \pm D/2) \text{ for even } D.$$

- S_n: Power spectrum density of quantization noise
- $NTF(\omega)$: Noise transfer function of ADC
- $H_{CIC}(\omega)$: Transfer function of CIC filter



Noise power around ω_k ($P_{n,k}$) and total noise power folded into ω_{BW} (P_n):

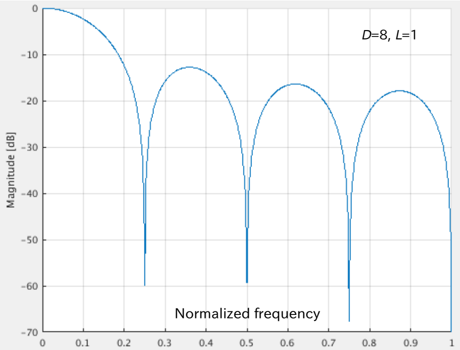
$$P_{n,k} = \int_{\omega_k - \omega_{BW}/2}^{\omega_k + \omega_{BW}/2} |NTF(\omega)|^2 \, |H_{CIC}(\omega)|^2 \, S_n d\omega, \ P_n = P_{n,0} + 2 \sum_{k=1}^{D/2} P_{n,k}.$$

Analysis of Folded Out-of-Band Blocker

Worst-case scenario:
Blocker at $\omega_1 \pm \omega_{BW}$ for N-stage CIC filter

- Minimum rejection
- Rejection only from Nth (last) stage, $|H_{N,CIC}|$

D_N: Decimation factor of Nth stage
L_N: Order of Nth stage

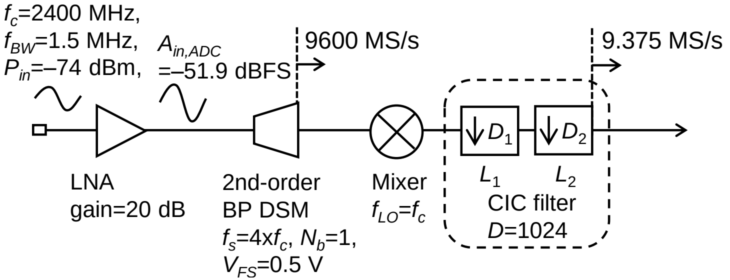


$$|H_{CIC}(\omega_1 \pm \omega_{BW}/2)| \approx |H_{N,CIC}\left(2\pi/D_N \pm D_1 \cdots D_{N-1}\omega_{BW}/2\right)|$$

$$= \frac{1}{D_N^{L_N}} \left| \frac{\sin\left(\pi \pm D\frac{\omega_{BW}}{4}\right)}{\sin\left(\frac{\pi}{D_N} \pm \frac{D}{D_N}\frac{\omega_{BW}}{4}\right)} \right|^{L_N} \approx \left(\frac{D\omega_{BW}}{4\pi}\right)^{L_N} = \left(\frac{Df_{BW}}{2f_s}\right)^{L_N}.$$

D and L_N almost determine the rejection for out-of-band blockers.

Design of Two-Stage CIC Filter



- 1-bit 2nd-order band-pass delta-sigma modulator (BP DSM)

Goal: To meet the following requirements with the lowest orders

Block	Performance	Requirement
CIC filter	SNR_{out}*	$\geq$ 14 dB
	Blocker rejection†@	
	3–401 MHz offset	61 dB
	≥402 MHz offset	66 dB

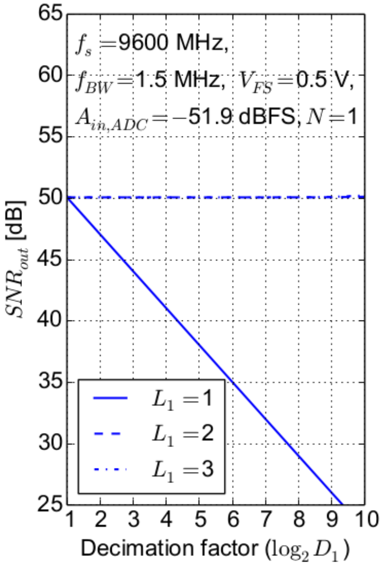
$^*P_{des,RX}$ = –74 dBm, $^\dagger P_{des,RX}$ = –67 dBm.

L_i Determined by SNR_{out}

Determine a lower limit for L_i to achieve the required SNR_{out} for the minimum $P_{des,RX}$.

- One-stage CIC filter with L_1 and $D_1 = 1024$.
- Calculated SNR_{out} versus D_1 with L_1 as a parameter.
- For $L_1 = 1$, SNR_{out} degrades as D_1 increases.
- $L_1 \geq 2$ keep SNR_{out} constant for a larger D_1.

$L_1 = 2$ is selected, becuase it has little impact on SNR_{out}.

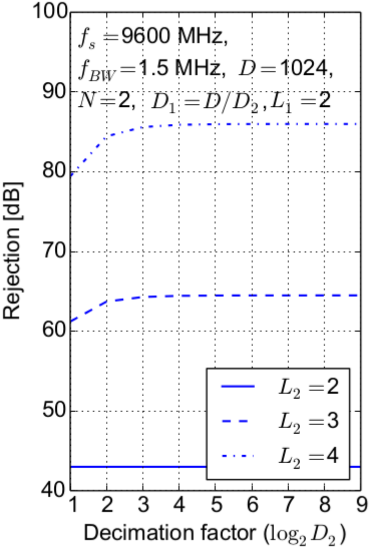


L_i Determined by Out-of-Band Rejection

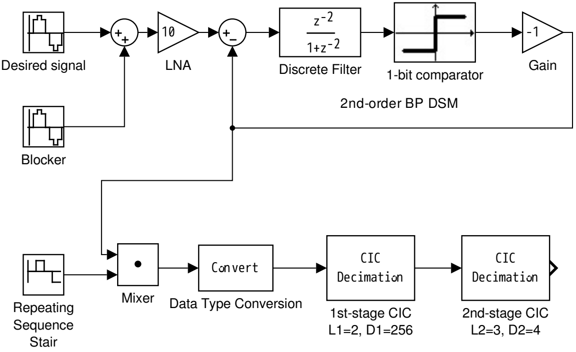
Determine L_i to achieve the required out-of-band rejection.

- Two-stage CIC filter with $L_1 = 2$, $D_1 = D/D_2$, and $D = 1024$.
- Calculated rejection versus D_2 with L_2 as a parameter.
- Rejection almost remains constant for $D_2 \geq 2^2 = 4$.
- $L_2 = 3$ and $D_2 = 4$ provide a rejection of 63 dB, satisfying the requirement.

$L_2 = 3$ and $D_2 = 4$ are selected, resulting in $D_1 = 256$.

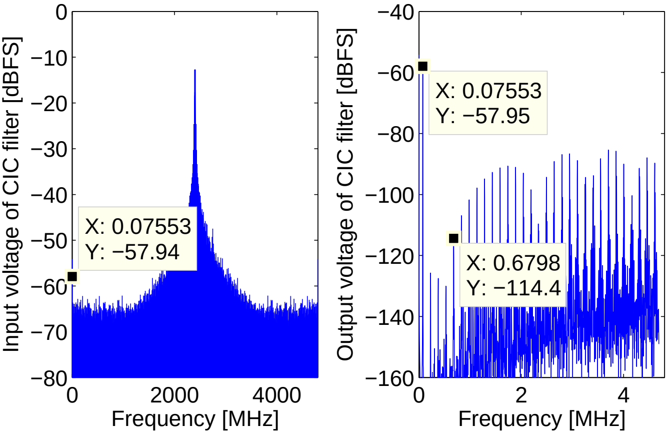


MATLAB/Simulink Model



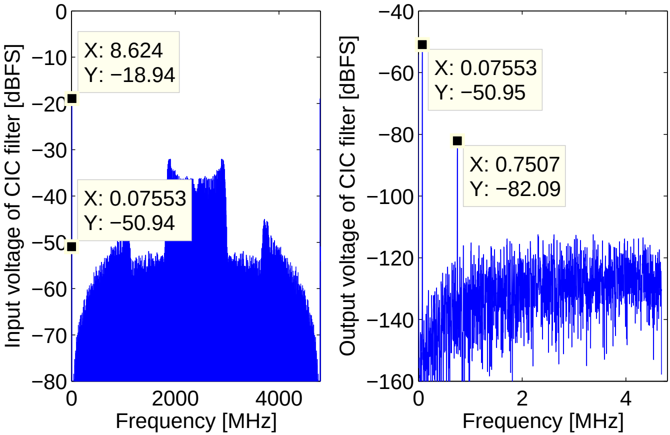
- Direct-RF sampling receiver designed on MATLAB/Simulink.
- CIC filters: 2nd-order stage with $D_1 = 256$ and 3rd-order one with $D_2 = 4$ ($D = 1024$).
- Desired frequency: $f_c + f_{BW}/(2 \cdot 10)$ =2400.075 MHz.

Simulated Spectra for Minimum Desired Power



- $P_{des,RX} = -74$ dBm without a blocker.
- Achieved SNR_{out} of 53.5 dB (= −57.9 dBFS +114.4 dBFS).

Simulated Spectra with Blocker



- $P_{des,RX} = -67$ dBm with −35-dBm blocker at 8.625-MHz offset (worst case).
- Achieved rejection of 63.1 dB (= −18.94 dBFS + 82.1 dBFS).

Summary

- Derived analytical expressions for SNR_{out} and out-of- band rejection of a multi-stage CIC filter.
- Presented a method to determine the lowest order of each CIC filter.
  - Enable a RF-direct sampling receiver to satisfy the SNR_{out} and out-of-band blocking requirements of BLE.
- Calculations agree well with simulations.

Performance	Required	Simulated	Calculated
$SNR_{out}{}^{*}$	> 14 dB	53.5 dB	50.0 dB
Blocker rejection†@			
8.625 MHz offset	61 dB	63.1 dB	63.7 dB
411.75 MHz offset	66 dB	110.4 dB	110.1 dB

$^{*}P_{des,RX} = -74$ dBm,

The presented method can reduce the power consumption and chip area of GS/s CIC filters.