Modified Inexact Adder Cell Designs for Approximate Low Power Image Addition

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Abstract: Image processing is the most common technique in the multimedia. The major block of the image processing is Discrete Cosine Transform (DCT) which comprises of adders and multipliers that are very power consuming. Therefore, it is very important to reduce power in adders and multipliers. That is why approximate adders are used in image processing. Many different types of approximate adder structure are available for the replacement of exact adder. Among all of the approximate adders, inexact adder cell InXA2 gives the better performance in terms of power consumption, delay and area occupied but have a disadvantage that they have very high average and worst delay and power dissipation. Therefore in this work, performance of inexact adder cells circuit has been modified by way of designing circuit through Transmission Gate (TG) which are fast and less power consuming instead of pass transistors. The modified inexact adder cells give better output in terms of error rate, power consumption and least delays.

Keywords: inexact adder, approximate adder, inexact computing, erroneous outputs, error rate, Transmission Gate (TG), Discrete Cosine transform (DCT).

Introduction

A conveyable system usually processes a huge amount of information that is computational and power demanding. The major backbone of all the multimedia devices are Digital Signal Processing (DSP) blocks and most of the DSP blocks are used to process image and video information. Hence, low energy DSP circuits have been explored to maintain a good quality of an image by approximate computing. Processing of an image and video is highly error tolerant. Hence approximate rather than the accurate computing is recommended for this type of applications. Algorithmic noise tolerance (ANT) [1] [2] [3] [4], significance driven computation (SDC) [5] [6] [7] and non-uniform voltage over- scaling (VOS) [8] are the various low power design through approximate computing at the algorithm and architecture level [9]. Therefore, to reduce the power dissipation at the circuit level, various adders are approximated to replace the exact adders. First is the complexity reduction of the Mirror Adder which is most commonly used implementation of full adder and they are approximated at the transistor level. The main advantage of the approximations of the Mirror Adder is that it has reduced number of transistors in the circuit but also reduced the internal node capacitances which led to shorter delay [9]. Secondly, to replace the exact adders, XOR/XNOR based adders are used. In XOR/XNOR based approximate adders the approximation is done on the 10-transistor based accurate full adder [10]. Third is to replace the full adder cell with the inexact adder cells which have less number of transistors than the exact adder cell design [11] [12].

Amongst all approximate adders, inexact adder cells give better performance in terms of delay, complexity and power consumption. As inexact adder cells are using CMOS logic for their implementation which cause longer critical path and high switching capacitance [13] [14]. Therefore, to further improve the performance, inexact adder cells architectures has been designed using the Transmission gates. In this paper, three new modified inexact (approximate) adder cell designs (denoted as modified MInXA's) are presented using transmission gate which provides lesser average and worst case delay as well as dissipates less power. These modified inexact adders act like the exact full adder circuit but having some errors in the outputs as compared to full adder. The performance of the modified inexact adder cells (MInXA's) has been analyzed by implementing image addition using the designed adders.

This paper is organized as follows. Section 2 presents the three new modified inexact adder cells. Section 3 presents performance analysis of the designed modified inexact adder cells. Section 4 presents the image addition using modified inexact adder cells and their analysis.

I. PROPOSED MODIFIED INEXACT ADDER CELLS

The modified inexact adder cells are made up of the transmission gate due to its advantage over the CMOS design such as having less average and worst case delay as well as low power dissipation. These modified inexact adders are named as MInXA1, MInXA2 and MInXA3 as discussed in following sections.

A. *First modified inexact adder (MInXA1) cell*

The first modified inexact adder (MInXA1) cell are designed by the attaining the exact sum while carry is approximated. The logic diagram and the circuit diagram using the transmission gate are presented in Figure 1 and Figure 2. The truth table of the first modified inexact adder cell are shown in Table 1 and also, they are compared with the truth table of the exact adder. After comparing it is seen that the first modified inexact adder cell introduced errors in row 2 and row 7 in the carry.

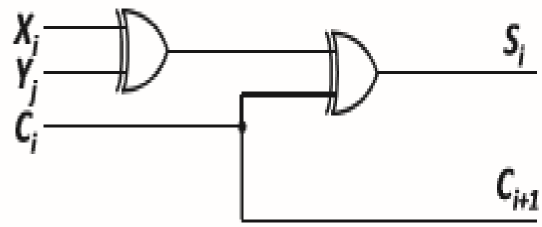

Figure 1 Logic Diagram of MInXA1

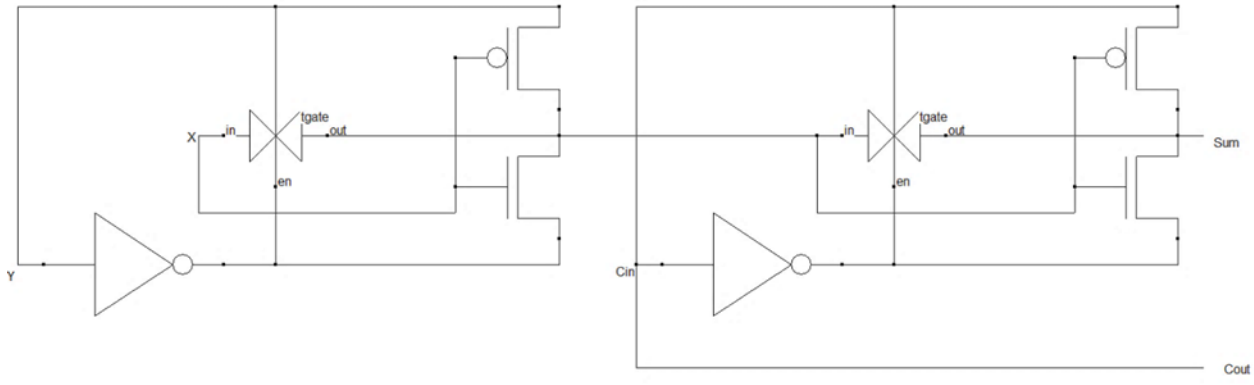

Figure 2 Circuit Diagram using of MInXA1 using TG

B. *Second modified inexact adder (MInXA2) cell*

In the second modified inexact adder cell, the sum is approximated while attaining the exact sum. The logic diagram and circuit level diagram of the second modified inexact adder cell are presented in Figure 3 and Figure 4 respectively. From the truth table 1, it is seen that the second modified inexact adder cell introduces errors in sum at row 4 and row 6.

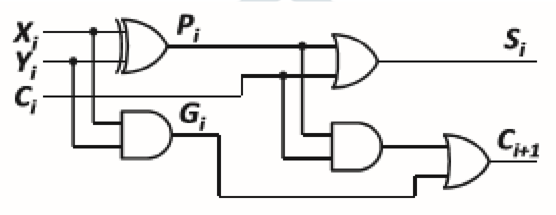

Figure 3 Logic diagram of MInXA2

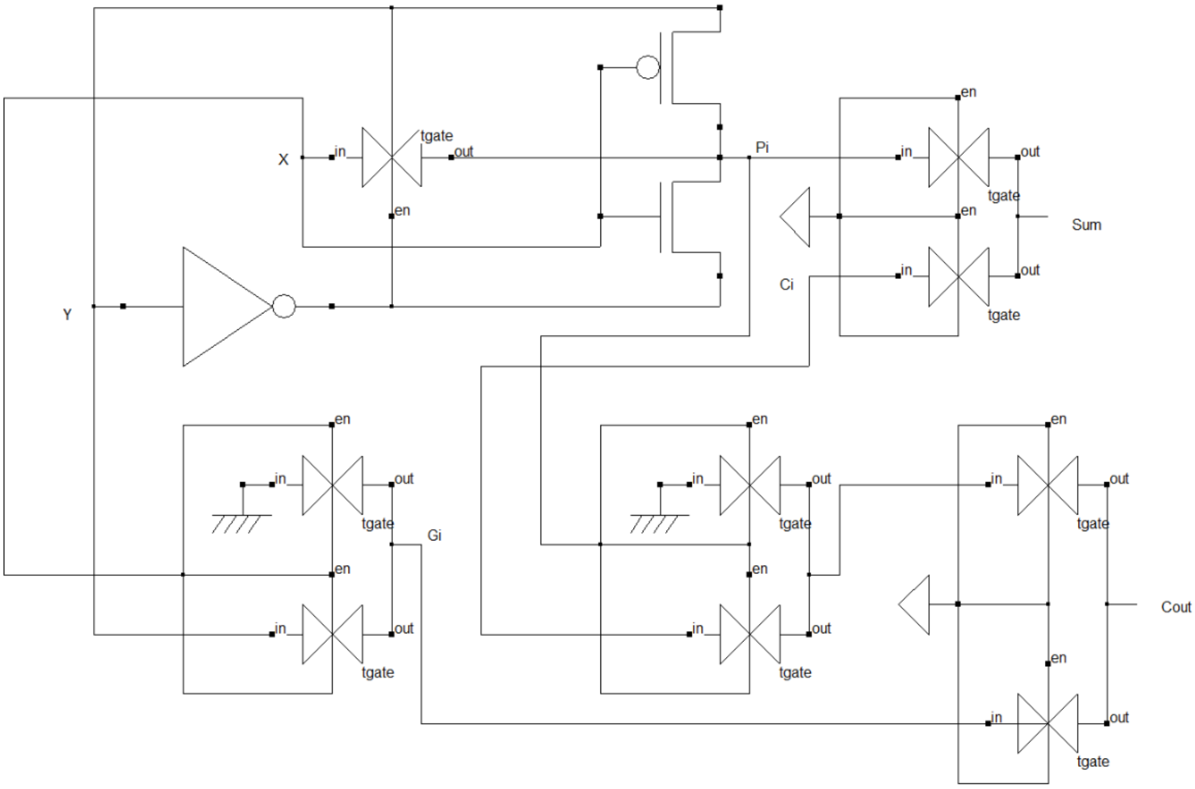

Figure 4 Circuit diagram of MInXA2 using TG

C. *Third modified inexact adder (MInXA3) cell*

In third modified inexact adder cell, sum is approximated while attaining the exact carry. The diagram and the circuit diagram of MInXA3 are represented in the Figure 5 and Figure 6. It is seen from the table 1 that there are errors in sum in row 1 and row 8 while having the exact carry.

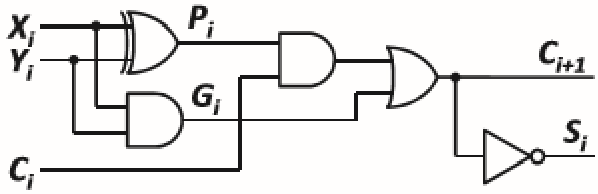

Figure 5 Logic Diagram of MInXA3

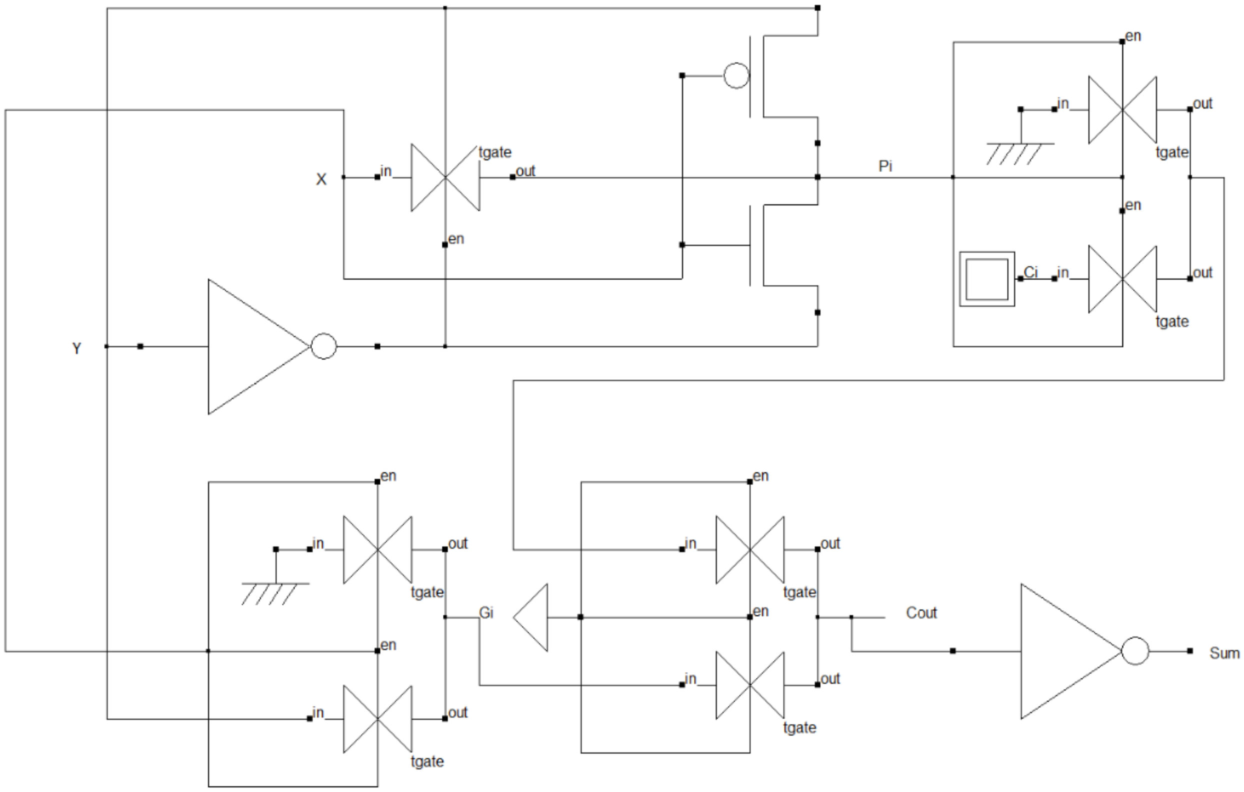

Figure 6 Circuit Diagram of MInXA3 using TG

Table 1 Truth table Proposed Modified Inexact Adder Cells

Inputs			Exact Outputs		Proposed Modified Inexact Adder Cells					
					MInXA1		MInAX2		MInAX3	
X	Y	Cin	Sum	Cout	Sum	Cout	Sum	Cout	Sum	Cout
0	0	0	0	0	0 ✓	0 ✓	0 ✓	0 ✓	1 ×	0 ✓
0	0	1	1	0	1 ✓	1 ×	1 ✓	0 ✓	1 ✓	0 ✓
0	1	0	1	0	1 ✓	0 ✓	1 ✓	0 ✓	1 ✓	0 ✓
0	1	1	0	1	0 ✓	1 ✓	1 ×	1 ✓	0 ✓	1 ✓
1	0	0	1	0	1 ✓	0 ✓	1 ✓	0 ✓	1 ✓	0 ✓
1	0	1	0	1	0 ✓	1 ✓	1 ×	1 ✓	0 ✓	1 ✓
1	1	0	0	1	0 ✓	0 ×	0 ✓	1 ✓	0 ✓	1 ✓
1	1	1	1	1	1✓	1 ✓	1 ✓	1 ✓	0 ×	1 ✓

From table 1, it is concluded that the modified inexact adder cell 1 (MInXA1) introduced 2 errors in the Cout when the input X = Y = 0 & Cin = 1 and X = Y = 1 & Cin = 0 while there is no error in the sum when compared with the full adder truth table. Modified inexact adder cell 2 (MInXA2), introduced no errors in the Cout while there are 2 errors in the sum when the inputs are Y = Cin =1 & X = 0 and X = Cin = 1 & Y = 0. In modified inexact adder cell 3 (MInXA3), there are 2 errors in sum when the inputs are X = Y = Cin = 0 and X = Y = Cin = 1 while the Cout has no errors when compared with the truth table of exact full adder.

The error rate as introduced by the proposed inexact adder cells are shown in table 5.2.

Table 2 Error Rate corresponding to proposed modified inexact adder cells

Modified Inexact Adder Cells	Error rate (%)	
	Sum	Cout
MInXA1	0	25
MInXA2	25	0
MInXA3	25	0

From the table 2 it is seen that MInXA1 has an error rate of 25% for sum while has 0% error rate for Cout. In MInXA2, there are 25% error rate in sum while 0% error rate for Cout. While for MInXA3, there is also 25% error rate in sum and 0% error rate in Cout.

II. PERFORMANCE ANALYSIS

The proposed modified inexact adder is analyzed on the basis of the performance of the following performance metrics. There are various types of performance metrics such as

1. **NAB**: For an n-bits adder, NAB is the number of bits starting at the Least Significant Bit (LSB) that utilize approximate cells i.e. NAB denotes the number of LSB bits that use approximate cells.
2. **Error Distance (ED)**: ED is defined as the arithmetic difference between the exact result (R) and the approximate result ($\hat{R}$) i.e.

$$ED = |R - \hat{R}|$$

3. **Average delay**: It is the average time taken by the both the inputs to reach the final output. It has a SI unit of Nano seconds (ns).
4. **Worst Delay**: It is the delay in the input cycle which takes the worst time as compared to another clock cycles of the input. It also has a SI unit of Nano seconds (ns).
5. **Average energy dissipation:** It is the average energy dissipated during the whole cycle of the input to output. Average energy dissipated are calculated in the femtojoule.

For worst delay and average delay, the eight combinations of the input patterns are supplied at an interval of 2ns by measuring the charging and discharging durations of sum and carry. Figure 7 shows the average delay and worst delay of proposed modified inexact adder cells and other approximate cells.

Table 3 Delays for the modified inexact adder cells (MInXA's)

Input Combinations			Delays for MInXA1	Delays for MInXA2	Delays for MInXA3
X	Y	Cin			
0	0	0	0.0079	0.011	0.06
0	0	1	0.01	0.021	0.07
0	1	0	0.0075	0.035	0.055
0	1	1	0.008	0.01	0.04
1	0	0	0.0079	0.008	0.055
1	0	1	0.008	0.018	0.045
1	1	0	0.0078	0.012	0.065
1	1	1	0.0085	0.007	0.06

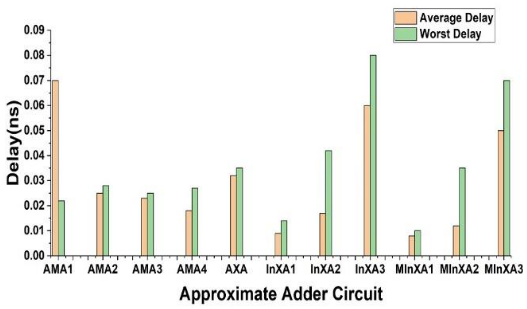

Figure 7 Average and Worst case delay for modified inexact adder cells

Figure 7 shows that the MInXA1 has the worst delay of 0.01ns and average delay of 0.008ns which is least among all the approximate adder cells. MInXA2 has worst delay of 0.035ns and average delay of 0.012ns. MInXA3 introduces worst delay of 0.07ns and average delay of 0.05ns. Therefore, with the introduction of the modified inexact adder cells average delay and worst delay is improved.

Power dissipation is the major concern in the circuit designing. Table 3 shows average power and worst power dissipation of the modified inexact adder cells.

Table 4 Average and worst power dissipation of modified inexact adder cells

Modified inexact adder cells	Power consumption (uW)	
	Average power	Worst power
MInXA1	1.5	3
MInXA2	1	1.6
MInXA3	3	4

From table 3, it is seen that the average power of MInXA2 is 1 uW and worst power of 1.6 uW which is least among all the proposed modified inexact adder cells.

III. Implementation in Image Addition

There are various parameters with which the quality of the image is defined such as Mean Square Error (MSE), Peak Signal to Noise Ratio (PSNR) and Maximum Absolute Difference (MD).

Mean Square Error (MSE)*:*

MSE represents the cumulative squared error between the exact image and image getting after inexact addition. The Mean Square Error for the image quality is defined as

$$MSE = \frac{1}{m \times n} \sum_{j=1}^{m} \sum_{k=1}^{n} (p_{j,k} - \hat{p}_{j,k})^2$$

In the above formula of Mean Square Error (MSE), $p_{j,k}$ is the accurate pixel value at row *j* and column *k* of the image, $\hat{p}_{j,k}$ is the approximate value of the same pixel, *m* and *n* are the size of the image (rows and columns respectively).

Peak Signal to Noise Ratio (PSNR): PSNR is an engineering term for the ratio between the maximum possible power of a signal and the power of corrupting noise that affects the fidelity of its representation. It is most easily defined via MSE. MSE is defined as

$$PSNR = 10 \log(2^n - 1)^2 / MSE$$

Normalized Cross Correlation (NK): Normalized cross correlation is a measure of similarity of two series as a function of the displacement of one relative to the other. NK is defined as

$$NK = \sum_{j=1}^{m} \sum_{k=1}^{n} (p_{j,k} \cdot \hat{p}_{j,k}) \Big/ \sum_{j=1}^{m} \sum_{k=1}^{n} {p_{j,k}}^2$$

Normalized Absolute Difference (NAE): MD of the two real m,n is given by |m-n|, the absolute value of their difference. It describes the distance on the real line between the points corresponding to m and n. It is defined as

$$NAE = \sum_{j=1}^{m} \sum_{k=1}^{n} |p_{j,k} - \hat{p}_{j,k}| \Big/ \sum_{j=1}^{m} \sum_{k=1}^{n} {p_{j,k}}^2$$

Average Difference (AD): The difference between the average values of a measure in one group and the average value of same measure in another group is known as average difference. Here the measure is the pixel values of an image. It is defined as

$$AD = \frac{1}{m \times n} \sum_{j=1}^{m} \sum_{k=1}^{n} (p_{j,k} - \hat{p}_{j,k})$$

Maximum Absolute Difference (MD): MD is the maximum value of the difference between the two images. The absolute value of difference is used to calculate MD. It is defined as:

$$MD = \max_{m,n}\{|p_{j,k} - \hat{p}_{j,k}|\}$$

Structural Content (SC): SC is a measurement method for predicting the perceived quality of the digital image. This measurement of image quality is based on initial uncompressed or distortion free image as reference. It is defined as

$$SC = \sum_{j=1}^{m} \sum_{k=1}^{n} {p_{j,k}}^2 \Big/ \sum_{j=1}^{m} \sum_{k=1}^{n} {\hat{p}_{j,k}}^2$$

The modified inexact adder cells are evaluated with respect to the exact adder and previously designed approximate adders. The proposed modified inexact adder cells are used for the addition of the two images and compared the image analysis parameters with the other approximate adders. For analyzing the image addition using the proposed modified inexact adder cells, two images are added to generate a new image. Two images are added of the same size, m = n = 256 and selected due to the opposite features of both the images. The images taken for the addition are in figure 8 and Figure 9.

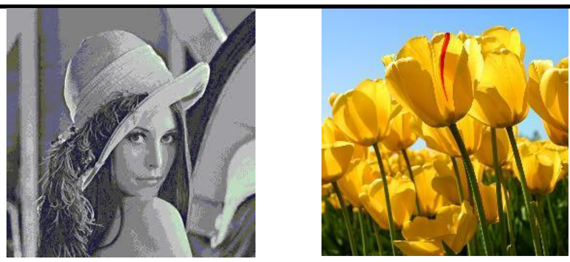

Figure 8. Sample Image 1 and Sample Image 2

The images in the Figure 1 and Figure 2 are added with the accurate addition and using MInXA2. The resulting image obtained after the accurate addition and approximate addition are shown in is shown in Figure 9.

Figure 9 (a, b, c, d) Image Addition using Accurate Adder, using MInXA1, using MInXA2 and using MINXA3

The image is analyzed using parameters PSNR, MSE, NAE, AD, MD, SC and NK is discussed above and analyzed for the sample image 1 and image 2.

1) ***Mean Square Error (MSE):*** MSE represents the cumulative squared error between the exact image and image getting after inexact addition.

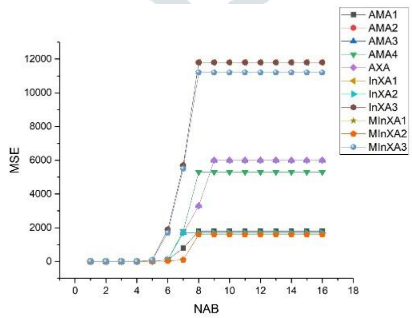

Figure 10 MSE results for addition of sample image 1 and image 2 using proposed approximation method & already available methods (AMA1 (Gupta *et al.*, 2013), AMA2 (Gupta *et al.*, 2013), AMA3 (Gupta *et al.*, 2013), AMA4 (Gupta *et al.*, 2013), AXA (Lin *et al.*, 2007), InXA1 (Almurib and Kumar, 2016), InXA2 (Almurib and Kumar, 2016), InXA3 (Almurib and Kumar, 2016)) for different values of NAB

Figure 10 shows the addition process of image 1 and image 2 using a 16-bits adder and it is seen that MInXA2 based Ripple Carry Adder (RCA) creates the minimum value of 1600 as compared to all the approximate adders.

2) ***Peak Signal to Noise Ratio (PSNR)***

Another parameter used for analyzing the image quality is Peak Signal to Noise Ratio (PSNR). PSNR is an engineering term for the ratio between the maximum possible power of a signal and the power of corrupting noise that affects the fidelity of its representation. The PSNR of modified inexact adder are shown in figure 11.

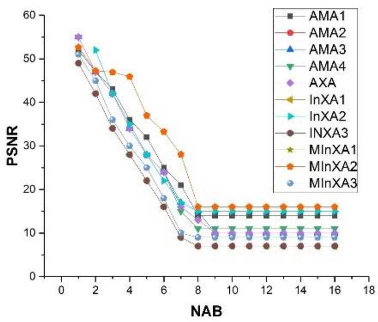

Figure 11 PSNR results for addition of sample image 1 and image 2 using proposed approximation method & already available methods (AMA1 (Gupta *et al.*, 2013), AMA2 (Gupta *et al.*, 2013), AMA3 (Gupta *et al.*, 2013), AMA4 (Gupta *et al.*, 2013), AXA (Lin *et al.*, 2007), InXA1 (Almurib and Kumar, 2016), InXA2 (Almurib and Kumar, 2016), InXA3 (Almurib and Kumar, 2016)) for different values of NAB

It is seen from the Figure 11 that PSNR at in the interval of 0-4 are higher for the InXA2 while for the 2-16 MInXA2 has the higher peak signal to noise ratio. The modified inexact adder cell 2 (MInXA2) based RCA accomplishes the best. InXA3 gives the least value of PSNR from all of the approximate adders.

3) ***Structural Content (SC)***

SC is another parameter for analyzing the quality of an image. Figure 12 shows the SC of the proposed inexact adder cells and other approximate adders.

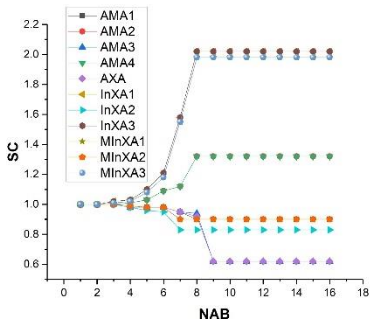

Figure 12 SC results for addition of sample image 1 and image 2 using proposed approximation method & already available methods (AMA1 (Gupta *et al.*, 2013), AMA2 (Gupta *et al.*, 2013), AMA3 (Gupta *et al.*, 2013), AMA4 (Gupta *et al.*, 2013), AXA (Lin *et al.*, 2007), InXA1 (Almurib and Kumar, 2016), InXA2 (Almurib and Kumar, 2016), InXA3 (Almurib and Kumar, 2016)) for different values of NAB

From figure 12, it is seen that MInXA2 based ripple carry adder has SC value of 0.99 which is least among all the approximate adder cells for all the NAB values. It is also seen that the AMA3, AXA and MInXA3 based ripple carry adder perform better after the NAB value of 8.

4) ***Normalized Cross Correlation (NK)***

Normalized cross correlation (NK) is another parameter for distinguishing the image quality of the picture. Figure 13 shows the normalized cross correlation of the addition of sample image 1 and sample image 2 using the proposed inexact adder cells.

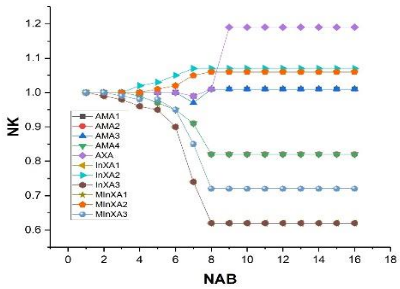

Figure 13 NK results for addition of sample image 1 and image 2 using proposed approximation method & already available methods (AMA1 (Gupta *et al.*, 2013), AMA2 (Gupta *et al.*, 2013), AMA3 (Gupta *et al.*, 2013), AMA4 (Gupta *et al.*, 2013), AXA (Lin *et al.*, 2007), InXA1 (Almurib and Kumar, 2016), InXA2 (Almurib and Kumar, 2016), InXA3 (Almurib and Kumar, 2016)) for different values of NAB

From figure 13 it is seen that for the NAB values form 1- 4, NK value is 1 for the AMA, InXA2 and MInXA2 based ripple carry adder. For the NAB value in period 5- 16, MInXA2 based ripple carry adder produces the NK value of 1.05 which is least among all the approximate adder cells. InXA3 based ripple carry adder NK value of 0.63 which is worst among all of the approximate adder cells.

5) ***Normalized Absolute Error (NAE)***

NAE is used to find the normalized absolute error between the images and is an important parameter to distinguish the quality of an image. Figure 14 shows the NAE of the addition of sample image 1 and sample image 2 using the proposed inexact adder cells.

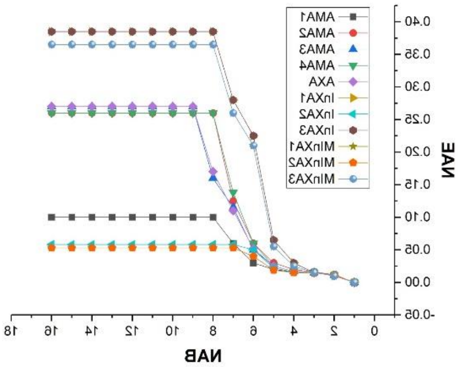

Figure 14 NAE results for addition of sample image 1 and image 2 using proposed approximation method & already available methods (AMA1 (Gupta *et al.*, 2013), AMA2 (Gupta *et al.*, 2013), AMA3 (Gupta *et al.*, 2013), AMA4 (Gupta *et al.*, 2013), AXA (Lin *et al.*, 2007), InXA1 (Almurib and Kumar, 2016), InXA2 (Almurib and Kumar, 2016), InXA3 (Almurib and Kumar, 2016)) for different values of NAB

From figure 14, it is seen that value of NAE in the interval 0 – 3 is 0 for all the ripple carry based approximate adder circuits. MInXA2 based ripple carry adder have NAE value of 0.04 which is least as compared to other approximate adder cells. InXA3 has NAE value 0.36 which is worst among all the approximate adder cells using ripple carry adder.

6) ***Maximum Absolute Difference (MD)***

Another measure for the image analysis is Maximum Absolute Difference (MD). Figure 15 shows the NAE of the addition of sample image 1 and sample image 2 using the proposed inexact adder cells.

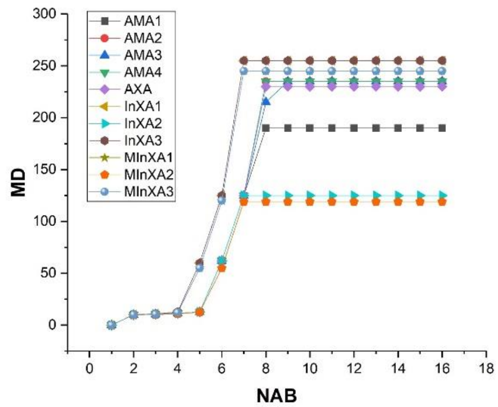

Figure 15 MD results for addition of sample image 1 and image 2 using proposed approximation method & already available methods (AMA1 (Gupta *et al.*, 2013), AMA2 (Gupta *et al.*, 2013), AMA3 (Gupta *et al.*, 2013), AMA4 (Gupta *et al.*, 2013), AXA (Lin *et al.*, 2007), InXA1 (Almurib and Kumar, 2016), InXA2 (Almurib and Kumar, 2016), InXA3 (Almurib and Kumar, 2016)) for different values of NAB

From figure 15, it is seen that MD for the InXA3 based ripple carry adder is 260 which is the worst among all the approximate adder cells. From period 1 – 4 of NAB, all the ripple carry based approximate adders have a same value of 10 of MD. While for the period 6 – 16, MInXA2 based ripple carry adder have 110 value of MD which is least among all the approximate adder cells.

7) ***Average Difference (AD)***

Average difference AD is another measure for the image analysis. Figure 16 shows the AD for the addition of sample image 1 and sample image 2 using the proposed inexact adder cells.

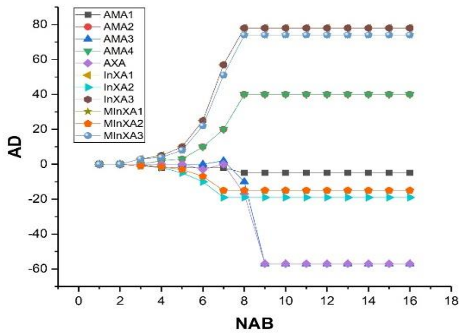

Figure 16 AD results for addition of sample image 1 and image 2 using proposed approximation method & already available methods (AMA1 (Gupta *et al.*, 2013), AMA2 (Gupta *et al.*, 2013), AMA3 (Gupta *et al.*, 2013), AMA4 (Gupta *et al.*, 2013), AXA (Lin *et al.*, 2007), InXA1 (Almurib and Kumar, 2016), InXA2 (Almurib and Kumar, 2016), InXA3 (Almurib and Kumar, 2016)) for different values of NAB

From figure 16, it is seen that AXA based ripple carry adder shows AD of -60 which is very large as compared to other ripple carry adder based approximate adder cells. MInXA2 based ripple carry adder shows AD of -11 which shows best performance as compared to other RCA based approximate adder cells.

From the simulation results it is seen that proposed modified inexact adder cells gives better performance as compared to other approximate adder cells as it has least value of error rate, less power dissipation. Also, when modified inexact adder-based ripple carry adder used in the image addition, it shows best performance in terms of image analysis measures like high PSNR, least AD and least MD.

Conclusion

This paper has presented three new modified inexact adder cell designs (MInXA) that have lower average and worst case delay as compared to other approximate circuits found in the technical literature. The simulation results show that the proposed MInXA2 adder outstrips the other proposed modified inexact adders and previous approximate adders in terms of average delay and worst delay.

The analysis is then extended to RCAs using the proposed modified inexact adder cells using image addition as application. Among all previous approximate adders, the MInXa2 based RCA has the least error rate while the error rates for MInXA1 and MInXA3 based RCAs are nearly same and resemble to least error rate among approximate adders. The MInXA2 based ripple carry adder shows better performance in image addition parameters among all the approximate adders.

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