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Energy-Efficient, Low Memory Listless SPIHT Coder for Wireless Multimedia Sensor Networks

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Abstract

The set partitioning in hierarchical trees (SPIHT) consists of linked lists to track coefficients, thus requiring large memory. In this paper, we propose an energy-efficient low memory listless SPIHT image transmission scheme which uses lifting scheme to calculate the discrete wavelet transformed coefficients of image. A state table is used instead of lists which uses 0.25 bit per coefficient marker to keep track of set partitions, thus replacing dynamic memory. The reduction in memory requirement facilitates image transmission over energy constrained wireless sensor network. Simulation results show that the low memory listless SPIHT coder saves 96.35% energy when compared to other state of art coders**.**

Keywords: Listless Set Partitioning in Hierarchical Trees (Listless SPIHT), Lifting Wavelet transform, Wireless sensor network, Energy efficient

I. INTRODUCTION

A. Motivation

In recent years, low cost, low power and tiny complementary metal oxide semiconductor (CMOS) cameras have grown interest in wireless multimedia sensor network which is a network of interconnected devices that are deployed to recover multimedia data (i.e. still image, audio and video) [1][2]. A huge amount of data is produced by camera sensors which are constrained in terms of memory, computation and energy. The compression of data in an efficient way before processing and transmission over sensor network without degrading the image quality is a challenging task. Low memory image compression has achieved importance in applications where processing and storage on portable devices (such as smart phones, tablets etc.), wireless transmission, streaming data on the Internet and transmission in band limited channels is considered [3].

Discrete Wavelet Transform (DWT) has multiresolution image representation which provides efficient coding algorithms that outperforms the DCT-based JPEG standard. Shapiro introduced the original zero tree algorithm, called embedded zerotree wavelet (EZW) which is efficient and computationally simple technique [4]. The performance of EZW is further enhanced by presenting a more efficient and faster technique called set partitioning in hierarchical tree (SPIHT) developed by Said and Pearlman which has excellent rate–distortion performance [5]. Embedded block coding with optimized truncation (EBCOT) algorithm [6] adopted in JPEG2000 provides higher compression efficiency than SPIHT but it is very complex and computationally intensive as it needs extra memory allocation. For hardware constraints, SPIHT is preferred over EBCOT. However, for high resolution images, SPIHT needs large memory bank which in turn increases cost of hardware and hence consumes more energy.

SPIHT coder uses three encoding/decoding lists to store the indices of wavelet coefficients. At high rates, list nodes can be more in number than the wavelet coefficients. The drawback of SPIHT is its high memory requirement to maintain these lists which increases the implementation cost. No list SPIHT (NLS) was proposed in [7] with performance very close to original SPIHT. NLS uses special markers placed in state table which is a fixed size array, with about four bits per coefficient to keep track of set partitions.

In this paper, a low memory listless SPIHT image coder is proposed which minimizes the total energy consumption by the sensor network.

B. Related Research

Large memory is needed in two-dimensional DWT with limited resources. Chrysafis [8] developed line based wavelet transform which read images line by line, buffering few lines and store compressed data in those buffers after compression, thus reducing memory. For a six-level transform of a 512x512 image it uses 26kB RAM [9]. J. Oliver and M. Malumbres [10] applied lifting algorithm to the line based wavelet transform, reducing memory requirement and improve communication among buffers. Bao and Kuo [11] proposed a block based implementation of DWT with similar memory resources as line based transform. Wavelet coefficients are generated in fixed size blocks and encoded by a low complexity binary description coding scheme which is used in the design of image codec with low implementational complexity. Yang *et al.* [12] proposed a block based VLSI architecture implementing lifting based DWT with reduced memory requirements. Chew *et al.* [13], [14] presented very low memory strip based architectures for image and video for wireless multimedia sensor networks where strip buffers are used to store the minimum number of lines, thus reducing memory. Bhattar [15] presented strip based coding technique for large images in which line based wavelet transform coefficients are stored in strip buffer using significantly less memory. Pipeline architecture is developed coding strip-by-strip for efficient utilization of bandwidth. Rein [16] introduced fractional wavelet filter that computes fractional values of DWT with about 2kB RAM transforming a 256x256 image using fixed point arithmetic.

Some of the low memory methods related to our work are briefly reviewed and discussed. Lin and Burgess [17] proposed a listless zerotree coder (LZC) for color images which is an extension of Su and Wu's Embedded Recursive Zerotree (ERZ) coding scheme [18]. This uses flag maps to reduce the memory requirement at higher bit rates and use markers to store the wavelet coefficients abandoning the lists. Also the sorting pass and refinement pass are merged into one resulting into simpler and faster hardware implementation. This work has been expanded for arbitrarily shaped objects proposed by C.Y. Su and B.F. Wu [19] using compact emplacement instead of regular emplacement with further reduction in memory at the cost of high execution time. In NLS [7], sparse markers are placed and updated during SOT partitioning. When breadth first scan moves through the lower nodes of trees, large sections of insignificant pixels are skipped. NLS uses four bits per coefficient whereas LMSPIHT [20] uses three bits per coefficient to store state information. Many listless versions of SPECK are proposed with reduced markers. Latte [21] proposed LSK with 2 bits per coefficient to store encoded information.

Over the past years, significant efforts are done which reduces the energy consumption of the wavelet-based image coders. D. Pham and S.M. Aziz [22] presented architecture and protocol that uses low complexity JPEG2000 image compression technique in energy constrained WSN that consumes less energy and is fast. Sensor nodes are power constrained. H. Wu and A. Abouzeid [23] proposed a distributed JPEG2000 that distributes the amount of work of wavelet transform to several nodes from source to the sink, thus eliminates computation power restriction of single nodes and increasing the lifetime of network upto four fold. M. Nasri *et.al.*[24] attempted to conserve energy using Skipped high pass subbands. Here multiple packets are combined, processed and multiple copies are transmitted over network to reduce lifetime. The computational energy saving for SHPS technique is high for different compression levels, hence energy is conserved. D. M. Pham and S. M. Aziz [25] presented a reliable image transmission protocol to remove packet errors and an efficient object extraction algorithm is also given that reduces the energy consumption of transmitted image. M. Nasri *et. al*. [26] proposed a priority image compression technique based on wavelet transformation. A. Chefi and G. Sicard [27] proposed a low power SPIHT based image compression technique with hardware and software implementation in terms of energy conservation. Y.Rahman et.al. [28] presented a novel object extraction technique that transmits image segments minimizing in-node energy consumption. W. Wang *et.al*. [29] proposed a novel image component technique for efficient energy image transmission with improvement in peak signal to noise ratio.

The organization of the paper is as follows: Section 2 briefly presents the background of lifting wavelet transform, SPIHT, listless SPIHT coder and energy consumption analysis. Section 3 explains linear indexing and state table marker in brief and then presents the proposed coder. Section 4 presents simulation results and discussions. Section 5 concludes the paper.

II. BACKGROUNG

Here, we briefly discuss lifting scheme for wavelet transform, Set partitioning in hierarchical trees (SPIHT) algorithm, listless SPIHT and energy consumption model.

A. Lifting Wavelet Transform

Sweldens proposed lifting scheme for second generation fast wavelet transform [30][31]. Lifting scheme require less operations and performs in-place computation, so it does not require extra memory buffer. The wavelet transform has two finite impulse response (FIR) analysis filters $\breve{h}$ and $\breve{g}$ and two FIR synthesis filters h and g. For the perfect reconstruction of a signal, the conditions are given below:

$$
\begin{aligned}
&h(z)\,\breve{h}(z^{-1})+g(z)\,\breve{g}(z^{-1})=2 \qquad (1)\\
&h(z)\,\breve{h}(-z^{-1})+g(z)\,\breve{g}(-z^{-1})=0.
\end{aligned}
$$

where h(z) is the z-transform of FIR filter h consisting even coefficients $h_e(z)$ and odd coefficients $h_o(z)$. The polyphase representation of analysis filters and synthesis filters is given by

$$h(z)= h_e(z^2)+z^{-1}h_o(z^2) \qquad (2)$$

$$g(z)= g_e(z^2)+z^{-1}g_o(z^2) \qquad (3)$$

$$\breve{h}(z)= \breve{h}_e(z^2)+z^{-1}\breve{h}_o(z^2) \qquad (4)$$

$$\breve{g}(z)=\breve{g}_e(z^2)+z^{-1}\breve{g}_o((z^2) \qquad (5)$$

The polyphase matrix $\acute{P}(z)$ and its dual P(z) can be expressed as

$$\acute{P}(z) = \begin{bmatrix} \breve{h}e(z) & \breve{h}o(z) \\ \breve{g}e(z) & \breve{g}o(z) \end{bmatrix} \qquad (6)$$

$$P(z) = \begin{bmatrix} he(z) & ho(z) \\ ge(z) & go(z) \end{bmatrix} \qquad (7)$$

The lazy wavelet transform (polyphase transform) subsamples the even and odd coefficients of input signal and produce low pass and high pass output samples, f_L and f_H respectively. The forward Discrete Wavelet Transform (DWT) and inverse DWT can be written as follows:

$$\begin{bmatrix} fL(z) \\ fH(z) \end{bmatrix} = \acute{P}(z) \begin{bmatrix} xe(z) \\ z^{-1}xo(z) \end{bmatrix}, \qquad (8)$$

$$\begin{bmatrix} xe(z) \\ z^{-1}xo(z) \end{bmatrix} = P(z) \begin{bmatrix} fL(z) \\ fH(z) \end{bmatrix} \qquad (9)$$

If the determinant of polyphase matrix $\acute{P}(z)$ is 1, then the analysis filter ($\breve{h}$,$\breve{g}$) as well as synthesis filter (h,g) are complementary. The polyphase matrix $\acute{P}(z)$ can be factorized into primal and dual lifting using Laurent polynomials $\acute{s}_i(z)$ and $\dot{t}_i(z)$ for $1 \leq i \leq n$ and a constant K as

$$\acute{P}(z) = \left(\prod_{i=1}^{n} \begin{bmatrix} 1 & \acute{s}_i(z) \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \dot{t}_i(z) & 1 \end{bmatrix}\right) \begin{bmatrix} K & 0 \\ 0 & 1/K \end{bmatrix} \qquad (10)$$

Primal Lifting Dual Lifting Scaling and its dual as

$$P(z) = \left(\prod_{i=1}^{n} \begin{bmatrix} 1 & 0 \\ -t_i(z^{-1}) & 1 \end{bmatrix} \begin{bmatrix} 1 & -s_i(z^{-1}) \\ 0 & 1 \end{bmatrix}\right) \begin{bmatrix} 1/K & 0 \\ 0 & K \end{bmatrix} \qquad (11)$$

The lifting based forward wavelet transform consists of following steps:

(i) Apply the lazy transform by decomposing the input signal into even and odd samples.
(ii) The primal and dual lifting steps are executed.
(iii) The output streams are scaled by 1/K and K to produce low pass and high pass subbands respectively.

The inverse DWT performs these steps in reverse order.

B. SPIHT

SPIHT [5] is a simple and highly efficient scheme that works in a progressive way. It consists of three passes: initialization, sorting and refinement and three linked lists: List of Insignificant pixels (LIP), List of Insignificant sets (LIS) and List of Significant Pixels (LSP). During initialization, a threshold is set according to the maximum value of the coefficient in an image. All the pixels of LL band are kept in LIP and tested against threshold for significance. These pixels if found significant are send to LSP which is kept initially empty otherwise they remain in LIP. Now the tree sets are tested for significance which is in LIS that consists of tree nodes except tree root. These tree sets are divided into Type A or Type B sets if found significant. Finally, in the refinement pass, output the n^{th} bit. The threshold is updated i.e. reduced by a factor of two and repeat the whole process until desired bit budget is achieved.

C. Listless SPIHT

No list SPIHT is a listless version of SPIHT which uses markers in place of lists to keep track of set partitions [7]. It uses same set partitioning rules as SPIHT and performs strictly breadth first search. Special markers are placed at lower nodes of trees and updated. A large part of image is skipped performing breadth first search scan. It consists of three passes: Insignificant Set Pass, Insignificant Pixel Pass and refinement pass. The state table stores information with 4 bits per coefficient marker.

D. Energy Consumption Analysis

A multihop wireless sensor network with few assumptions is considered. The characteristics of all sensors are the same. During the transmission of an image from source to destination, the energy of a node remains the same. When an image is transmitted from source to destination with n intermediate nodes in between, a steady network path is established.

A radio transceiver energy model is considered for energy analysis [32]. The energy consumption in k-byte message transmission is

$$E_{TX}=(\mathcal{E}_e+\mathcal{E}_a d^{\alpha}).k \tag{12}$$

The energy consumption in k-byte message reception is

$$E_{RX}=\mathcal{E}_e.k \tag{13}$$

The energy consumption in DWT of k-bytes is

$$E_{DWT}=\mathcal{E}_{DWT}.k \tag{14}$$

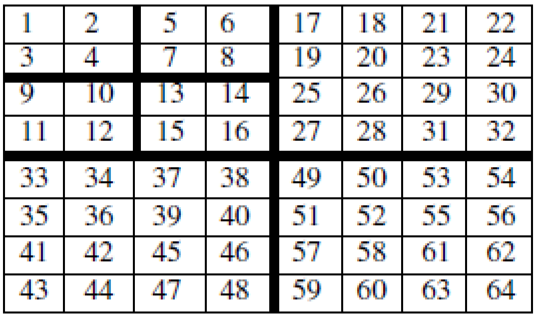
For k-bytes of message, the energy consumed in entropy coding is given by

$$E_{ENT}=\mathcal{E}_{ENT}.k \tag{15}$$

III. PROPOSED CODER

A. Linear Indexing

Linear indexing allows a single number instead of two (one for row and another for column) to represent a coefficient of an image. Consider an image Ỉ which consists of Ṙ rows and Ḉ columns. The linear index i varies from 1 to Ỉ where Ỉ= ṘḈ. Consider an example of wavelet transformed image of size 8x8 shown in Figure 1 that arranges the coefficients from higher energy to lower energy with one index.



1	2	5	6	17	18	21	22
3	4	7	8	19	20	23	24
9	10	13	14	25	26	29	30
11	12	15	16	27	28	31	32
33	34	37	38	49	50	53	54
35	36	39	40	51	52	55	56
41	42	45	46	57	58	61	62
43	44	47	48	59	60	63	64

Figure 1. Two level linear indexing for an image of size 8x8

It performs one operation on set coefficients instead of two. Linear indexing uses single level of iteration to represent tree set coefficients, viz. ỉ= ỉ+1, ỉ+2, ỉ+3, ỉ+4. The length of linear indices for offsprings in a tree is 4 and for grandchildren it is 16. Linear indexing performs Z-scan that facilitates breadth first search of set partitions.

B. State Table Marker

The state table is named as mark which is an array of length Ḯ that stores the magnitude part of the coefficients and sign part as array *sign*. No symbols are used to mark pixels. Only two markers are placed in the state table that keeps track the set partition coefficients, 1 bit per coefficient. The markers which are used, given below:

MDES: The tree root pixel is the direct child in a set consisting of all descendants of its parent.

MGRANDES: The tree root pixel is the grandchild in a set consisting of all granddescendants of its grandchild excluding the children of grandparent root pixel.

C. Low Memory Listless SPIHT (LMLS)

Low memory listless SPIHT is a listless form of SPIHT with reduced markers. This replaces the linked lists to store the coefficients of image of size RxC with small size static memory. An image is transformed using lifting wavelet transform. These transformed coefficients are stored in linear array with the high energy coefficients storing first in descending order. The low memory listless SPIHT follows the set partitioning method of listless SPIHT (NLS). The pseudo code of the proposed coder is given below. It starts encoding in a progressive fashion starting from most significant bit plane with a set threshold decrementing down to zero until a prescribed bit budget is met. This coder does not use any marker to mark the state of pixels. This uses only two markers to mark the state of descendant and granddescendant sets MDES and MGRANDES respectively.

Pseudo Code

Insignificant Pixel Pass

```
ỉ=0, while ỉ< Ḯ                      Start IP pass
if mark[ỉ]                           insignificant pixel
output (d=val [ỉ] AND s)             send bit
if d
output (sign [ỉ])                    send the sign
if mark [ỉ]                          significant pixel
output (val [ỉ] AND s)               refine the pixel
ỉ = ỉ+1                              move the pixel
```

Insignificant Set Pass

```
ỉ=0, while ỉ < Ḯ                     Start IS pass
if mark [ỉ]=MDES                     a set of descendants
output (d=(dmax[ỉ /4] AND s)
if d if the set is significant
mark [ỉ]= mark[ỉ+1]= mark [ỉ +2]= mark [ỉ +3]    split into 4 children
mark [4ỉ]=MGRANDES                               a set of grand descendants
if d                                             if the pixel is significant
output (sign [ỉ])                                send the sign of the pixel
output (val [ỉ] AND s)                           refine the pixel
else ỉ=ỉ +4                                      move past the siblings in this set
elseif mark [ỉ]= MGRANDES                        a set of grand descendants
```

```
output (d=(gmax[ỉ/16] AND s))
if d                                          if the set is significant
mark[ỉ]= mark [ỉ+4]= mark [ỉ+8]= mark [ỉ +12]= MDES split into 4 sets
else
ỉ= ỉ+16                               move past the cousins in this set
```

IV. SIMULATION RESULTS AND DISCUSSIONS

Low memory listless SPIHT is implemented and simulated on MATLAB software. At low bit rates the performance of the proposed coder is slightly inferior to other listless coders but at higher bitrates, its performance is better compared to other state of the art listless coders.

A. Memory analysis

No list SPIHT (NLS) [7] algorithm needs fixed size static memory to store the state of pixels and sets. This requirement depends only on the image size and is independent of encoding/decoding bitrates. NLS uses 4 bits per coefficient marker to track the state, therefore the static memory for NLS is

$$M_{NLS} = 4\ RC \text{ bits} \tag{16}$$

Memory efficient listless SPIHT (MELS) algorithm [33] uses only four markers to define the state of trees/sets, but in hierarchical arrangement of wavelet coefficients, only one-fourth of total nodes need to be assigned SMT markers. Thus the total memory requirement for MELS algorithm is

$$M_{MELS} = 2(RC/4) = 0.5\ RC \text{ bits} \tag{17}$$

Low Memory Listless SPIHT (LMLS) algorithm does not use any marker to define the state of the pixels; therefore it does not use even a single bit to define the state of pixel. LMLS uses only two markers to define the state of trees/sets. The total memory requirement for LMLS algorithm is

$$M_{LMLS} = RC/4 = 0.25\ RC \text{ bits} \tag{18}$$

For an image of size 512x512 with R = 512 and C = 512,
M_{NLS} = 4 x512x512 =131072 bytes
M_{MELS} = 0.5 x512x512 =131072 bits =16384 bytes
M_{LMLS}=0.25x512x512=65536 bits=8192 bytes
The memory required for NLS, MELS and LMLS algorithms are as follows:
M_{NLS}: M_{MELS}: M_{LMLS} = 131072: 16384: 8192
Therefore from the above discussion, it can be concluded that the LMLS algorithm is more memory efficient than NLS and MELS coding algorithms.

B. Energy consumption

We consider a network with 50 nodes randomly placed in an area with source node close to center and destination node varies as distance from 1 to 25 hops. From Joule Track [34], the value of $\mathcal{E}_{DWT}$ and $\mathcal{E}_{ENT}$ is estimated to be 1.76 μJoule/byte and 0.16 μJoule/byte respectively. For the wireless energy model [35], the typical values of parameters are $\mathcal{E}_a=100x10^{-12}$ and $\mathcal{E}_e=50x10^{-9}$. The communication range of a node, d is taken as 10 m and is fixed for all nodes. The path loss parameter α is chosen as 2.
The energy consumed for transmission and reception of a single bit at one node is calculated using equation (12) and (13). The energy consumption for NLS, MELS and LMLS is calculated.

Table 1. Energy Consumption (in mJ) of listless techniques for image of size 512x512

No. of Nodes	Energy consumption (mJ)		
	NLS	MELS	LMLS
10	1845.494	230.6867	115.3434
20	2369.782	296.2227	148.1114
30	3523.215	440.4019	220.201
40	4676.649	584.5811	292.2906
50	5830.083	728.7603	364.3802

The energy consumption at different nodes for various coding techniques is plotted. The proposed coder is compared with other direct state of art techniques.

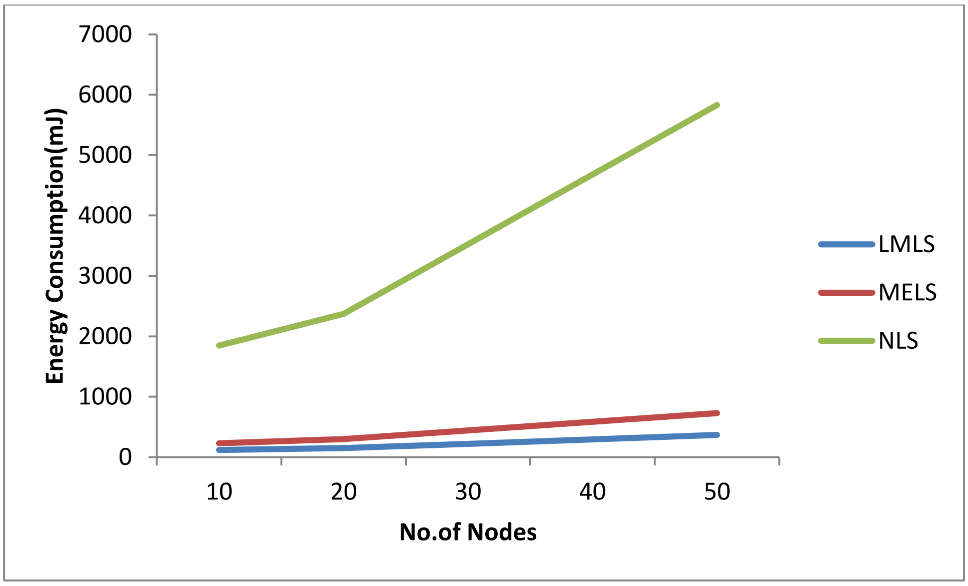


Figure 2. Energy Consumption versus number of nodes

Table 2 compares the proposed method with other direct state of art coding techniques [36][28].

Table 2. Comparison of Techniques

Technique	Energy consumption (mJ)	% Energy Saving
Lecuire et. al [36]	1252.6	87.47
Rehman et. al [28]	411.3	95.88
Proposed method (LMLS)	364.38	96.35

V. CONCLUSION

In this paper, an energy efficient low memory listless SPIHT with lifting wavelet transform is proposed which reduces memory requirement with the elimination of linked lists. With low memory requirements, the proposed coder saves 96.35% energy which is best among other coding techniques so far. One direction of future work can be to investigate the link error. Another direction can be to reduce packet loss.

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