Zigzag low-complexity approximate DCT using frequency upscaling technique

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Abstract. Approximate computing is widely used in image processing field for reducing the energy dissipation, increasing the throughput, and decreasing the amount of computation by sacrificing some accuracy in the output results. Thus, this paper presents a runtime-based approximate computing approach by using frequency upscaling (FUS) technique into zigzag low-complexity approximate DCT (ZLCADCT). The presented technique allows to change the degree of approximation without changing the circuit of ZLCADCT while providing increased throughput by applying the input vectors of circuits at a rate beyond the maximum operating frequency. The results show that when FUS are implemented into ZLCADCT, approximate full adder can sustain significant higher input frequency (around 19.2GHZ using 32nm adders) when compared with an exact full adder (at around 15.4GHZ) without having significant decreases in PSNR value. The number of completed DCT operations for ZLCADCT (2.95 to 3.53 for approximate full adder at 16.6GHZ) is higher than 2.3 to 2.77 for ADCT by using FUS technique.

1. Introduction
Approximate computing is introduced as fault-tolerant approach to make circuits more efficient in image processing field[1]. Its basic principle is to sacrifice accuracy by allowing some acceptable errors to decrease circuit complexity and reduce power dissipation[2]. Approximate computing can be applied at different abstractions in an image processing field, such as circuit level, logic level and algorithmic level [3]. In the circuit level, the main approach is to reduce the number of transistors in a single adder cells and hence causing tolerable errors while reducing the parameters such as energy dissipation, area, etc. [1, 4, 5]. Other two schemes in circuit level focus on voltage overscaling (VOS) technique via scaling supply voltage for CMOS circuits to save energy[6, 7] and frequency upscaling (FUS) technique via rising the frequency of input vectors to increase throughput[8, 9]. Next, in logic level generally focus on structure simplification of multi-bit adders and multiplier while improving the parallelism calculations[10-13]. Finally, in algorithmic level, the main research focus is on approximate discrete cosine transform (ADCT) matrix design including low-power DCT design[14, 15] and reduction of DCT computational complexity[16-21].

It can be observed from the existing approximate computing techniques that researchers are mainly targeting to apply approximate computing only at certain level of the system rather at the complete system. Techniques (except FUS technique[8, 9]) from different levels has never been integrated together to realize optimized approximate computing. For example, algorithmic based approximate technique has never implemented and integrated with approximate designs at circuit level. In [8, 9], FUS technique is proposed by increasing the frequency of input vectors beyond the maximum corrected frequency to increase the through puts, thereby causing errors in the outputs. FUS is integrated with
ADCT technique in [8, 9] to realize optimized approximation, such that the processing speed of ADCT is increased.

In this paper, FUS technique is further applied to ZLCADCT [21] to realize optimized approximation and improve the performance of ADCT using FUS, such that the number of required additions can be reduced and the processing speed can increase. ZLCADCT through a deterministic approach configures the T matrix while keeping the relationship between the number of targeted coefficient retained (TCR) and the number of rows of the T matrix[21]. When compared with ADCT, ZLCADCT can avoid the computations for all redundant coefficients, thereby reducing required adders and energy dissipation[21]. The computation of ZLCADCT is dynamically be adjustable according to different number of reserved coefficients; the output image quality is retained[21]. It has been demonstrated in [9] that the throughput of ADCT can increase by using FUS technique. Since ZLCADCT requires a smaller number of additions than ADCT, the processing speed can be further increased by applying ZLCADCT using FUS. The results show that irrespective of type of adders, the number of completed DCT operations for ZLCADCT is higher than ADCT by using FUS. In ZLCADCT, the number of completed DCT operations for approximate full adder is higher than EFA (Exact Full Adder). Approximate full adder can sustain higher input frequency (higher throughout) when compared with an EFA without having significant decreases in PSNR by using FUS.

This paper is organized as follows. Section 2 reviews FUS and ZLCADCT techniques. Section 3 presents results about ZLCADCT using FUS. Section 4 concludes this paper.

2. Reviews for FUS and ZLCADCT

2.1. FUS Technique

FUS technique proposed in [8, 9] is an energy-efficient, latency-efficient and area-efficient approximate technique; it increases input frequency of input vectors for exact/ approximate (AMA1) full adders (shown in Figure 1) beyond the maximum operating value, thereby causing errors in the outputs and increasing the computational throughput. FUS realizes different approximation (number of errors) in a given circuit at the runtime without changing the architecture of the design by incurring extra hardware. Meanwhile, there is no additional reduction in circuit complexity. FUS also is technology independent thereby it can be applied to circuits of different technology node without redesigning the circuits. At a constant supply voltage, the number of errors in the output can be changed when input frequency increases.

The results from [8] about the number of errors in Sum and Carry and the number of effective errors for FUS by applying exhaustive simulation using all eight possible input vectors are shown in Figure 2. It can be found that AMA1 exhibits largest number of possible errors at 1.3 times larger frequency (29.0GHZ) than exact adder (21.3GHZ) [8]. Thus, AMA1 sustains higher frequency of operation for same number of errors, when compared with EFA. Also, in [8], it has been demonstrated that AMA1 dissipates about 50% less energy than exact cell. For both EFA and AMA1, decreasing the feature size of transistors can increase the range of FUS and decrease energy consumption.

Next, process variations in frequency and energy dissipation due to gate length and supply voltage are evaluated in [8]; the frequency upscaled adder cells are then applied to design ripple carry adder (RCA[22]) for performance evaluation in [8]. The results show that the decrease of both gate length variation and supply voltage variation results in reduced frequency variations and energy variations for the same number of errors by using FUS. As for RCA using FUS, approximate full adder can sustain 1.18 to 1.37 times higher frequency than EFA at the maximum ER (error rate) by keeping lower NMED (normalized mean error distance) and MRED (mean relative error distance). In addition, in [9], a detailed mathematical model of FUS is proposed. The estimated results show in good agreement with simulation results. The subtractors, image addition operations and ADCT operations are also evaluated when subjected to FUS in [9]. The PSNR results for addition of two images show that approximate full adder achieves a higher output image quality than the EFA by using FUS technique. As for ADCT using FUS, the results show that PSNR of ADCT using AMA1 remains nearly the same at a higher range of
frequency compared with exact cell. The results about ADCT [16] using FUS from [9] are included for making comparison with ZLCADCT using FUS in Section 3.

Figure 1. (1): EFA [4] and (2): AMA1 [4].

Figure 2. Using FUS the number of errors in Carry and Sum & effective errors of AMA1 and EFA cell using 32nm [8].

2.2. ZLCADCT

ZLCADCT proposed in [21] configure the T matrix by establishing the relationship between the number of targeted coefficient retained (TCR) and the number of rows of the T matrix by using a deterministic approach. By applying ZLCADCT, computations for all unused coefficients in $Y = T_p \cdot X \cdot T_p^T$ are avoided; the zigzag scanning process is eliminated. It can reduce the number of required hardware resources (adders, gates and LUTs), delay and energy dissipation; meanwhile, it retains a nearly similar image quality when compared with ADCT. ZLCADCT is scalable and realized modularly; it does not require a complete reconfiguration of FPGAs when the number of retaining coefficients is changed. Figure 3 shows the flow chart of ZLCADCT.

Figure 3. The flow chart of ZLCADCT[21].
number of additions is reduced; X1 only has coefficients only for ‘m’ rows since \( T_p \) only has ‘m’ rows. Next, during the process of \( Y = X1 \cdot T_p^T \), Look Up Table about TCR range and number of reserved coefficients in each row ‘k’ is utilized; different ‘k’ value for each row of X1 is determined according to ‘m’ value and the range that covers the TCR value. Then, the \( T \) matrix is pruned to design \( T_p \) matrix according to the ‘k’ value for each row of \( X1 \). By using proposed TCR range table and LUT, the calculation for unnecessary coefficients are totally avoided.

The mathematical model in [21] to demonstrate the validity of ZLCADCT in detail. Meanwhile, ZLCADCT is implemented into Matlab for simulation evaluation to measure the number of additions, energy consumption and delay; then ZLCADCT is implemented in FPGA-based platform (Spartan 3E and Spartan 6 XC6SLX45) for hardware assessment of resources in [21]. Extensive simulation and experimental hardware results show that when compared with ADCT, ZLCADCT decreases the number of additions, hardware requirements (i.e., the number of adders, LUTs and XOR gates), the energy consumption and delay while retaining the PSNR of the compressed image. Since the number of adders, UTs and XOR gates are reduced significantly by using ZLCADCT in [21], the total circuit size for applied hardware resources of ZLCADCT is lower than ADCT.

3. ZLCADCT using FUS technique

This section presents the FUS technique proposed in [8, 9] is applied to ZLCADCT[21] of image compression at 32nm and 45nm technology nodes to improve the performance of ADCT using FUS and realize optimized approximation across circuit level to algorithmic level; then, the results for ZLCADCT using FUS is compared with that for ADCT using FUS. Two ADCT matrixes (including ADCT matrix \( T_a \) [16] (by setting the arbitrary parameter ‘a’ to zero) and ADCT matrix \( T \) [18]) are used for evaluation, and 10 coefficients are retained in the process of zigzag scanning. The pruned method proposed in ADCT [20] is also compared in this section. The NAB denotes the number of bits in an RCA subjected to FUS (beginning from the lowest bit)[9]. Besides, it should be noted that results about ADCT [16] using FUS in this section has been discussed in [9]; for making comparisons with ADCT [20] and ZLCADCT, the results of ADCT [16] from [9] are shown in this section.

Figure 4 shows the PSNR value of output images by ADCT[16], ADCT [20] and ZLCADCT by using FUS technique under different NAB values (2, 4 and 6). Also, Figure 5 illustrates the Sum in pixel variation of ADCT[16], ADCT [20] and ZLCADCT by comparing input images with output images at different NAB values. Results about PSNR and Sum in pixel variation for ADCT[18], ADCT[20] and ZLCADCT are shown in Figure 6 and Figure 7 respectively.

![Figure 4](image-url)  
**Figure 4.** PSNR ((a) for ADCT[16] or ZLCADCT, (b) for ADCT [20]) by using FUS when NAB=2 for (1), NAB=4 for (2) and NAB=6 for (3).
Figure 5. Sum in pixel variation of DCT by using FUS ((a) for ADCT[16] or ZLCADCT, (b) for ADCT [20]) when NAB=2 for (1), NAB=4 for (2) and NAB=6 for (3).

It can be seen from Figure 4 that ADCT[16] and ZLCADCT have the same PSNR value by using FUS technique. Also, when compared with ADCT[16] and ZLCADCT, the curve for ADCT [20] shows similar variation trend in the PSNR value, and PSNR of ADCT [20] is a little higher than ADCT[16] and ZLCADCT. Considering ADCT[16] and ZLCADCT in Figure 4 (a), the PSNR of DCT using AMA1, independent of the size of the transistor, remains nearly the same value at a higher range of frequency (from 8.01GHZ to 19.2GHZ for both 32nm and 45nm) when compared with the EFA (from 8.01 GHZ to15.4GHZ and 11.4GHZ for 32nm and 45nm respectively). So, in ZLCADCT, at a higher frequency the AMA1 can be scaled up when compared with an EFA without having a substantial degradation in performance. Moreover, the EFA-based ZLCADCT experiences a significant decrease in PSNR at lower frequency than AMA1. This is mainly caused by a rapid increase in pixel variation for Sum (Figure 5). Irrespective of type of adders, the frequency of ZLCADCT can increase to higher level at the same PSNR value as the feature size of transistors decreases. So by FUS, with increase in NAB, the sum in pixel variation increases at the same time the PSNR value decreases significantly. The same trends about PSNR and pixel variation as for ADCT[18], ADCT [20] and ZLCADCT are reported in Figure 6 and Figure 7.

Figure 6. PSNR (a) for ADCT[18] or ZLCADCT, (b) for ADCT [20]) by using FUS when NAB=2 for (1), NAB=4 for (2) and NAB=6 for (3).
Figure 7. Sum in pixel variation of DCT by using FUS ((a) for ADCT [18] or ZLCADCT, (b) for ADCT [20]) when NAB=2 for (1), NAB=4 for (2) and NAB=6 for (3).

The output images of ADCT[16], ADCT [20] and ZLCADCT of EFA and AMA1 for three increasingly different frequencies ($f_1$, $f_2$, $f_3$) at different NAB values (2, 4 and 6) using transistor node of 32nm are shown in Figure 8 and the corresponding PSNRs are presented in Table 2. Among $f_1$, $f_2$, $f_3$, of a full adder, the maximum operating frequency for the error free operation is $f_1$ while scaled up frequencies are $f_2$ and $f_3$ whose values are presented in Table 1. So by increasing the frequency of the full adder beyond $f_1$ new errors are introduced[9]. For ADCT[16], ADCT [20] and ZLCADCT, irrespective of the NAB value, when the frequency increases to $f_2$, the output images of AMA1-based DCT is substantially better than an EFA-based DCT. As shown in Table 1, irrespectively of the type of applied ADCT, the PSNR of $f_2$ for AMA1 is higher than that for EFA showing that the AMA1-based DCT yield better output images when operating at a higher input frequency. In addition, the comparisons in terms of output images among ADCT[18], ADCT [20] and ZLCADCT using 32nm EFA and AMA1 under $f_1$, $f_2$ and $f_3$ frequency across NAB values of 2, 4 and 6 are illustrated in Figure 9, and their PSNR results are shown in Table 3. It can be found that for any NAB value and any type of ADCT, the output images quality for AMA1-based DCT is still substantially better than that for EFA-based DCT when input frequency increases to $f_2$.

Table 1. Input frequency applied to EFA and AMA1 (at 32nm)[9].

| Input Frequency (HZ) | EFA 32nm | AMA1 32nm |
|----------------------|----------|-----------|
| ($f_1$)              | 1.1490E+10 | 1.6595E+10 |
| ($f_2$)              | 1.5503E+10 | 1.9535E+10 |
| ($f_3$)              | 2.1569E+10 | 2.8974E+10 |

Next, the approximate DCT computation on 32nm based AMA1 and EFA designs are analysed over a time window of 0.4 ms for parameters namely the number of completed DCT operations (based on the average number of fully processed input matrixes by DCT algorithm), the total energy dissipation for the completed DCT operations and the PSNR (Figure 8) by applying input frequencies (Table 1) and NAB values (2, 4 and 6) [9]. The comparison results of ADCT[16] from [9], ADCT [20] and ZLCADCT are shown in Table 2, and the results for ADCT[18], ADCT [20] and ZLCADCT are illustrated in Table 3. It can be found from Table 2 that irrespective of type of ADCT, using FUS, more number of DCT operations are completed at the cost of higher total energy dissipation. In ZLCADCT, the number of
completed DCT operations for AMA1 is higher than EFA. The difference between AMA1 and EFA increases with the increase in NAB at the same time the total energy dissipation of the EFA is a marginally higher than AMA1.

Figure 8. Image compression using (a): ADCT[16] or ZLCADCT and (b): ADCT[20] by using FUS (f1 to f3) for different NABs (2, 4 and 6) with 32nm based EFA and AMA1.

Figure 9. Image compression using (a): ADCT[18] or ZLCADCT and (b): ADCT[20] by using FUS (f1 to f3) for different NABs (2, 4 and 6) at 32nm based EFA and AMA .
Table 2. Effect of FUS (f1 to f3) on ADCT[16], ADCT[20] and ZLCADCT designed using 32nm EFA and AMA1.

| Number of completed DCT operations | Applied frequency for ADCT[16] | Applied frequency for ADCT [20] | Applied frequency for ZLCADCT |
|------------------------------------|-----------------------------|-------------------------------|-------------------------------|
| EFA                               |                              |                               |                               |
| NAB=2                             | 2.06                        | 2.07                          | 2.39                          | 2.50                        | 2.58                          | 2.85                          | 2.71                        | 2.83                          | 3.10                          |
| NAB=6                             | 2.06                        | 2.17                          | 3.10                          | 2.50                        | 2.77                          | 3.61                          | 2.71                        | 3.06                          | 3.94                          |
| AMA1                              | NAB=2                       | 2.30                          | 2.51                          | 7.02                        | 2.50                        | 3.21                          | 7.91                        | 2.71                        | 3.60                          | 8.50                          |
|                                   | NAB=2                       | 2.56                          | 2.81                          | 3.41                        | 3.01                        | 3.28                          | 3.95                        | 3.26                        | 3.56                          | 4.30                          |
|                                   | NAB=6                       | 2.77                          | 3.59                          | 8.33                        | 3.26                        | 4.09                          | 9.32                        | 3.53                        | 4.42                          | 10.03                         |
|                                   | NAB=2                       | 1.65                          | 1.71                          | 1.72                        | 1.65                        | 1.71                          | 1.71                        | 1.65                        | 1.71                          | 1.71                          |
|                                   | NAB=6                       | 1.65                          | 1.79                          | 1.80                        | 1.65                        | 1.77                          | 1.79                        | 1.65                        | 1.77                          | 1.79                          |
|                                   | AMA1                        | NAB=4                         | 1.65                          | 1.79                          | 1.80                            | 1.65                          | 1.77                          | 1.79                        | 1.65                        | 1.77                          | 1.79                          |
|                                   | NAB=2                       | 1.64                          | 1.72                          | 1.82                        | 1.63                        | 1.72                          | 1.82                        | 1.63                        | 1.72                          | 1.82                          |
|                                   | NAB=6                       | 2.71                          | 25.46                          | 26.63                        | 28.63                        | 25.64                          | 27.40                        | 27.17                        | 25.46                          | 26.63                         |
|                                   | AMA1                        | NAB=4                         | 2.71                          | 22.24                          | 24.20                        | 28.63                        | 21.94                          | 24.26                        | 27.17                        | 22.24                          | 24.20                         |
|                                   | NAB=2                       | 2.71                          | 17.70                          | 18.79                        | 28.63                        | 17.52                          | 18.76                        | 27.17                        | 17.70                          | 18.79                         |
|                                   | NAB=6                       | 2.71                          | 27.09                          | 26.63                        | 28.62                        | 28.42                          | 27.40                        | 27.16                        | 27.09                          | 26.63                         |
|                                   | AMA1                        | NAB=4                         | 26.74                          | 26.27                          | 24.20                        | 27.70                        | 26.84                          | 24.26                        | 26.74                        | 26.27                          | 24.20                         |
|                                   | NAB=6                       | 24.71                          | 23.44                          | 18.79                        | 24.63                        | 23.48                          | 18.76                        | 24.71                        | 23.44                          | 18.79                         |

Table 3. Effect of FUS (f1 to f3) on ADCT[18], ADCT[20] and ZLCADCT designed using 32nm EFA and AMA1.

| Number of completed DCT operations | Applied frequency for ADCT[18] | Applied frequency for ADCT [20] | Applied frequency for ZLCADCT |
|------------------------------------|-----------------------------|-------------------------------|-------------------------------|
| EFA                               |                              |                               |                               |
| NAB=2                             | 2.48                        | 2.50                          | 2.89                          | 3.13                        | 3.25                          | 3.60                          | 3.44                        | 3.58                          | 3.94                          |
| NAB=4                             | 2.48                        | 2.63                          | 3.75                          | 3.13                        | 3.49                          | 4.62                          | 3.44                        | 3.88                          | 5.05                          |
| NAB=6                             | 2.48                        | 3.01                          | 8.33                          | 3.13                        | 4.00                          | 10.09                         | 3.44                        | 4.52                          | 10.88                         |
| AMA1                              | NAB=4                       | 3.10                          | 3.42                          | 4.15                        | 3.81                        | 4.18                          | 5.05                        | 4.14                        | 4.55                          | 5.54                          |
|                                   | NAB=6                       | 3.36                          | 4.36                          | 9.97                        | 4.13                        | 5.22                          | 11.93                       | 4.50                        | 5.66                          | 12.91                         |
|                                   | AMA1                        | NAB=4                         | 1.65                          | 1.72                          | 1.72                        | 1.65                        | 1.71                          | 1.71                        | 1.65                        | 1.71                          | 1.71                          |
|                                   | NAB=2                       | 1.65                          | 1.79                          | 1.80                        | 1.65                        | 1.78                          | 1.79                        | 1.65                        | 1.78                          | 1.79                          |
|                                   | NAB=6                       | 1.65                          | 1.88                          | 1.92                        | 1.65                        | 1.86                          | 1.90                        | 1.65                        | 1.86                          | 1.90                          |
|                                   | AMA1                        | NAB=2                         | 1.64                          | 1.67                          | 1.69                        | 1.64                        | 1.67                          | 1.69                        | 1.64                        | 1.67                          | 1.69                          |
|                                   | NAB=6                       | 1.64                          | 1.70                          | 1.75                        | 1.64                        | 1.69                          | 1.74                        | 1.64                        | 1.69                          | 1.74                          |
|                                   | AMA1                        | NAB=2                         | 25.34                          | 22.05                          | 23.52                        | 26.42                        | 21.91                          | 23.76                        | 25.34                        | 22.05                          | 23.52                         |
|                                   | NAB=6                       | 25.34                          | 17.80                          | 18.66                        | 26.42                        | 17.65                          | 18.68                        | 25.34                        | 17.80                          | 18.66                         |
|                                   | AMA1                        | NAB=4                         | 25.09                          | 24.82                          | 23.52                        | 25.91                        | 25.47                          | 23.76                        | 25.09                        | 24.82                          | 23.52                         |
|                                   | NAB=6                       | 23.91                          | 22.80                          | 18.66                        | 24.03                        | 22.94                          | 18.68                        | 23.91                        | 22.80                          | 18.66                         |

In addition, for both EFA and AMA1 in Table 2, the number of completed DCT operations for ADCT [20] is significantly higher than that for ADCT[16] at the same frequency level, and the value for ZLCADCT is highest. For example, by using AMA1 at the frequency of f1(16.6GHz), the number of
completed DCT operations for ZLCADCT varies from 2.95 to 3.53, higher than 2.3 to 2.77 for ADCT[16] and 2.73 to 3.26 for ADCT [20]. For AMA1 using NAB=4 under f2, the number of completed DCT operations for ADCT[16], ADCT [20] and ZLCADCT are 2.81, 3.28, and 3.56 respectively, while their result of total energy dissipation (1.70E-09J, 1.69E-09J and 1.69E-09J respectively) are quite close. This mean that when compared with ADCT[16] and ADCT [20], more DCT operations can be completed by using ZLCADCT and the total energy dissipation are kept nearly stable. Meanwhile, the PSNR of ZLCADCT is the same with ADCT[16], while that for ADCT [20] is a little higher. The same trends as for ADCT[18], ADCT [20] and ZLCADCT is found in Table 3.

4. Conclusion

In this paper, an integrated approximate computing technique is proposed by applying FUS technique into ZLCADCT technique across circuit level to algorithmic level. The results are compared with ADCT using FUS. The results show that by using FUS technique for both ADCT and ZLCADCT, approximate full adder (AMA1) can be scaled up to higher frequency (19.2GHZ for 32nm) when compared with EFA (15.4GHZ) by keeping the PSNR nearly unchanged. Meanwhile, when compared with EFA, AMA1 can yield substantially higher number of completed DCT operations. At any frequency level, the number of completed DCT operations over a time window for ZLCADCT using EFA/AMA1 (e.g. 2.95 to 3.53 at 16.6GHZ) is significantly higher than ADCT (2.3 to 2.77) by having the close values in energy dissipation and PSNR.

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