Flexible Signals and Images Lossless Compression Chip Design for IoT and Industry 4.0

Shih-Lun Chen,
Department of Electronic Engineering
Chung Yuan Christian University
Taoyuan City, Taiwan
chrischen@cycu.edu.tw

Tsun-Kuang Chi
Department of Electronic Engineering
Chung Yuan Christian University
Taoyuan City, Taiwan
balance578942@gmail.com

Chiung-An Chen*
Department of Electrical Engineering
Ming Chi University of Technology
New Taipei City, Taiwan
joannechen@mail.mcut.edu.tw

Chi-Hao Liao
Department of Electronic Engineering
Chung Yuan Christian University
Taoyuan City, Taiwan
daughtry1745@gmail.com

Ting-Lan Lin,
Department of Electronic Engineering
Chung Yuan Christian University
Taoyuan City, Taiwan
tinglan@cycu.edu.tw

***Abstract*—This paper presents a lossless compression algorithm and its chip design for signals and images applied to Internet of Things (IoT) and industry 4.0. Since the sensing signals, such as thermal, photo, gas, etc., are important for IoT and industry 4.0, a lossless signal compression technique based on an adaptive prediction and a hybrid entropy coding is proposed in this study. In addition, since applications of images are more and more important for IoT and industry 4.0, a flexible lossless image compression technique based on pixel restoration, median edge detection, and a hybrid entropy coding was developed for the proposed algorithm. The proposed algorithm can provide lossless compression for images in different types which includes grayscale, color (RGB), color filter array (CFA), and infrared images. In order to meet the demands of tiny and low-power-consumption for IoT, the proposed algorithm was realized by VLSI technique. A hardware sharing and pipeline scheduling techniques were used to reduce hardware cost and improve the operating frequency of the proposed design. The proposed design was synthesized by using a TSMC 0.18-μm CMOS process and it contained 5.46 k gate counts. Compared with previous JPEG-LS based designs, this work has benefits of better compression rates, lower cost, lower memory requirement and more lossless compression functions than previous designs. It is suitable for development of IoT and industry 4.0.**

Keywords—Color Filter Array; Infrared Image; Industry 4.0, Internet of Things; Lossless Compression; VLSI

I. INTRODUCTION

Recently, Internet of Things (IoT) have been developed in high-speed and applied to industry 4.0. The concept of IoT is using sensors to capture information from environment and then collecting these sensing data for cloud and big data analysis. The sensing data, such as thermal, gas, photo, motion, infrared, etc., are interesting in industry. In recent years, the data of grayscale, color, color filter array (CFA) and infrared images become more and more important in IoT. Since the amount of sensing and image data are very huge and the bandwidth of wireless transmission and storage space are limited, the signal and image compression techniques are necessary to be developed.

In order to avoid losing the information in compression process, lossless data compression methodology is useful for the purpose. The lossless signal and image compression techniques are widely used in biomedical applications. It is popular and important applying in body signals and biomedical images compression. Hence, many efficient lossless compression algorithms had been developed. A first-order prediction and Huffman coding lossless signal compression algorithm for wireless thermal sensing node was proposed in [1]. A second-order prediction and a two-stage Huffman coding algorithm was presented in [2]. Recently, a fuzzy decision prediction [3] and an adaptive trending prediction [4] were proposed for advancing lossless body signal compression. These algorithms mentioned above are low-complexity lossless signal compression algorithms.

For lossless image compression, JPEG-LS based algorithms [5-8] are popular because of its low complexity and low memory requirement. A hardware architecture based on JPEG-LS was proposed in [5]. An efficient JPEG-LS based algorithm [6] and a high-performance ASIC implementation [7] were proposed. A fully pipelined architecture for LOCO-I algorithm was presented in [8]. A new approach for lossless CFA image compression VLSI design was proposed in [9]. A high-performance and VLSI-oriented lossless image compression engine based on FELICS algorithm was presented in [10]. To be able to increase the correlation between neighboring pixels of CFA image, a context-free lossless image compression algorithm and VLSI design was proposed in [11].

Although the algorithms and VLSI implementations mentioned above are high-performance and low-complexity methodologies, each of previous studies supported for one signal or one image compression only. With the various and wide applications of IoT and industry 4.0, it is necessary to develop a more flexible and multi-function lossless compression chip design. This paper presents a flexible lossless compression algorithm and

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its VLSI design. The proposed flexible algorithm and design can support both of signal and image compression. Moreover, the proposed flexible algorithm and design can support various types of images such as grayscale, color (RGB), color filter array (CFA), and infrared images.

The organization of this paper is as following: Section II introduces the concept of the proposed lossless compression algorithm. Section III describes the VLSI architecture and simulation results for the proposed algorithm and chip design. Finally, a brief conclusion is presented.

II. Lossless Compression Algorithm

Figure 1 illustrates the flowchart of the proposed signal and image lossless compression algorithm. It includes a signal prediction function to predict the sensing signals, a pixel restoration to restore color pixels for CFA images, an image prediction to predict the grayscale, color (RGB), CFA and infrared images. In order to reduce the complexity of the proposed lossless compression algorithm and save the hardware cost of the proposed lossless compression design, the Huffman coding, improved Golomb-Rice coding, and VLC coding packer were shared for the signal and various types of images. The details of each function will be described as following.

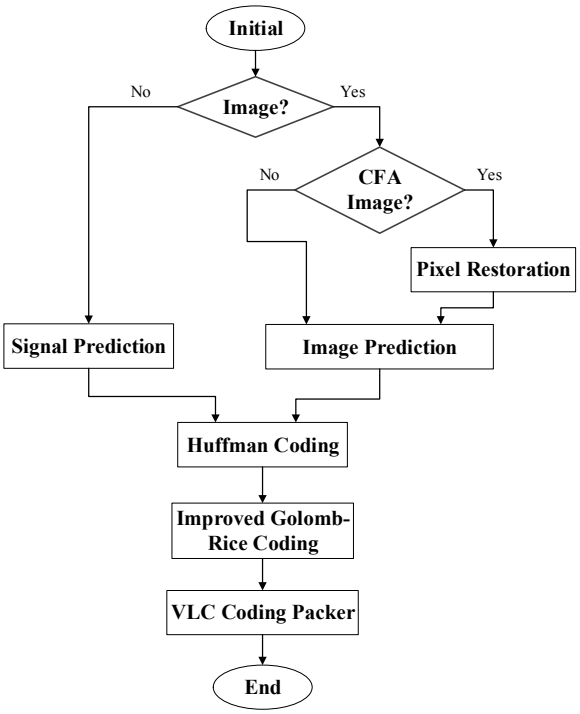


Fig. 1 Flowchart of the proposed lossless image compression algorithm

A. Signal Prediction

There are two signal prediction methods used in the proposed algorithm as shown in Fig. 2. The first method is slope prediction method, in which the value of current sample x(n) can be predicted by using the past three samples of x(n-1), x(n-2) and x(n-3) as shown in Fig. 2 (a). The value of *diff1* is the difference between x(n-1) and x(n-2) and the value of *diif2* is the difference between x(n-2) and x(n-3). The concept of the slope prediction method is based on slope-feature for prediction. The prediction will be accurate when the relation of samples in the signal is linear. The slope prediction method is suitable for the signals without violent changing. The other signal prediction method is trend prediction, which predicts the value of current sample x(n) by using two slopes *diff2* and *diff3*. Hence, the trend prediction method demands the values of past three samples x(n-1), x(n-2) and x(n-3) to find the trend of signals and then predict the value of current sample x(n). Since the proposed two signal prediction methods are suitable for different situations in the signals, an adaptive technique is used to select one of these two signal prediction methods. For example, if the relationship in past three samples are close to linear, the controller will select the slope prediction method to predict the value of the next sample. Otherwise, the controller will select trend prediction method to predict the value of the next sample. By using the adaptive technique, the signal prediction function is smart to select a suitable method for signal prediction. Hence, it improved the accuracy of signal prediction and further to improve the compression rates of the signals for the proposed lossless compression algorithm and design.

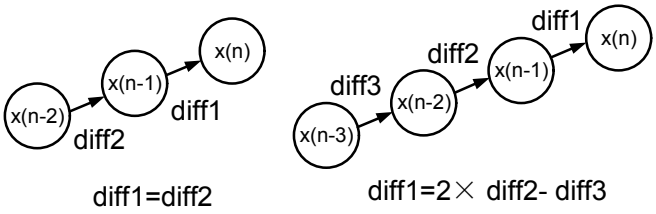


Fig. 2 Signal prediction methods. (a) Slop prediction (b) Tread prediction

B. Image Prediction

There are two modes used in JPEG-LS standards. One is regular mode and the other is run mode. Since the complexity and memory requirement of run mode is quite a few, the techniques of the regular mode are used in the proposed algorithm. In the regular mode, a median edge detection is used for prediction. The predicted value of the value of the current pixel *x* can be predicted by selecting one of three situations. For example, if the value of *c* is greater than the maximum value of *a* and *b*, the predicted value of current pixel *x* will be assigned to the minimax value of *a* and *b*. The positions between *a*, *b*, *c* and *x* are shown in Fig. 3. *T*he predicted value of the current pixel *x* can be obtained according to the relationship of *a*, *b* and *c* as shown in Eq. (1). By using the median edge detection technique, the accuracy of prediction for grayscale, color (RGB), CFA and infrared images can be improved efficiently and the complexity of prediction is limited. It is suitable for hardware implementation.

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$$x = \begin{cases} \min(a,b), & c \geqq \max(a,b) \\ \max(a,b), & c < \min(a,b) \\ a+b-c, & others \end{cases} \quad (1)$$

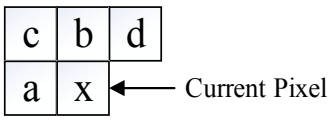
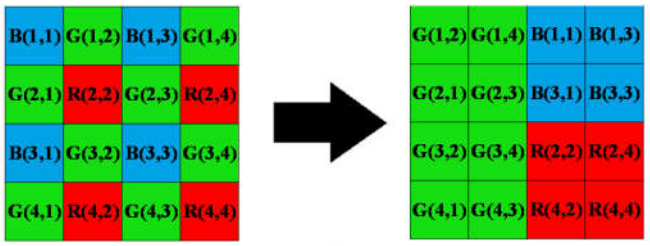


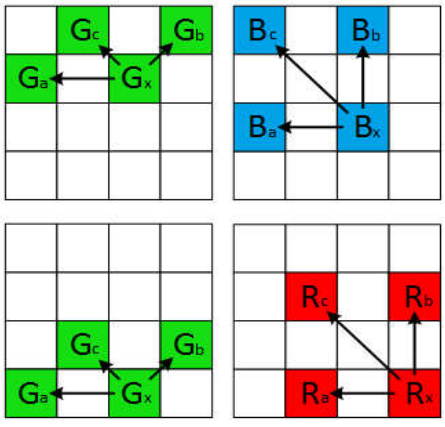
Fig. 3 Positions between current and neighboring pixels

C. Pixel Restoration

Since three colors R, G, and B pixels are integrated a CFA format image, the correlation between neighboring pixels are very low. Hence, in order to improve the accuracy of prediction, it is necessary to restore the pixels for the CFA images. Fig. 4 (a) shows the relationship between a CFA image and a restored image, in which the R, G and B pixels in CFA image are replaced into three collections. It provides an efficient way to increase the correlation of neighboring pixels and further to improve the accuracy of prediction. Furthermore, to consider the requirement of memory, the proposed algorithm does not change the arrangement of the color pixels. It only redefines the positions of a, b, c, and the current pixel x for prediction in Eq. (1), as shown in Fig 4 (b). Hence, there is no additional memory requirement for the proposed restoration. The proposed restoration technique can increase the accuracy of prediction further to improve the compression performance of the CFA images.



(a)



(b)

Fig. 4 (a) CFA image restored to R, G and B collections. (b) The redefined positions of *a*, *b*, *c* and *x* for prediction.

D. Huffman Coding

After prediction process, a variable-length coding (VLC) algorithm called Huffman coding was used for entropy coding. Since the Huffman coding is designed based on the probability distribution of data, it is popular for lossless data compression. Fig. 5 illustrates an example of Huffman coding tree, in which the prediction error value has the most probability and it will be encoded by the shortest Huffman code. Since the decoding process is from the root node of the Huffman tree to find the decoded value in the leaf node, the decoded target is unique. So, the Huffman coding method is a lossless compression method.

The most important feature of Huffman encoding tree is that there is one branch for each encoding datum. Hence, the Huffman coding tree will grow huge number of branches when the source data distribute in a large range. For this reason, in the proposed entropy algorithm, the Huffman coding is used for encoding the data with most of probabilities and others will be encoded by the Golomb-Rice coding method illustrated in the next section. Based on the proposed hybrid entropy coding technique, most of prediction errors will be encoded by Huffman coding and other prediction errors will be encoded by Golomb-Rice coding, which will limit the complexity and hardware cost of the Huffman coding tree and help to develop a cost-efficient entropy encoder design.

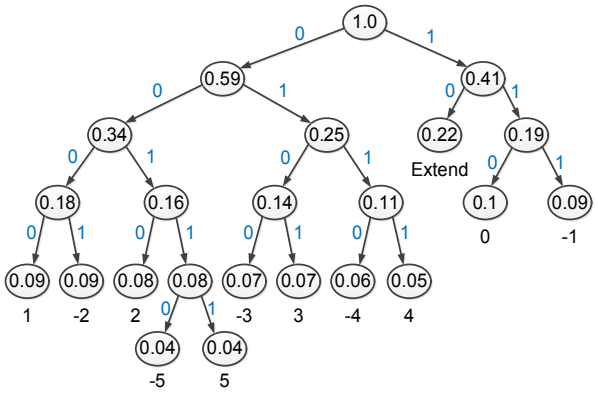


Fig. 5 An example of Huffman coding tree

E. Improved Golomb-Rice Coding

Golomb-Rice (GR) coding is also a variable-length coding method, which can encode the data with sign information. The Golomb-Rice encodes data according to the degree of data rather than probability of data. Hence, the smallest value will be encoded as the shortest codes by Golomb-Rice coding. In contrast, the largest value will be encoded as the longest codes by Golomb-Rice coding. It used the relation between the quotient and remainder to encode the data. Thus, the encoding data *x'(n)* can be obtained by

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$$x'(n) = \begin{cases} 2 \times x(n) - 2 \times k, & x(n) \geq 0 \\ 2 \times |x(n)| - 1 - 2 \times k, & x(n) < 0 \end{cases} \quad (2)$$

where *k* is the first position value in GR table and *x(n)* is the value of the prediction error in the current sample or pixel.

Since the Golomb-Rice coding will provide all the codes for positive and negative numbers for encoding, the entropy table is quite a longe. Hence, the Golomb-Rice algorithm adds a sign bit is more efficient than traditional Golomb-Rice coding. The improved Golomb-Rice coding technqiue can limit the size the Golomb-Rice table, which can reduce the hardware cost efficiently.

III. VLSI Architecture and Simulation Results

A. Lossless CFA Images Compression Results

In order to evaluate the performance of the proposed lossless compression algorithm for CFA images, four testing images Lena, Airplane, Peppers and House widely used in image processing fields were selected, as shown in Fig. 6. TABLE I lists the comparisons of compression rates of JPEG-LS [6-8], context-free [11] and the proposed lossless compression algorithm. As results shown, the proposed algorithm improved the average compression rate in these four testing images by over 20.4% and 1.4% than previous studies [6-8] and [11], respectively.



Fig. 6. Four CFA testing images (a) Lena (b) Airplane (c) Peppers (d) House.

TABLE I. Comparisons of Lossless Compression Rate for Four CFA Images

CFA Images	*JPEG-LS [6][7][8]*	*Context-Free [11]*	*This Work*
Lena	1.0744	1.4551	1.4553
Airplane	1.5364	1.5309	1.5850
Peppers	1.0402	1.4703	1.4642
House	1.2792	1.4028	1.4359
Average	1.2326	1.4648	1.4851

Compression Rate = Compressed Data/Original Data

B. Lossless Infrared Images Compression Results



Fig. 7 Eight testing infrared images from [12] with (a) Image 01, (b) Image 02, (c) Image 03, (d) Image 04, (e) Image 05, (f) Image 06, (g) Image 07, and (h) Image 08.

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TABLE II. COMPARIONS OF PREVIOUS LOSSLESS COMPRESSION DESINGS WITH THIS WORK

	[6]	*[7]*	*[8]*	*[9]*	*[10]*	*[11]*	*This work*
Year	2007	2007	2009	2009	2010	2015	2017
Compression Functions	Color-Image	Color-Image	Color-Image	CFA-Image	Color-Image	CFA-Image	Signal Color-Image CFA-Image Infrared-Image
Algorithm	JPEG-LS	JPEG-LS	JPEG-LS	LOCO-I	FELICS	Context-Free	Adaptive Prediction Hybrid Entropy
Process	0.18 μm	0.18 μm	FPGA	0.18 μm	0.18 μm	0.18 μm	0.18 μm
Operating Frequency	20 MHz	183 MHz	21 MHz	20~24 MHz	200 MHz	200 MHz	200 MHz
Resolution	640	640	640	640	640	640	640
Gate Counts	50 k	27.68 k	37.3 k	19.5 k	11.57 k	5.54 k	5.46 k
Memory (bits)	29 k	20.81 k	146 k	17.5 k	15.2 k	10.2 k	10.2 k
Normalized Area	9.16	5.07	6.83	3.57	2.12	1.01	1

The normalized core area is normalized by the NAND-equivalent gate counts

TABLE III. ORIGINAL DATA AMOUNT, COMPRESSED DATA AMOUNT, AND COMPRESSION RATES FOR EIGHT INFRARED IMAGES BY THE PROPOSED LOSSLESS COMPRESSION ALGORITHM

Infrared Images	***Original Data***	***Compressed Data***	***Compression Rates***
Image 01	331,830 Bytes	159,841 Bytes	2.076
Image 02	331,830 Bytes	160,692 Bytes	2.065
Image 03	331,830 Bytes	159,918 Bytes	2.075
Image 04	331,830 Bytes	163,980 Bytes	2.0236
Image 05	331,830 Bytes	161,789 Bytes	2.051
Image 06	331,830 Bytes	176,037 Bytes	1.885
Image 07	331,830 Bytes	169,128 Bytes	1.962
Image 08	331,830 Bytes	172,738 Bytes	1.921
Average	331,830 Bytes	165,516 Bytes	2.01

Compression Rate = Compressed Data/Original Data

To be able to evaluate the performance of the proposed lossless compression algorithm for infrared images, eight infrared images from [12] were selected as infrared image dataset. Fig. 7 shows these eight testing infrared images. The original data amount, compressed data amount and compression rates by the proposed lossless compression algorithm were listed in TABLE II. As results shown, more than 50% average data amount of the infrared images can be reduced by the proposed lossless compression algorithm. The proposed lossless infrared image compression technique can decrease the bandwidth of wireless transmission and storage space for IoT, big data, and clould applications.

C. VLSI Architecture and Chip Resutls

The VLSI architecture of the proposed flexible lossless signal and image design is shown in Fig. 8. It is composed of a register bank cooperating with a memory buffer to prepare neighboring pixels information for prediction, a one dimension register array for slope and trend signal prediction, a pixel restore module for CFA restoration, a signal predictor for thermal signal prediction, an image predictor for grayscale, color (RGB), CFA and infrared images prediction, an Huffman and improved GR encoders for entropy coding, and a VLC coding packer for collecting VLC codes into a bit-stream. The proposed lossless compression design also includes a controller to handle the processes for different signals and images well. In order to reduce the hardware cost, the Huffman encoder, improved GR encoder, and VLS coding packer were shared for signal and image compressions. In addition, a pipeline scheduling design scheme was also used to improve the performance and throughput of the proposed lossless signal and image compression design.

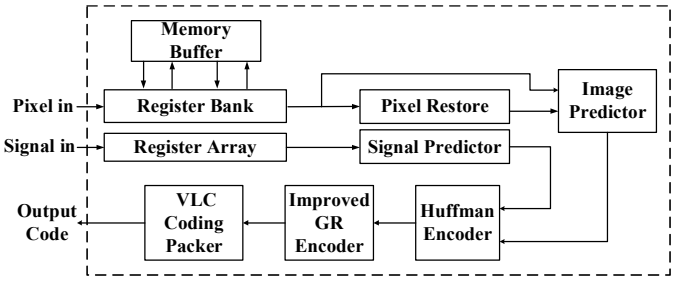


Fig. 8 VLSI architecture of the proposed lossless signal and image compression design.

The proposed lossless signals and images compression design was realized by using a hardware description language (HDL) Verilog. The VLSI results illustraed in TABLE III were synthesized by using Design Vision tool with TSMC 0.18-μm process standard cells. TABLE III lists the comparisons of the compression functions, algorithm, process, operating frequency, resolution, gate counts, memory, and normalized area of previous lossless compression designs [6-11] and this work. As results shown, this design supports four lossless compression functions

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including signal, grayscale, color (RGB) image, CFA image, and infrared image, which is more powerful than previous design [6-11] to support only one lossless compresion function.

Moreover, the gate counts and memory requirement of this work are less than previous designs [6-11], which means the proposed design has the benefits of lower cost and less power consumption than previous designs [6-11]. Compared with the previous studies, this design has benefits of higher performance, lower cost, lower memory requirement, and more lossless compression functions than previous designs. In summary, this study provided an efficient multi lossless compression functions for IoT and industry 4.0.

CONCLUSION

A flexible signals, grayscale image, color image, CFA image, and infrared image lossless compression chip design is presented for IoT and industry 4.0 applications. Compared with the previous lossless compression designs, this work advanced the compression rate, cost, memory, and functions than previous studies. The proposed lossless compression algorithm and design provided a powerful and cost-efficient lossless compression solution for IoT and industry 4.0.

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