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A Power-Efficient Multichannel Low-Pass Filter Based on the Cascaded Multiple Accumulate Finite Impulse Response (CMFIR) Structure for Digital Image Processing

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Abstract
The author offers a power-efficient multichannel low-pass filter for digital image processing based on the cascade multiple accumulate finite impulse response (CMFIR) structure in this study. The CMFIR filter was created using the outputs of a linear time-invariant system (LTI), which was built using a cascaded integrator comb (CIC) and a MAC low-pass filter. The sample rate convertor based on CIC filters effectively conducts decimation or interpolation. The sample rate convertor with the CIC filter can only accommodate narrowband transmissions and so cannot be utilized for wideband signals. The MAC architecture-based sample rate convertor is a good solution for high-bandwidth signals, but it uses more resources like registers and flip-flops, which increases power consumption. Here, the CMFIR low-pass filter acts as an interpolator, introducing a sample to boost the image's resolution. CMFIR is a useful tool for addressing the issue of aliasing during sampling. In addition, the genetic algorithm was used to increase the filter's resource utilization and power consumption efficiency.

Keywords Linear time-invariant system · Cascaded multiple accumulate finite impulse response · Cascaded integrator comb · Multiple accumulate unit · Intensity

1 Introduction

Digital image processing applications are indicated in many areas of the present world [8, 24] such as medicine (e.g., microscopes [21], digital mammography [7], X-ray computed tomography [28]), automotive applications (e.g., license plate recognition[4],

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dimensional verification of crankshafts [15], detection of objects [29]), geo engineering (maps classification [2], detection of Earth's surface features changes[34]), industrial applications (package inspection [17], sorting [6], quality inspection[36]).

The filtering technique is a part of the normal image enhancement process. It helps in solving problems of the image display [10] and, additionally, enables the improvement of image quality. The problems that always happened in images are illumination, noise, and under-light images [20]. Hence, one of the challenges is to remove noise from images [16, 32]. Therefore, there is a need to develop a sample converter that works as a low-pass filter to remove the noise from images at low power consumption [13, 26].

A low-pass filter is used to avoid aliasing in the linear time-invariant (LTI) system [22, 38]. In the past, the Cascaded Integrator Comb finite impulse response (CIC FIR) filter was employed as a low-pass filter. However, the sample rate converter using the CIC filter has limitations in supporting only narrowband signals and thus cannot be used for large bandwidth signals [11, 18, 19]. A multiply-accumulator (MAC) architecture-based sample rate converter is an efficient solution for large bandwidth signals, but it requires additional resources such as registers and flip-flops which lead to an increase in power consumption [14, 25, 31].

To optimize the sample rate converter in terms of acceptable power consumption, we have developed a model named Cascaded Multiple Accumulate Finite-Impulse Response (CMFIR) filter-based sample rate converters [12]. The CMFIR filter is the combination of CIC FIR and MAC FIR filters incorporating promising features of both filters [35].

To reduce the power consumption of the sample rate converter, we apply the multi-objective genetic algorithm on coefficients of the CMFIR filter. The power consumption of the multichannel sample rate converter is reduced by minimizing the hamming distance between the successive coefficients of the CMFIR filter. Eventually, we have developed a multichannel up sample rate converter, where time-division multiplexing is used to increase the number of channels. The number of channels is selected based on the intensity level of the light via artificial intelligence [35].

Then the comparison between CMFIR architecture-based up converter with genetic algorithm application and CIC Filter, MAC Filter, and CMFIR architecture-based up converter without genetic algorithm was realized in point of static power consumption efficiency, dynamic power consumption efficiency, total power consumption efficiency, register utilization efficiency, LUT utilization efficiency, LUT-flip flop pairs utilization efficiency. Additionally, the comparison with results of the literature position was realized concerning total power and device utilization like LUT, flip flop, and slice LUT-flip flop pairs.

The article is organized as follows: Sect. 2 presents the background for the proposed solution in the article. Section 3 shows the efficiency of the proposed CMFIR structure. Section 4 is a discussion of the proposed structure to other literature propositions. Section 5 concludes and indicates possible appliances.

2 Methods

2.1 Mathematical Modeling of the FIR Filter

1. As recorded from the synthesis report following simulation of the proposed model, the time required to produce the output was approximately equal to 3.259 ns, including 2.923 ns was the logical delay, and 0.336 ns was for the routing delay. We set the number of iterations (N) in the genetic algorithm as10.
2. Ripple in the passband was 0.01, the corresponding value of the passband angular frequency w_p was 0.18π.
3. Ripple in the stopband was 0.01, the corresponding value of stopband angular frequency w_s was 0.22 π 7 [23].

The fitness function for the genetic algorithm is given by:

$$U(x) = \frac{1}{f(x)} + \mu(\text{SNZ}), \tag{1}$$

$U(x)$ = Fitness Function. $f(x)$ = Initially generated filter coefficient using Kaiser window techniques. SNZ = Sum of non-zero. M = Transition Bandwidth Constant.

Transition bandwidth is given by:

$$w_s - w_p = 2 * \pi\left(f_s - f_p\right) = 2 * \pi * \delta f = 2 * \pi * \left(\frac{\mu}{N}\right), \tag{2}$$

where N = Number of the iteration, f_s = Stop band frequency, f_p = Pass band frequency, w_s = Stop band angular frequency, w_p = Pass band angular frequency.

The transition bandwidth of design is: $0.04 * \pi$

$$0.04 * \pi = 2 * \pi * \left(\frac{\mu}{10}\right), \tag{3}$$

By solving Eq. 3, we get the value of μ to be 0.2 [23].

2.2 Genetic Algorithm

A genetic algorithm is applied to the coefficient of the filter to reduce the hamming distance. The basic steps of genetic algorithm implementation are described in Fig. 1 [27].

1. *Evaluate the fitness function*: The fitness function is defined over the genetic representation and measures the quality of the generated coefficient. The fitness function here is used to generate the filter coefficients to meet the requirement. In the current research problem, the fitness function for the genetic algorithm is given by:

$$U(x) = \frac{1}{f(x)} + \mu(\text{SNZ}), \tag{4}$$

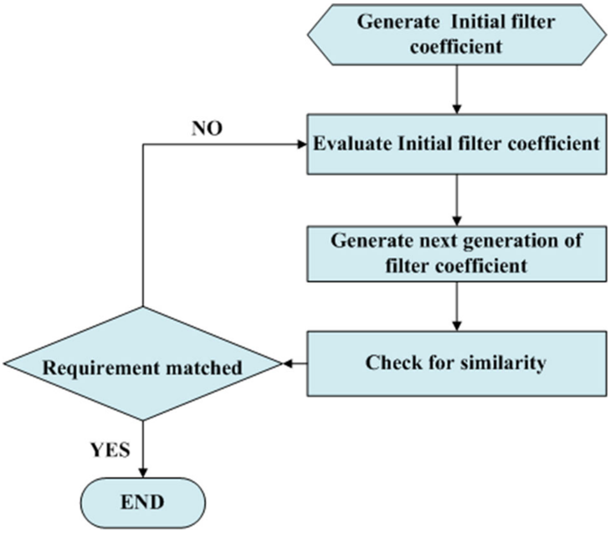

Fig. 1 Genetic algorithm flow chart

2. *Selection*: During every consecutive generation of the filter coefficients, a proportion of the existing coefficients is selected to generate the class of new coefficients.
3. *Crossover*: By applying the mathematical operation on the existing generation of coefficients, the next generation of coefficients is achieved.
4. *Mutation*: With the help of mutation, we ensure that the new coefficient is not similar to the parent coefficient [27].

2.3 Analysis in Light of Artificial Intelligence

The intensity of fog can be predicted based on various learning rules [1, 30, 33]. Initially, a study of the fog intensities over a certain period of time has to be carried out. Afterward, the regular, irregular, seasonal and cyclic variations of data at the location of interest need to be carefully analyzed for generating a particular mathematical model. The curve fitting can also be applied in this perspective, and a polynomial of the degree of n will be generated. Exponential growth models can also be sensed in order to find out a relation between the fog intensity level and the corresponding time instant. The mathematical representation is as follows:

$$I_{F.t} = ae^{t}, \tag{5}$$

where $I_{F.t}$ = fog intensity level at t time, a = amplitude of fog noise.

Let the timing interval of observation be t_1, t_2,t_3, t_4, and it is in equivalent nature.

$$I_{F.t1} = ae^{t1}, I_{F.t2} = ae^{t2}, \tag{6}$$

In the case of mid-interval pattern analysis is given by:

$$I_{F.\frac{t1+t2}{2}} = ae^{\frac{t1+t2}{2}}, \tag{7}$$

$$I_{F.\frac{t1+t2}{2}} = [a^2 e^{t1+t2}]^{\frac{1}{2}}, \tag{8}$$

$$I_{F.\frac{t1+t2}{2}} = \left[ae^{t1}.ae^{t2}\right]^{\frac{1}{2}}, \tag{9}$$

$$I_{F.\frac{t1+t2}{2}} = \left[I_{F,t1}.I_{F,t2}\right]^{\frac{1}{2}}, \tag{10}$$

2.4 Power Utilization

When FIR is implemented on FPGA, the design on FPGA is developed by the interconnection of various gate arrays. The gates are implemented by CMOS transistor. By reducing the hamming distance of successive coefficients of CMFIR filter, it reduces the switching of CMOS transistor for the transition from 0 to 1 or 1 to 0 without affecting the frequency response of a multichannel fractional sample rate convertor. Thus, the power utilization of a multichannel fractional sample rate converter is reduced. The total power utilization is given by [9]:

$$P_T = P_{\text{static}} + P_{\text{dynamic}}, \tag{11}$$

$$P_{\text{dynamic}} = P_t + P_c, \tag{12}$$

$$P_t = C_{dp} * V_{ss}^2 * f_i * B_t, \tag{13}$$

$$P_c = C_l * V_{ss}^2 * f_o * B_t, \tag{14}$$

where P_T = Total power used by CMOS transistor, P_{static} = Static power, P_{dynamic} = Dynamic power, P_t = Power consume in Transient Response of capacitance, P_c = Power consume by Capacitive load, C_{dp} = Dynamic power dissipation in capacitance, B_t = Number of bits changes from 0 to 1 or 1 to 0 of consecutive CMFIR filter coefficient, f_i = Input signal frequency, f_o = Output signal frequency [9, 37].

2.5 Objective

- To design & optimize a suitable CM FIR filter using CIC and MAC Unit for removing the remove the noise from the digital image.
- Increase power efficiency and resource utilization efficiency.

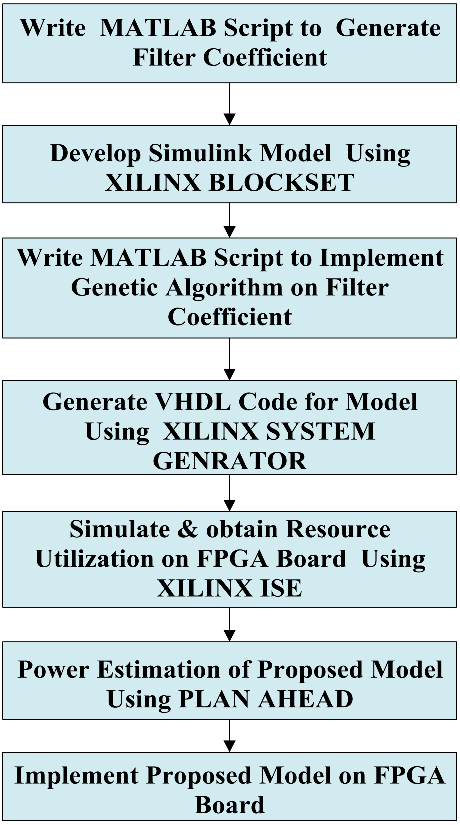

Fig. 2 Workflow chart

2.6 Work Flow

(Fig. 2).

3 Result

In this section, the comparison between the proposed CMFIR architecture-based up converter with genetic algorithm application and:

- CMFIR Filter without genetic algorithm application,
- CIC Filter,
- MAC Filter.

Firstly, the comparison between CMFIR Filter with and without genetic algorithm is realized in the basement of the hamming distance between coefficients. Results are indicated in Table 1. The results show that the total Hamming distance for CMFIR filter before application of GA (genetic algorithm) is equal to 77 and after it is equal to 50. Therefore, the application of GA (genetic algorithm) enables the reduction of the hamming distance by 27.

Table 1 Hamming distance between the coefficients of CMFIR filter with and without genetic algorithm

Hamming distance between the coefficients of CMFIR filter					
Without genetic algorithm			With genetic algorithm		
Value in integer	Value in binary	Hamming distance	Value in integer	Value in binary	Hamming distance
0.05936	0.0000111100110010	0	0.04299	0.0000101100000001	0
0.09885	0.0001100101001110	7	0.04569	0.0000101110110010	5
0.11730	0.0001111000000111	6	0.09395	0.0001100000110010	4
0.03713	0.0000100110000001	7	0.04947	0.0000110010101010	5
0.44611	0.0111001000110100	11	0.31859	0.0101000110001110	7
0.37935	0.0110000100011111	7	0.45713	0.0111010100000110	4
0.44611	0.0111001000110100	7	0.31859	0.0101000110001110	4
0.03713	0.0000100110000001	11	0.04947	0.0000110010101010	7
0.11730	0.0001111000000111	7	0.09395	0.0001100000110010	5
0.09885	0.0001100101001110	6	0.04569	0.0000101110110010	4
0.05936	0.0000111100110010	8	0.04299	0.0000101100000001	5

Then the comparison between CMFIR architecture-based up converter with genetic algorithm application and CIC Filter, MAC Filter, and CMFIR architecture-based up converter without genetic algorithm was realized in point of:

- Static power consumption efficiency, Dynamic power consumption efficiency, Total power consumption efficiency:

$$\text{Power efficiency} = \left(\frac{P_{\text{old}} - P_{\text{new}}}{P_{\text{old}}}\right) \times 100$$

  - Where P_{old} is the power consumed by the old or existing model
  - Where P_{new} is the power consumed by the new or proposed model
  - Power efficiency is more means system is power consumption decreases.

- Register utilization efficiency, LUT Utilization efficiency, LUT-flip flop pairs utilization efficiency:

$$\text{Resource utilization efficiency} = \left(\frac{R_{\text{old}} - R_{\text{new}}}{R_{\text{old}}}\right) \times 100$$

  - Where R_{old} is resource utilization by the old or existing model.
  - Where R_{new} is resource utilization by the new or proposed model.
  - Resource utilization efficiency is more means resource utilization decreases.

Figure 3 and Table 2 present the efficiency CMFIR architecture-based up converter with genetic algorithm application versus CIC Filter, MAC Filter, and CMFIR

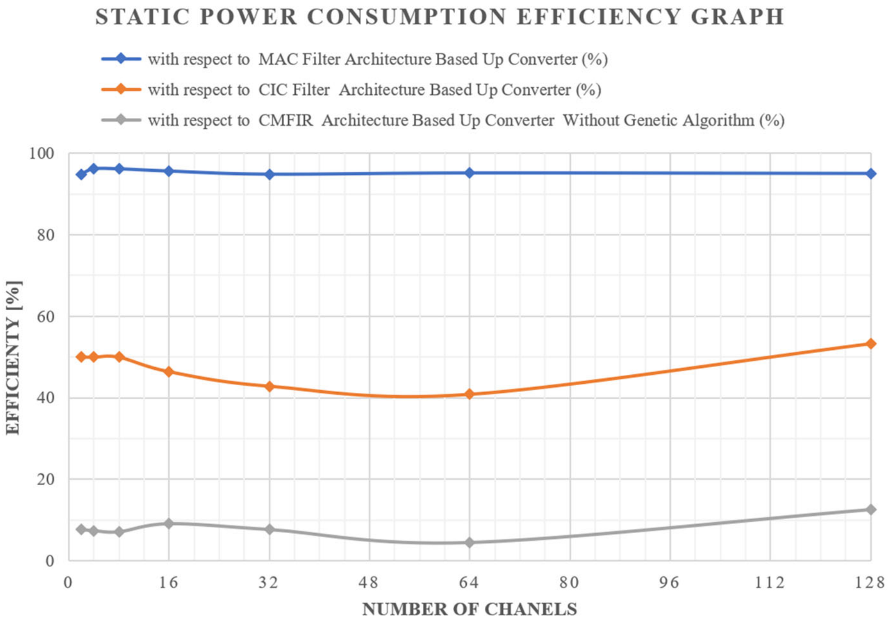

Fig. 3 Static power consumption efficiency graph with respect to other structures

Table 2 Static power efficiency of CMFIR architecture-based up converter with genetic algorithm with respect to other up converters

Number of channel(s)	1	2	4	8	16	32	64	128
CMFIR architecture-based up converter with genetic algorithm efficiency with respect to MAC filter architecture-based up converter (%)	93.92	94.92	96.21	96.20	95.66	94.89	95.19	95.08
CMFIR architecture-based up converter with genetic algorithm efficiency with respect to CIC filter architecture-based up converter (%)	50.00	50.00	50.00	50.00	46.43	42.86	40.85	53.33
CMFIR architecture-based up converter with genetic algorithm efficiency with respect to CMFIR architecture-based up converter without genetic algorithm (%)	8.00	7.69	7.41	7.14	9.09	7.69	4.55	12.50

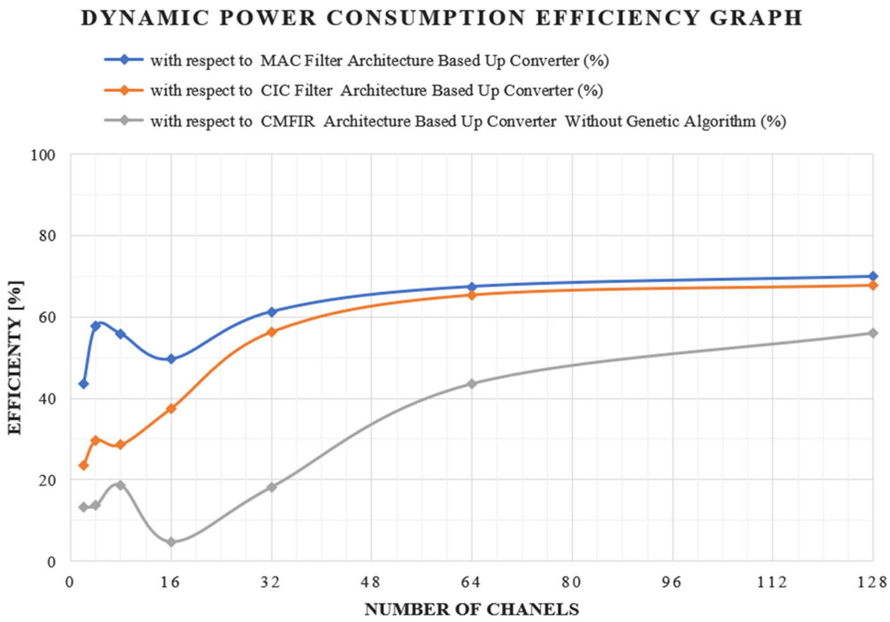

Fig. 4 Dynamic power consumption efficiency graph with respect to other structures

architecture-based up converter without genetic algorithm in point of static power consumption.

Figure 4 and Table 3 present the efficiency of CMFIR architecture-based up converter with genetic algorithm application versus CIC Filter, MAC Filter, and CMFIR architecture-based up converter without genetic algorithm in point of dynamic power consumption.

Figure 5 and Table 4 present the efficiency of CMFIR architecture-based up converter with genetic algorithm application versus CIC Filter, MAC Filter, and CMFIR architecture-based up converter without genetic algorithm in point of total power consumption.

Figure 6 and Table 5 present the efficiency of CMFIR architecture-based up converter with genetic algorithm application versus CIC Filter, MAC Filter, and CMFIR architecture-based up converter without genetic algorithm in point of for register utilization.

Figure 7 and Table 6 present the efficiency of CMFIR architecture-based up converter with genetic algorithm application versus CIC Filter, MAC Filter, and CMFIR architecture-based up converter without genetic algorithm in point of LUT utilization.

Figure 8 and Table 7 presents the efficiency of CMFIR architecture-based up converter with genetic algorithm application versus CIC Filter, MAC Filter, and CMFIR architecture-based up converter without genetic algorithm in point of LUT – flip flop pairs utilization.

Table 3 Dynamic power efficiency of CMFIR architecture-based up converter with genetic algorithm with respect to other up converters

Number of channel(s)	1	2	4	8	16	32	64	128
CMFIR architecture-based up converter with genetic algorithm efficiency with respect to MAC filter architecture-based up converter (%)	26.67	43.48	57.78	55.70	49.58	61.24	67.38	69.86
CMFIR architecture-based up converter with genetic algorithm efficiency with respect to CIC filter architecture-based up converter (%)	15.38	23.53	29.63	28.57	37.50	56.22	65.28	67.65
CMFIR architecture-based up converter with genetic algorithm efficiency with respect to CMFIR architecture-based up converter without genetic algorithm (%)	8.33	13.33	13.64	18.60	4.76	18.18	43.56	56.00

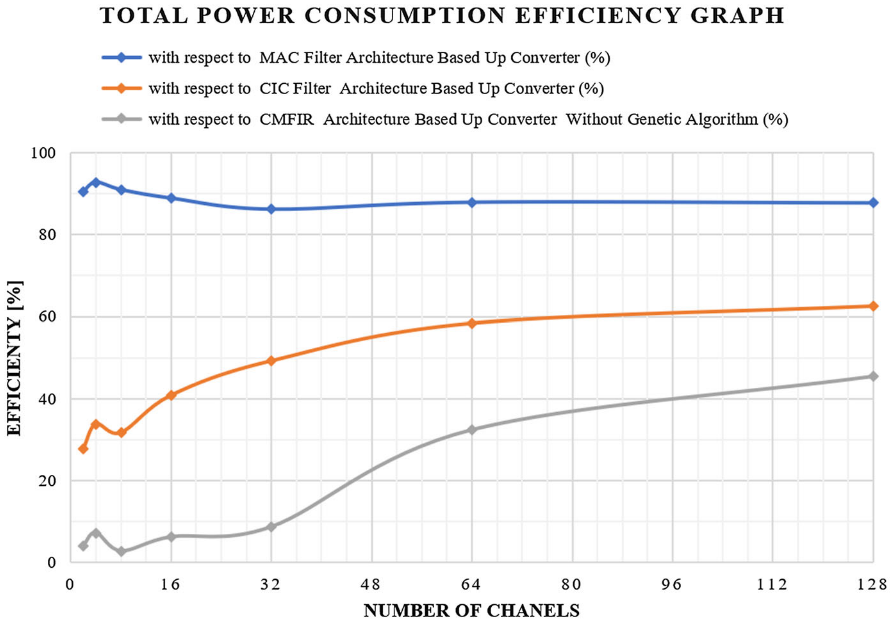

Fig. 5 Total power consumption efficiency graph with respect to other structures

Table 4 Total power efficiency of CMFIR architecture-based up converter with genetic algorithm with respect to other up converters

Number of channel(s)	1	2	4	8	16	32	64	128
CMFIR architecture-based up converter with genetic algorithm efficiency with respect to MAC filter architecture-based up converter (%)	90.33	90.51	92.76	90.96	88.89	86.20	87.88	87.73
CMFIR architecture-based up converter with genetic algorithm efficiency with respect to CIC filter architecture-based up converter (%)	35.59	27.69	33.77	31.68	40.79	49.19	58.33	62.47
CMFIR architecture-based up converter with genetic algorithm efficiency with respect to CMFIR architecture-based up converter without genetic algorithm (%)	19.15	4.08	7.27	2.82	6.25	8.70	32.37	45.42

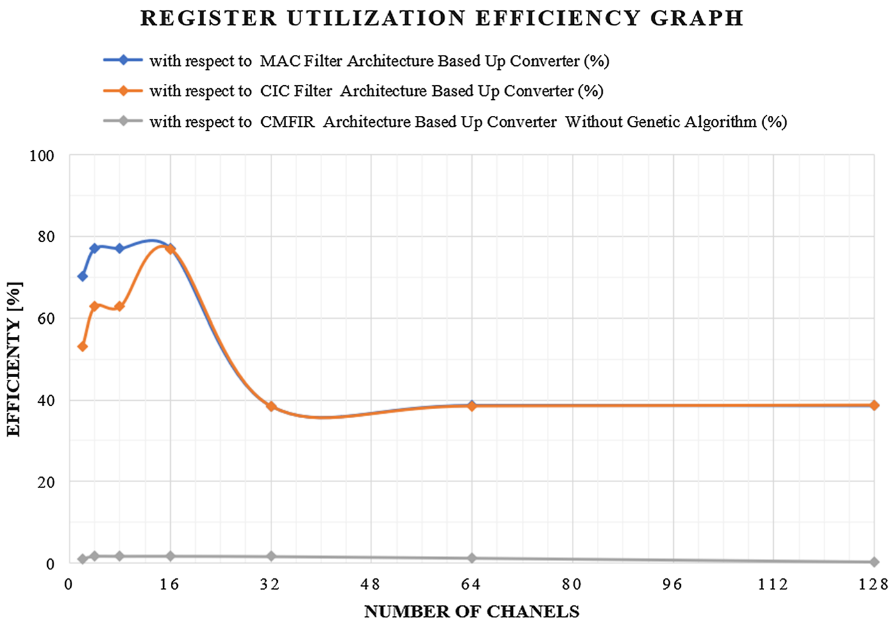

Fig. 6 Register utilization efficiency graph with respect to other structures

Table 5 Efficiency table of register utilization of CMFIR architecture-based up converter with genetic algorithm with respect to other up converters

Number of channel(s)	2	4	8	16	32	64	128
CMFIR architecture-based up converter with genetic algorithm efficiency with respect to MAC filter architecture-based up converter (%)	70.30	77.00	76.98	76.98	38.48	38.66	38.59
CMFIR architecture-based up converter with genetic algorithm efficiency with respect to CIC filter architecture-based up converter (%)	53.06	62.92	62.81	76.93	38.49	38.55	38.77
CMFIR architecture-based up converter with genetic algorithm efficiency with respect to CMFIR architecture-based up converter without genetic algorithm (%)	1.14	1.71	1.73	1.74	1.65	1.24	0.28

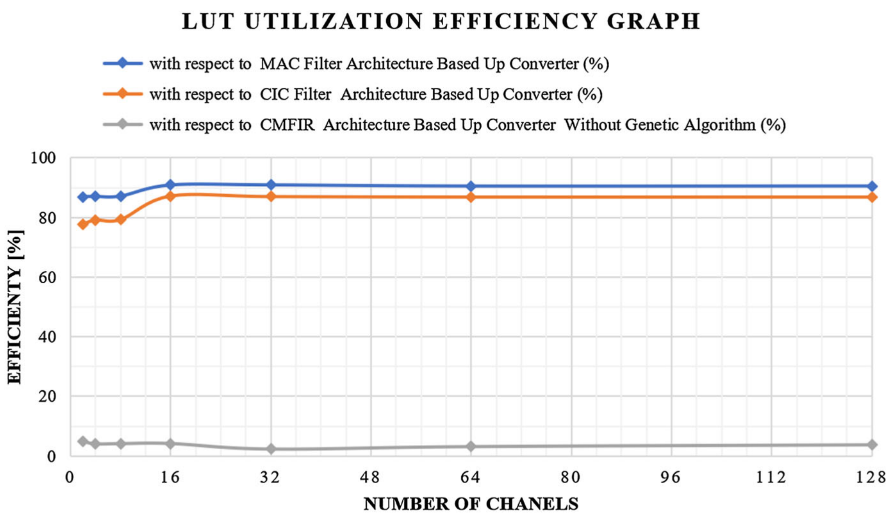

Fig. 7 LUT utilization efficiency graph with respect to other structures

4 Discussion

With an applied genetic algorithm model to the CMFIR approach, the overall hamming distance is reduced by 27. The multichannel CMFIR-based converter efficiency has been also improved in terms of power & resource utilization. More specifically, the following observations are made:

Table 6 Efficiency table of LUT utilization of CMFIR architecture-based up converter with genetic algorithm with respect to other up converters

Number of channel(s)	2	4	8	16	32	64	128
CMFIR architecture-based up converter with genetic algorithm efficiency with respect to MAC filter architecture-based up converter (%)	86.96	87.02	87.12	90.89	90.91	90.53	90.55
CMFIR architecture-based up converter with genetic algorithm efficiency with respect to CIC filter architecture-based up converter (%)	77.75	79.20	79.33	87.17	86.98	86.84	86.83
CMFIR architecture-based up converter with genetic algorithm efficiency with respect to CMFIR architecture-based up converter without genetic algorithm (%)	4.81	4.00	4.08	4.12	2.34	3.13	3.70

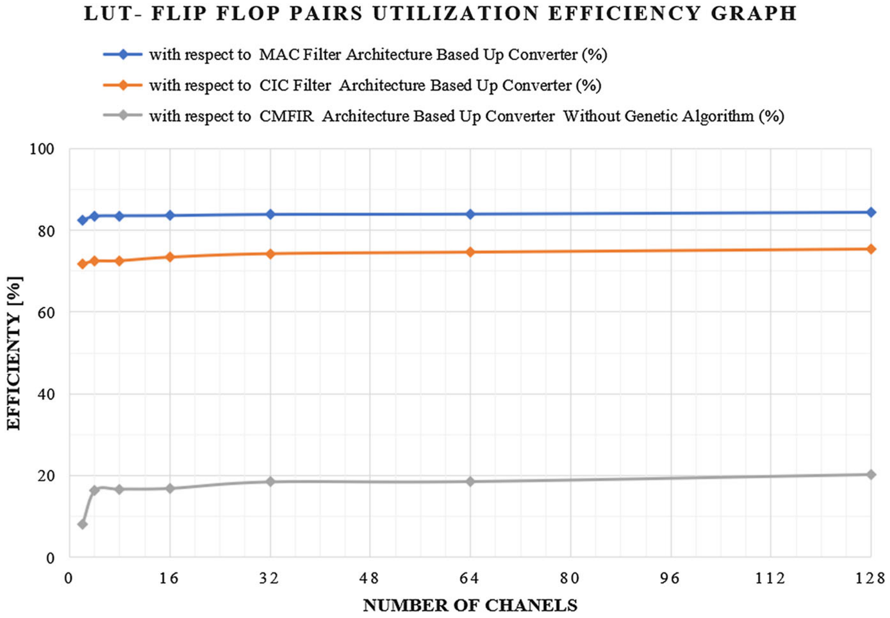

Fig. 8 LUT-flip flop pairs utilization efficiency graph with respect to other structures

Table 7 Efficiency table of LUT-flip flop pairs utilization of CMFIR architecture-based up converter with genetic algorithm with respect to other up converters

Number of channel(s)	2	4	8	16	32	64	128
CMFIR architecture-based up converter with genetic algorithm efficiency with respect to MAC filter architecture-based up converter (%)	82.46	83.43	83.54	83.59	83.86	83.95	84.38
CMFIR architecture-based up converter with genetic algorithm efficiency with respect to CIC filter architecture-based up converter (%)	71.70	72.44	72.53	73.43	74.32	74.72	84.38
CMFIR architecture-based up converter with genetic algorithm efficiency with respect to CMFIR architecture-based up converter without genetic algorithm (%)	8.16	16.33	16.67	16.84	18.42	18.50	20.19

- The multichannel system efficiency in terms of the average total power reduction is 89.40%, the average dynamic power reduction is 53.96, and the average static power reduction is 95.26% with respect to the MAC-based architectures;
- The multichannel system efficiency in terms of the average total power reduction is 42.43%, the average dynamic power reduction is 40.47%, and the average static power reduction is 47.93% with respect to the CIC-based architectures;
- The multichannel system efficiency in terms of the average total power reduction is 15.75%, the average dynamic power reduction is 22.05%, and the average static power reduction is 8.01% with respect to the CMFIR without genetic algorithm-based architectures.

The additional comparison of the obtained results in point of other researches [3, 5] was conducted. The comparison was realized with regard to total power. The results are presented in Table 8. The total power consumption was at least half less than in other studies. Additionally, the deep comparison was realized to [5] with regard to device utilization like LUT, flip flop, and slice LUT-flip flop pairs. The results are

Table 8 Comparison in point of total power between literature results and the proposed solution

FIR structure	Total power(watt)
FIR Filter developed using booth low power serial multiplier and serial adder, combinational booth multiplier, shift/add multipliers, folding transformation [3]	0.110
FIR developed using combination booth multiplier and carry look ahead adder [5]	0.242
Investigated in this article CMFIR filter after applying genetic algorithm	0.056

Table 9 Comparison in point of device utilization between literature results and the proposed solution

Device utilization	LUTs	Flip-flops	Slice LUT-flip flop pairs
FIR developed using combination booth multiplier and carry look ahead adder [5]	3056	2218	2604
Investigated in this article CMFIR filter after applying genetic algorithm	392	1850	384
Reduction of resource utilization in terms of percentage (%)	87	17	85

presented in Table 9. The obtained results are satisfying, and there is a decrease of at least 17% for each parameter.

5 Conclusions

This article proposes the Cascaded Multiple Accumulate Finite Impulse Response (CMFIR) filter-based sample rate converters. The CMFIR filter is the combination of CIC FIR and MAC FIR filters incorporating promising features of both filters. Investigation indicated that the proposed CMFIR solution ensures higher static power consumption efficiency, dynamic power consumption efficiency, total power consumption efficiency, register utilization efficiency, LUT utilization efficiency, LUT-flip flop pairs utilization efficiency than MAC and CIC structure. Additionally, the proposed application of the genetic algorithm to the CMFIR filter provides even better results. The proposed CMFIR filter may respond to the challenge of removing noise from images at low power consumption. Thus, in future, the CMFIR filter can be included as a part of the anti-fog driver assistance system. This application is a direction for future research of the authors.

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Data availability All data generated or analyzed during this study are included in this published article and its supplementary information files.

Declarations

Conflict of interest The authors declare no conflict of interest.

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