Parallel Inverse Halftoning by Look-Up Table (LUT) Partitioning

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Abstract

Look-Up Table *(LUT)* method for inverse halftoning is computation less, fast, and also yields goods results. It employs a single LUT that is stored in a ROM and contains pre-computed contone (gray level) values for inverse halftone operation. This paper proposes an algorithm that can perform parallel inverse halftone operation by partitioning the single LUT into N smaller Look-Up Tables *(s-LUTs)*. Thereby, upto k $(k \leq N)$ pixels can be concurrently fetched from the halftone image, and their contone values can also be fetched concurrently from separate smaller Look-Up Tables *(s-LUT)*. The parallelization increases the speed of inverse halftoning by upto k times while the total entries in all *s-LUTs* remains equal to the entries in the single LUT of the serial LUT method. Some degradation in image quality is possible due to pixel loss during parallel fetching. This is due to some contone values cannot be fetched in the same cycle because some other contone value is being fetched from the *s-LUT*. The complete implementation of the algorithm requires two *CPLD* devices for computational portion, external content addressable memories *(CAM)* and static RAMs to store *s-LUTs*.

Keywords: (1) Inverse Halftoning, (2) Hardware Implementation, (3) Look-Up Table Inverse Halftoning, (4) Complex Programmable Logic Devices (CPLD), (5) Image Processing, (6) Parallelizing, (7) Complex Programmable Logic Devices (CPLD).

1. Introduction

The process of rendition of continuous tone pictures on media on which only two levels can be displayed is defined as Halftoning [1]. The problem has gained importance since the time of printing press when attempts were made to print images on paper by adjusting the size of dots according to the local print intensity. This process is termed as analog halftoning. With the availability and adoption of bi-level devices such as fax machines and plasma displays, digital halftoning has become important [2]. The input to a digital halftoning system is a gray level image in which pixels have more than two levels (e.g. 256 levels), and the result of the halftoning process is an image that has only two levels i.e., 1 or 0. Inverse halftoning on the other hand, is the reconstruction of gray level images from halftone images. Inverse halftone operation finds application in areas where processing is required on printed images. The images are first scanned, inverse halftoned and then operations like zooming, rotation and transformation are applied. Standard compression techniques cannot process halftones directly and therefore inverse halftoning is required before compression of printed images can be performed [1].

Look-Up Table (LUT) inverse halftoning is a fast and low computation method [3]. LUT inverse halftoning was first introduced by Netravali and Bowen [4], but requires some information to be known that is not always available for halftone images. Subsequently Ting and Riskin [5] proposed another LUT method but did not aimed to obtained good quality. In the recent past a computation free LUT method was proposed by Mese and Vaidyanathan [1, 3]. It can provide fast inverse halftoning with good image quality, and it can be applied on several different halftones. Two more methods for LUT inverse halftoning [6, 7] were suggested by Kuo-Liang Chung et al. and P. C. Chang et al. and their methods can give better

image quality but they are not completely computation free and require computation in addition to Look-Up Table (LUT) access. In Mese et al. method, one template that consists of the pixel to be inverse halftoned, and pixels in its neighborhood is fetched from the halftone image in a *p-bits (p=17, 21, 22)* vector and is used to form the address for the LUT. Its pre-computed contone value is fetched from this address of the LUT. However, this method is serial and is able to inverse halftone only one template at a time. In this paper, we present an algorithm that can perform parallel inverse halftone operation by partitioning the single LUT of Mese at al. method into *N* number of smaller Look-Up Tables *(s-LUTs)*. The *N s-LUTs* contain total entries equal to the entries in the single LUT of serial LUT method. In this way, the proposed algorithm can provide significant advantage in speed of inverse halftone operation and at the same time provides saving in memory requirements. In the proposed algorithm, *'k'* templates are concurrently fetched from the halftone image and their contone values are obtained through *s-LUTs*. The rest of this paper is organized as follows: First the serial LUT method is described then the parallelization of LUT method for inverse halftoning is described in detail that basically employs partitioning the LUT based on some partitioning. This is followed by the simulation of the proposed algorithm and discussion about its performance. In the last section, implementation details of the proposed algorithm using CPLD devices are discussed.

2 Look-Up Table (LUT) Method for Inverse Halftoning

In the LUT method for inverse halftoning a template represented by '*t'* is a group of pixels that consists of pixel to be inverse halftoned and the pixels in its neighborhood. The LUT method uses three types of templates namely: *16pels, 19pels and Rect*. The *16pels* consists of 17-pixels, *19pels* consists of 20-pixels and *Rect* consists of 22 pixels. The templates are

fetched from the halftone image following the raster-scan style, i.e., from left to right, in a row and from top to bottom. One pixel with surrounding ones (so called a template *(t)*) is fetched and inverse halftoned before the next template is fetched. The Look-Up Table (LUT) stores pre-computed contone values of a large number of templates. The templates for storage in the LUT are obtained from a training set of images that comprise halftone images and corresponding continuous tone images. The templates are fetched from the halftone images and their contone values are fetched from corresponding continuous tone images. When a template occurs more than once then its contone value is the mean of all contone values that corresponds to that template in the training set. The inverse halftone operation is performed in this way that a template *(t)* is fetched from the halftone image and it is sent to the Look-Up Table (LUT). If the LUT has the stored contone value for the template *(t)* it returns it otherwise the template *(t)* undergoes through anyone of these methods: (a) Low Pass Filtering, or (b) Best Linear Estimator [1]. When same halftone algorithm is used in training set images and the images going through inverse halftone operation then all templates always find corresponding contone value in the LUT, and consequently, this method becomes completely computation free. The LUT method for inverse halftoning can also be applied to color halftones where a separate LUT exists for color planes *R, G, and B*.

3 Parallel Look-Up Table (LUT) Inverse Halftoning

In order to perform parallel LUT inverse halftoning, two or more templates should be fetched from the halftone image and LUT (Look-Up Table) inverse halftone operation is applied to them at the same time. The main problems in parallelizing LUT method for inverse halftoning are the following:

(a) The Look-Up Table (LUT) is composed of a single memory block that does not allow simultaneous access to more than one location. Therefore, parallel templates cannot fetch their contone values at the same time.

(b) If the LUT method for inverse halftoning is parallelized as it is then the memory requirements grow very large because one needs to store one template *(t)* for each template that is fetched in parallel.

The next section presents an algorithm to parallelize the LUT method for inverse halftoning while solving the above problems.

4. Algorithm to Perform Parallel LUT Inverse Halftoning

This section shows the algorithms that can perform parallel inverse halftone operation by enhancing the serial LUT method of Mese and Vaidyanathan [3]. In the proposed algorithm N smaller Look-Up Tables *(s-LUTs)* are used in place of a single LUT of serial LUT method. The proposed algorithm also introduces a circuitry that can distinguish k templates that are concurrently fetched from the halftone image through unique numbers. As a result of these two modifications, k templates can be fetched concurrently and go through parallel inverse halftone operation using N *s-LUTs* and therefore their contone values can be obtained simultaneously. The proposed parallel inverse halfoning using *s-LUTs* consists of two steps: (1) Algorithm to generate 'N' smaller Look-Up Tables *(s-LUTs)*, and (2) Algorithm to send 'k' concurrently fetched templates to distinct *s-LUTs*. In the rest of this section the algorithms are described in detail.

4.1 Idea behind Proposed Algorithm

The proposed algorithm to perform parallel inverse halftone operation is based on the initiation to partition the single LUT into N smaller Look-Up Tables *(s-LUTs)*. The

partitioning can be done linearly or can use any sophisticated technique. In linear partitioning the contents from the training set are assigned to *s-LUTs* based on some fixed criteria like equal number of contents in all *N s-LUTs*. This approach has the problem that during inverse halftone operation it becomes difficult to estimate which template value exists in which *s-LUT*. The algorithm proposed in this paper, instead partition the LUT into *N s-LUTs* by using a new approach. The new approach is initiated when some halftone images are observed and it is found that adjacent, i.e., either top-bottom, or left-right template values differ from each other in terms of number of ones present in them. The paper defines a function that takes XOR between the fetched template and *m*, where *m* is the mean of all template values present in the training set. Then the bits in the XOR result are added to calculate the number of ones. At this point a unique result is obtained for each concurrently fetched template, i.e., *k* unique value are obtained. However, their values vary from 0 to 2^P-1, whereas number of *s-LUTs* is *N*. In next step, *mod N* operation is applied and numbers in range from *0* to *N-1* are obtained for all concurrently fetched templates. The graph in Figure 1 shows the percentage of times this approach is successful is distinguishing concurrently fetched templates. Taking *mod N* is computation free when *N* is an exponent of *2, i.e., 2, 4, 8, 16, 32, or etc* then *mod N* operation is performed by only keeping least significant log_2N*-bits* of the input.

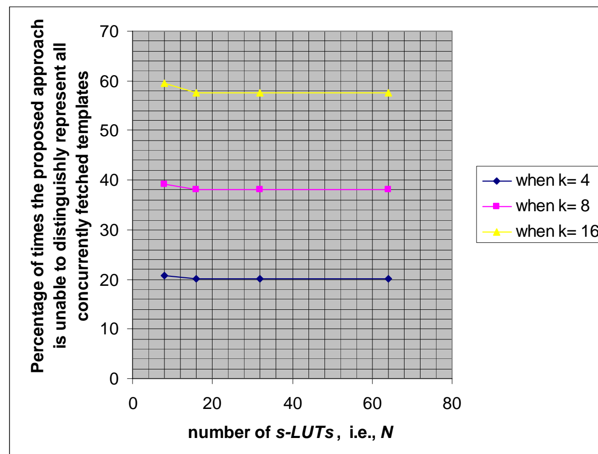

Figure 1: Graph showing performance of proposed approach to distinguish concurrently fetched templates.

The *N s-LUTs* will be stored in *N* external memories and templates fetched from the halftone image act as input addresses to memories. Distribution of templates among *N s-LUTs* should be uniform so that memories of equal sizes can be utilized, however when *s-LUTs* do not have equal sizes than large *s-LUTs* can be stored in more than one memories and in that case *(number of memories)* > *N*. Two other approaches that can be also be used are: (1) to add the bits in the templates and then take *mod N*, and (2) directly take *mod N* of the fetched template. However, first taking *XOR* with *m* yields the best image quality among them therefore the algorithm proposed in this paper uses only this approach.

4.2 Algorithm to generate *N* smaller Look-Up Tables *(s-LUTs)*

N number of smaller Look-Up Tables *(s-LUTs)* must be generated before inverse halftone operation is performed, similar to the procedure of serial LUT method. The *s-LUTs* are numbered from *0* to *N-1*, where *N* must be an exponent of *2, i.e.*, *2, 4, 8, 16, etc*. The algorithm is shown in Figure 2. It starts by building *'Training_set',* that consists of continuous tone images and their halftone versions. In step 2, a template represented by *'t'* is fetched from the halftone image. In step 3, first the fetched templates *t* is taken XOR gated with *m*, where *m*= mean of all template values present in the training set. Then bits in the obtained result are added and finally its *mod N* operation is taken by keeping only least significant log_2N*-bits.* The result now obtained is the result of step 3. In the next step, template *'t'* is sent to *s-LUT* that has same number as the result returned in step 3. Now procedure from step 2 to step 4 are repeated by fetching another template from the training set and it continuous until all templates in the training set are fetched and stored in *s-LUTs*.

1. Build training set 'Training_set' that consists of continuous tone images and corresponding halftone images,

2. Fetch one template *'t'* from the halftone image,

3. Apply the following operations on *t*:

   $v_1(0...p-1) = t(0...p-1)\ XOR\ m(0...p-1)$,
   $v_2(0...log_2p-1) = ADD(v_1(0), v_1(1),..., v_1(p-1))$,
   $result(0...log_2N-1) = v_2(0...log_2N-1)$.

4. Store *t* and its contone value as present in the corresponding continuous tone image in the *s-LUT* that has same number as the value in variable result. If a same value of *t* occurs more than once then store *contone* value equal to the mean of all *contone* values that corresponds to that template value in the training set.

5. Fetch another template from the training set and apply steps *2* to *4* on it.

6. Repeat the above procedure until all templates in the training set are stored in corresponding *s-LUTs*.

Figure 2: Algorithm to generate smaller Look-Up Tables *(s-LUTs)*.

4.3 Algorithm to send *'k'* concurrently fetched templates to distinct *s-LUTs*

This algorithm performs the task to assign unique numbers in range from *0* to *N-1* to *k* concurrently fetched templates and then send them to distinct *s-LUTs* using their unique numbers. In this way it can perform parallel inverse halftone operation using *s-LUTs*. The algorithm is shown in Figure 3. It starts by fetching *k* templates from the halftone image in which the templates are numbered from *1* to *k*. Then in step 3, *mod N* operation is performed on templates by keeping their only significant log_2N-bits. In step 4, if any two or more templates have same value returned in step 3 then among them only the template that has the highest number assigned to it in step 2 is kept and others having same step 3's result are discarded. The templates that are not discarded are now sent to *s-LUTs* that have same numbers as their values returned in step 3. In step 6, *contone* values to templates that were discarded in step 4 or the templates that do not find their contone values in their *s-LUTs* are assigned by copying *contone* values from their neighbors. Finally *contone* values of all *k* fetched templates are delivered to the output. This process repeats until all templates present in the halftone image are inverse halftoned. This algorithm is pipelined therefore, each step

can be performed in parallel on different data inputs and new k templates can be fetched on every clock cycle from the halftone image.

1. Concurrently fetch k templates represented by $t_0, t_1, \ldots, t_{k-1}$ from the halftone image,

2. Assign numbers to the fetched templates from *1* to k,

3. Apply the following operations to each template simultaneously:

   $u_i(0...p-1) = t_i(0...p-1)\ XOR\ m(0...p-1)$,
   $w_i(0...log_2p-1) = ADD(u_i(0)\ , u_i(1)\ , \ldots\ , u_i(p-1))$,
   $v_i(0..log_2N-1) = w_i(0...log_2N-1)$,
   where p is the number of bits in the template, and $i= 0$ to $k-1$.

4. if $v_i=v_j$ where $i \neq j$ and $i>j$, then discard if v_j, both i and j varies from *0* to $k-1$.

5. Send templates whose results from step 3 are not discarded to *s-LUTs* that has same number as the values returned in step 3. In this step templates obtained their contone values from *s-LUTs*.

6. Assign *contone* values to templates that were not send to *s-LUTs* in step 5 or to templates whose *contone* value are not found in the corresponding s-LUT by copying *contone* values of template that has the nearest higher number assigned to it in step 2 and whose step 3's result was not discarded in step 4.

7. Yield *contone* values of input templates.

Figure 3: Algorithm to perform parallel inverse halftoning using *s-LUTs*.

5. Simulation

This section shows simulation of the proposed algorithm. The simulation is performed by implementing it in Java programming language. It starts by building a training set of *17* gray level and corresponding halftone images. Then value of N is chosen and *s-LUTs* are generated. The parallel inverse halftone operation is performed by setting different values of k. In this section, first the results of generating *s-LUTs* are shown and then some halftone images that are not present in the training set are inverse halftoned and are shown with their image quality in terms of Peak Signal to Noise Ratio (PSNR).

5.1 Generation of *s-LUTs*

The *s-LUTs* are generated using the training set and partitioning of templates among N *s-LUTs* is shown in Figures 3 and 4. Figure 3 shows the partitioning when $N= 8$ and Figure 4 shows the partitioning when $N=16$. It is shown that each *s-LUT* stores almost equal number

of contents when *N= 8* and when *N= 16* large variation in *s-LUT* sizes occur with some *s-LUTs* remains emptied.

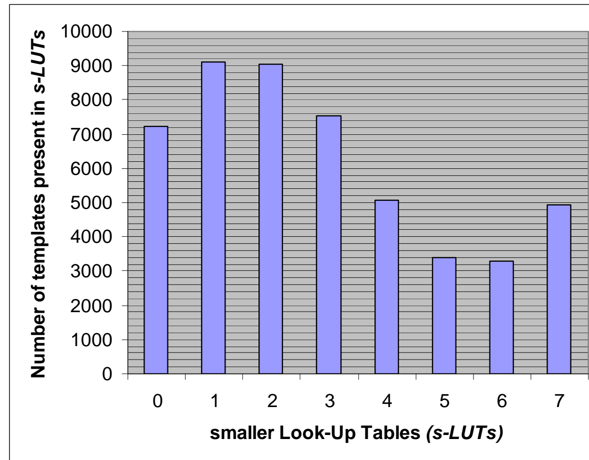

Figure 4: Distribution of templates to *s-LUTs* (when *N=8*).

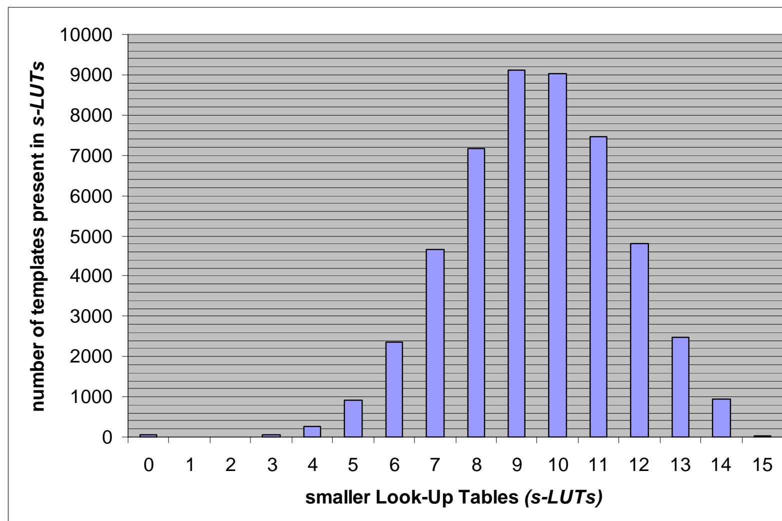

Figure 5: Distribution of templates to *s-LUTs* (when *N=16*).

5.2 Parallel Inverse Halftoning

This section shows the simulation of the proposed algorithm to perform parallel inverse halftone operation using *s-LUTs*. The simulation shows inverse halftone operation accomplished with different values of '*k'* and '*N*'. The graph in Figure 6 shows average image quality when compared to quality of images obtained from the proposed algorithm in

terms of PSNR. The graph shows curves drawn for different values of *k* and their *y-axis* values i.e., image quality varies with increase in the value of *N*. However, *N* should an exponent of 2 i.e., 2, 4, 8, 16, etc. The results show an average of results obtained from images: Boat, peppers, and clock. Some sample images obtained from the serial LUT method and from proposed algorithm are shown in Figures 7 to 15, along with their original continuous tone versions.

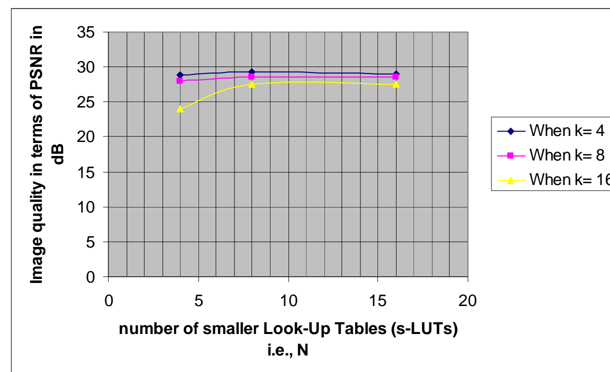

Figure 6: Performance of the proposed algorithm in terms of image quality for different values of *k* and *N*.

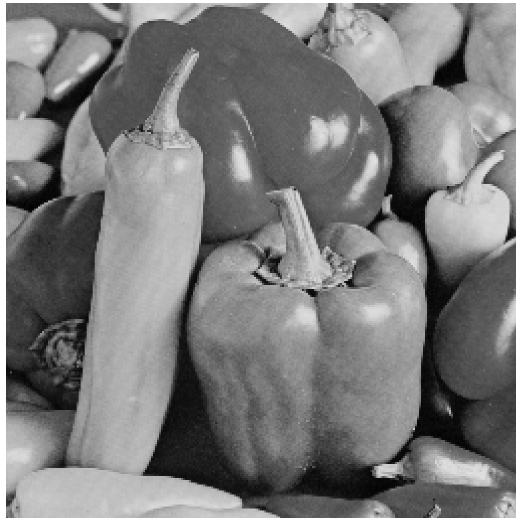

Figure 7: Original continuous tone image named ‘peppers’.

Figure 8: Peppers obtained from serial LUT method, PSNR= 29.4154 dB.

Figure 9: Peppers obtained from inverse halftone operation using proposed algorithm with k=4 and N=8, PSNR= 29.2605 dB.

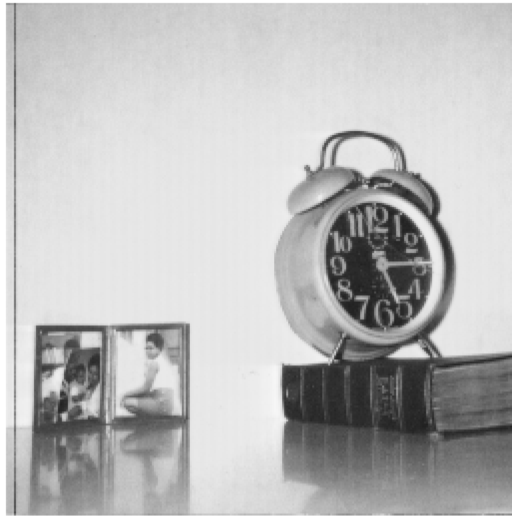

Figure 10: Original continuous tone image named ‘clock’.

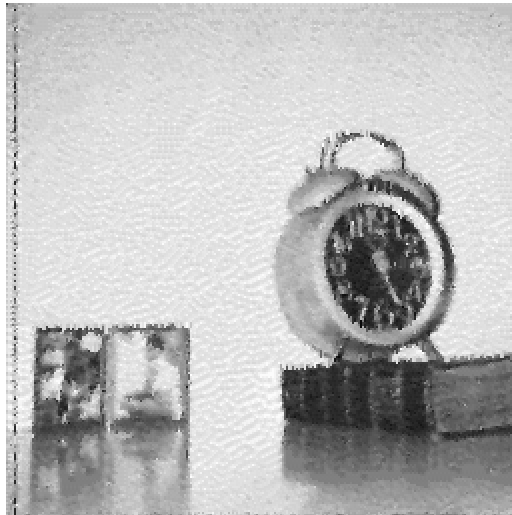

Figure 11: Clock obtained fro serial LUT method, PSNR= 30.1681 dB.

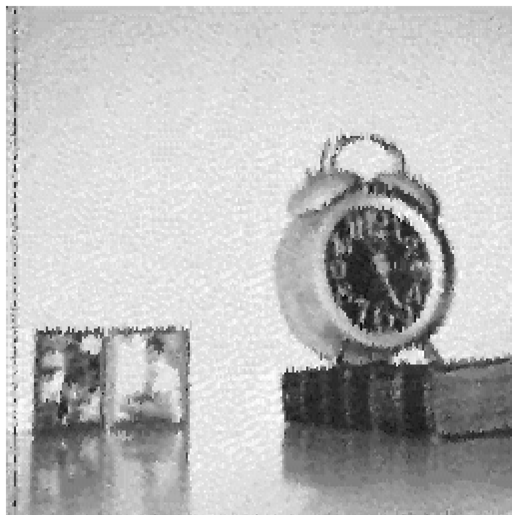

Figure 12: Clock obtained from inverse halftone operation using proposed algorithm with *k*=4 and *N*=8, PSNR= 30.0846 dB.

Figure 13: Original continuous tone image named ‘boat’.

Figure 14: Boat obtained from serial LUT method, PSNR= 28.7071 dB.

Figure 15: Boat obtained from inverse halftone operation using proposed algorithm with k=4 and N=8, PSNR= 28.5449 dB.

6. Integrated Circuit Design

The integrated circuit that can implement the proposed algorithm with parameters $k=4$ and $N=8$ is designed. The target platform is Field Programmable Gate Array (FPGA) devices. The circuit is divided into blocks and each block is represented through Boolean equations and can work independently on different inputs. The following text shows the details of the integrated circuit.

Block 1: In this stage four templates I_0, I_1, I_2 and I_3 are fetched from the halftone image and stored in registers t_0, t_1, t_2 and t_3 respectively. The Boolean equations representing logic in this block are shown below:

$$t_0(0\ldots p-1) = I_0(0\ldots p-1),\ t_1(0\ldots p-1) = I_1(0\ldots p-1),\ t_2(0\ldots p-1) = I_2(0\ldots p-1),\ t_3(0\ldots p-1) = I_3(0\ldots p-1) \qquad \textbf{(6.1)}$$

Block 2: In this block bits in each template are added using Carry Save Adder (CSA) Tree. The Boolean equations representing operations in this block are shown below and the CSA tree for $N= 8$ and $p=20$ is shown in Figure 16:

$$S_i = \textbf{CSA_TREE}(t_i(0\ldots p-1)),\ \text{Where } i= 0, 1, 2, \&\ 3. \qquad \textbf{(6.2)}$$

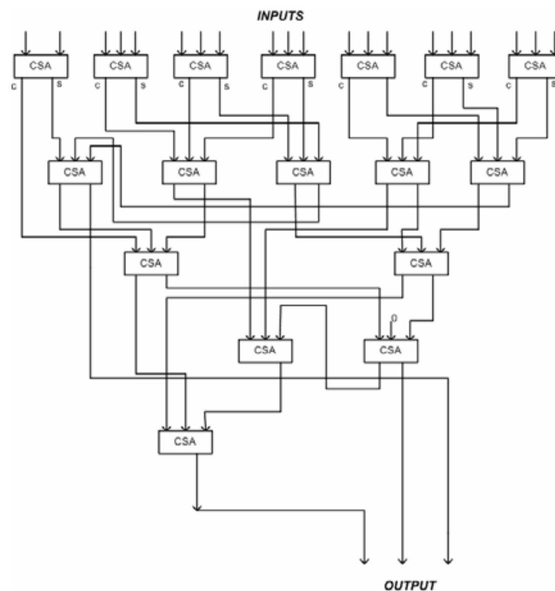

Figure 16: Carry Save Adder (CSA) Tree when *p*=20 and *N*=8.

Block 3: In this block templates t_0, t_1, t_2 and t_3 are appended with sequence numbers 001, 010, 011, and 100 respectively. The Boolean expressions representing operations in this block are:

$t_0'(0...p+2) = t_0(0...p-1)$ & 001, $t_1'(0...p+2) = t_1(0...p-1)$ & 010,

$t_2'(0...p+2) = t_2(0...p-1)$ & 011, $t_3'(0...p+2) = t_3(0...p-1)$ & 100. **(6.3)**

Block 4: This block consists of four *1x8* multiplexers. The Boolean expressions that represent the logic in this block are:

$$\begin{aligned}
A_i[0](0...p+2) &\leftarrow \overline{slut_i(2)} \cdot \overline{slut_i(1)} \cdot \overline{slut_i(0)} \cdot (t_i'(0...p+2)),\\
A_i[1](0...p+2) &\leftarrow \overline{slut_i(2)} \cdot \overline{slut_i(1)} \cdot slut_i(0) \cdot (t_i'(0...p+2)),\\
A_i[2](0...p+2) &\leftarrow \overline{slut_i(2)} \cdot slut_i(1) \cdot \overline{slut_i(0)} \cdot (t_i'(0...p+2)),\\
A_i[3](0...p+2) &\leftarrow \overline{slut_i(2)} \cdot slut_i(1) \cdot slut_i(0) \cdot (t_i'(0...p+2)),\\
A_i[4](0...p+2) &\leftarrow slut_i(2) \cdot \overline{slut_i(1)} \cdot \overline{slut_i(0)} \cdot (t_i'(0...p+2)),\\
A_i[5](0...p+2) &\leftarrow slut_i(2) \cdot \overline{slut_i(1)} \cdot slut_i(0) \cdot (t_i'(0...p+2)),\\
A_i[6](0...p+2) &\leftarrow slut_i(2) \cdot slut_i(1) \cdot \overline{slut_i(0)} \cdot (t_i'(0...p+2)),\\
A_i[7](0...p+2) &\leftarrow slut_i(2) \cdot slut_i(1) \cdot slut_i(0) \cdot (t_i'(0...p+2)),
\end{aligned} \qquad \textbf{(6.4)}$$

In the above equations i= 0 to 7. i=0 for first de-multiplexer, i=1 for second de-multiplexer and so on. The indices $A_i[0]$ to $A_i[7]$ represents *8* outputs from a de-multiplexer.

Block 5: This block consists of eight *4x1* multiplexers that are connected to *s-LUTs*. The Boolean expressions that represent logic operations in this block are shown below:

$$\begin{aligned}
& g_i(0..p+2) \leftarrow (A_4[i](p) + A_4[i](p+1) + A_4[i](p+2)) \cdot A_4[i](0..p+2) + \overline{(A_4[i](p) + A_4[i](p+1) + A_4[i](p+2))} \cdot \\
& (A_3[i](p) + A_3[i](p+1) + A_3[i](p+2)) \cdot A_3[i](0..p+2) + \overline{(A_4[i](p) + A_4[i](p+1) + A_4[i](p+2))} \cdot \\
& \overline{(A_3[i](p) + A_3[i](p+1) + A_3[i](p+2))} \cdot (A_2[i](p) + A_2[i](p+1) + A_2[i](p+2)) \cdot A_2[i](0..p+2) + \\
& \overline{(A_4[i](p) + A_4[i](p+1) + A_4[i](p+2))} \cdot \overline{(A_3[i](p) + A_3[i](p+1) + A_3[i](p+2))} \cdot \overline{(A_2[i](p) + A_2[i](p+1) + A_2[i](p+2))} \cdot \\
& (A_1[i](p) + A_1[i](p-1) + A_1[i](p+2)). A_1[i](0..p+2)
\end{aligned} \qquad \textbf{(6.5)}$$

In the above equation, i= 0 to 7 and i=0 refers to first multiplexer, i=1 refers to second multiplexer and so on. The output g_0 is from first multiplexer, g_1 is from second multiplexer and so on.

Block 6: In this block templates fetch their gray level values from *s-LUTs*. In hardware, it contains implementation of eight smaller Look-Up Tables *(s-LUTs)* using Content

Addressable Memory *(CAM)* and Read Only Memory *(ROM)* pairs. A combination of *CAM-ROM* is used because each *s-LUT* stores a very small fraction of values out of 2^p possible values, when templates are *p-bits* wide. The block diagram in Figure 17 shows the implementation of one *s-LUT*. The *CAM* stores the templates that are assigned to the *s-LUT* and *ROM* stores the gray level values. The Boolean equations illustrating the operations in this block are shown below:

$$\begin{aligned} &number\ of\ entries\ in\ a\ smaller\ Look-Up\ Table\ (sLUT)\ =\ 2^d-1 \\ &number\ of\ grey-levels\ =\ 256\ i.e.\ 8-bits \\ &x_i(0..d-1)\ \leftarrow\ CAM_i(g_i(0..p-1)), \\ &c_i(0..7)\ \leftarrow\ ROM_i(x_i(0..d-1) \\ &f_i(0...p+2) \leftarrow g_i(0...p+2) \end{aligned} \qquad \textbf{(6.6)}$$

In the above expressions, *i= 0* for *s-LUT* number *0, i=1* for *s-LUT* number *1* and so on. *i* varies from *0* to *7*.

When the contents of an *s-LUT* are large and cannot fit in a single memory module than more one memory modules or CAM-ROMs should be used. Figure 18 shows one *s-LUT* implemented using two CAM-ROM pairs. The CAM returns zero ROM address for entries not present in it and as a result of this output from all *ROMs* can be *OR* gated to get one valid result of that *s-LUT*.

Block 7: In this block gray level values of non-discarded templates are copied to templates that were discarded. The approach used is that, a discarded template is assigned gray level value of template that was not discarded and has nearest highest number appended to it in Step 2 of the algorithm. The Boolean expressions representing integrated circuit that perform operations in this block are shown below:

$$\begin{aligned} &a_i \leftarrow \overline{f_i(p)} \cdot \overline{f_i(p+1)} \cdot f_i(p+2), where\ i=0\ to\ 7 \\ &a_8(0..7) \leftarrow a_0 \cdot c_1(0..7)+a_1 \cdot c_2(0..7)+a_2 \cdot c_3(0..7)+a_3 \cdot c_4(0..7)+a_4 \cdot c_5(0..7)+a_5 \cdot c_6(0..7)+a_6 \cdot c_7(0..7)+a_7 \cdot c_8(0..7) \\ &a_9 \leftarrow a_0+a_1+a_2+a_3+a_4+a_5+a_6+a_7 \\ &a_{10}(0..7) \leftarrow a_9 \cdot a_8(0..7)+\overline{a_9} \cdot b_8(0..7) \\ &Gray_level_{t0}(0..7) \leftarrow a_{10}(0..7) \end{aligned} \qquad \textbf{(6.7)}$$

where $Gray_level_{t0}$ is the gray level value corresponding to template t_0.

$$
\begin{aligned}
& b_i \leftarrow \overline{f_i(p)}.\, f_i(p+1)\, .\, \overline{f_i(p+2)},\ where\ i = 0\ to\ 7 \\
& b_8(0..7) \leftarrow b_0 \cdot c_1(0..7) + b_1 \cdot c_2(0..7) + b_2 \cdot c_3(0..7) + b_3 \cdot c_4(0..7) + b_4 \cdot c_5(0..7) + b_5 \cdot c_6(0..7) + b_6 \cdot c_7(0..7) + b_7 \cdot c_8(0..7) \\
& b_9 \leftarrow b_0 + b_1 + b_2 + b_3 + b_4 + b_5 + b_6 + b_7 \\
& b_{10}(0..7) \leftarrow b_9 \cdot b_8(0..7) + \overline{b_9} \cdot d_8(0..7) \\
& Gray_level_{t1}(0..7) \leftarrow b_{10}(0..7)
\end{aligned} \tag{6.8}
$$

where $Gray_level_{t1}$ is the gray level value corresponding to template t_1.

$$
\begin{aligned}
& d_i \leftarrow \overline{f_i(p)}.\, f_i(p+1).\, f_i(p+2),\ where\ i = 0\ to\ 7 \\
& d_8(0..7) \leftarrow a_0 \cdot c_1(0..7) + a_1 \cdot c_2(0..7) + a_2 \cdot c_3(0..7) + a_3 \cdot c_4(0..7) + a_4 \cdot c_5(0..7) + a_5 \cdot c_6(0..7) + a_6 \cdot c_7(0..7) + a_7 \cdot c_8(0..7) \\
& d_9 \leftarrow d_0 + d_1 + d_2 + d_3 + d_4 + d_5 + d_6 + d_7 \\
& d_{10}(0..7) \leftarrow d_9 \cdot d_8(0..7) + \overline{d_9} \cdot e_8(0..7) \\
& Gray_level_{t2}(0..7) \leftarrow d_{10}(0..7)
\end{aligned} \tag{6.9}
$$

where $Gray_level_{t2}$ is the gray level value corresponding to template t_2.

$$
\begin{aligned}
& e_i \leftarrow f_i(p).\, \overline{f_i(p+1)}.\, \overline{f_i(p+2)},\ where\ i = 0\ to\ 7 \\
& e_8(0..7) \leftarrow e_0 \cdot c_1(0..7) + e_1 \cdot c_2(0..7) + e_2 \cdot c_3(0..7) + e_3 \cdot c_4(0..7) + e_4 \cdot c_5(0..7) + e_5 \cdot c_6(0..7) + e_6 \cdot c_7(0..7) + e_7 \cdot c_8(0..7) \\
& Gray_level_{t3}(0..7) \leftarrow e_8(0..7)
\end{aligned} \tag{6.10}
$$

where $Gray_level_{t3}$ is the gray level value corresponding to template t_3.

The four gray level values: $Gray_level_{t0}$, $Gray_level_{t1}$, $Gray_level_{t2}$ and $Gray_level_{t3}$ are stored at correct *(row, column)* coordinates in the output gray level image. The algorithm is pipelined in which each step can work independently on different inputs.

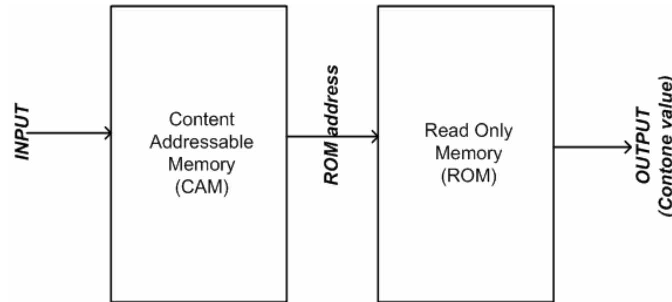

Figure 17: smaller Look-Up Table (s-LUT) implemented in terms of CAM and ROM

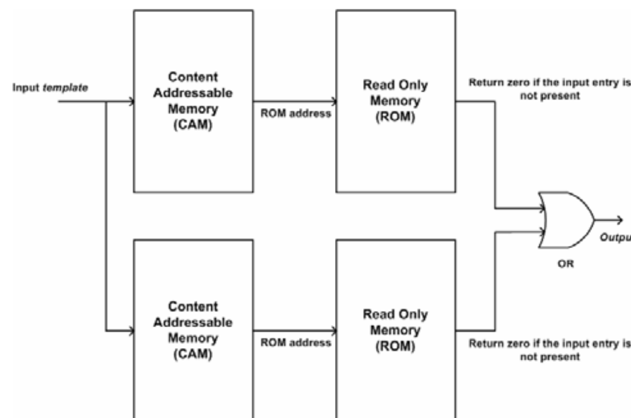

Figure 18: One *s-LUT* implemented using two ROMs and CAMs.

7 Hardware Implementation

The computational part of the proposed algorithm with k=4 and N= 8 is implemented using *VHDL* language on Altera Complex Programmable Devices *(CPLD)*. It consumes two *CPLDs* and external *CAMs* and *SRAMs* are used to store *s-LUTs*. Figure 18 illustrates the system block diagram. The *CPLDs* used are Altera [9] MAX II and *CAM* and *SRAM* are implemented in Altera APEX *FPGA* devices but can be replaced with discrete devices in future designs. The *CPLD I* contains the proposed parallelization algorithm and *CPLD II* contains the pixel compensation circuit. The assignment of template numbers to incoming "19pels" is performed partially in both *CPLD I & II* in order to fit the design within *MAX II* pin count and to reduce fitting complexity of CPLD I.

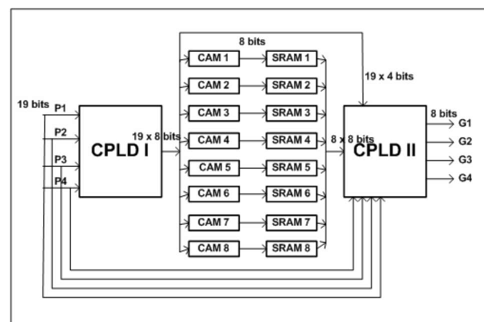

Figure 19: Block diagram of the algorithm implementation.

In Figure 17, *CPLD I* accepts 4 *"19pels"* from the halftone image and sent each *"19pels"* according to value return by *XM* function to its four outputs out of total eight output ports. The ports from *CPLD I* are connected to *CAMs* that are connected to *SRAMs*. The grey level values from *SRAMs* go to *CPLD II* where circuits for gray level value copying are present. The *CPLD II* gives grey level values in the correct sequence, i.e., *G1* corresponds to contone value of P_1 and so on. The results of *CPLD* implementation obtained from Fitter and Timing analyzer tools present in Altera Quartus II 5.0 are tabulated in Table I.

Table I: Results of CPLD implementations

Device	Area	I/O pins	Clock Frequency
CPLD I EPM2210GF324I5	Logic elements: 2049/2210	261/272	33.86 MHz
CPLD II EPM2210GF324I5	Logic elements: 262/2210	262/272	164.85 MHz

8. Conclusion

The parallelization of LUT inverse halftoning is performed which has the following advantages: (a) In place of one pixel, now up-to k pixels can be fetched and inverse halftoned simultaneously, (b) N number of smaller Look-Up Tables *(s-LUTs)* are used in place of a single LUT, however, total entries in all *s-LUTs* remain equal to the entries present in the single LUT of serial LUT method, and (c) Fast parallel inverse halftone operation can be performed on fast hardware instead of on embedded hardware-software.

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