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Low power hardware-based image compression solution for wireless camera sensor networks

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ABSTRACT

In this paper, we present and evaluate a hardware solution for user-driven and packet loss tolerant image compression, especially designed to enable low power image compression and communication over wireless camera sensor networks (WCSNs). The proposed System-on-Chip is intended to be designed as a hardware coprocessor embedded in the camera sensor node. The goal is to relieve the node microcontroller of the image compression tasks and to achieve high-speed and low power image processing. The interest of our solution is twofold. First, compression settings can be changed at runtime (upon reception of a request message sent by an end user or according to the internal state of the camera sensor node). Second, the image compression chain includes a (block of) pixel interleaving scheme which significantly improves the robustness against packet loss in image communication. We discuss in depth the internal hardware architecture of the encoder chip which is planned to reach high performance running in FPGAs and in ASIC circuits. Synthesis results and relevant performance comparisons with related works are presented.

1. Introduction

The technological advances in wireless communication and microelectronics allow today to build small, inexpensive, and battery-powered sensing devices with on-board processing and communication capabilities. These devices, called wireless sensor nodes, can be densely deployed over large regions of space in order to collect data from their surrounding and to send them to a sink node. The data packets are transmitted in multi-hop mode through a self-organized and infrastructure-less wireless sensor network which is built by coordination between the sensor nodes [18].

There is a wide range of applications envisioned for such wireless sensor networks, including, e.g., environmental monitoring, habitat sensing, precision agriculture, disaster management, structural health monitoring, target imaging and tracking, and military operations. However, the energy supply to these nodes is scarce due to the limited capacities of the batteries. This makes the energy efficiency as one of the fundamental problems in wireless sensor networks and consequently, special challenges for energy-efficient data processing and communication must be addressed.

More recently, there is a growing interest for the applications which require image sensing in order to achieve object detection, localization, tracking, and counting [2,5]. In this case, some nodes in the wireless sensor network are equipped with a small CMOS camera [1,6,7]. Such a sensor network is referred to as Wireless Camera Sensor Network (WCSN). However, digital images are usually represented by a very large amount of bits, and hence image-based applications raise up the problems related to energy consumption, memory size in the sensor nodes and available bandwidth in the wireless links [3]. Considering that the radio transceiver is one of the most power greedy components of sensor nodes, image compression at the source node seems a natural solution to make significant energy savings at the camera node as well as at the nodes forwarding packets towards the sink, and hence to extend the network lifetime [1,2,5]. Besides, the compression of image data contributes to reduce the risk of network congestion, and consequently the probability of packet loss. However, most current camera sensor platforms are software-based, as is the well-known Cyclops sensor board [6] and CMUcam3 [7]. Some works [8–10] have shown that popular algorithms such as JPEG, JPEG2000 or SPIHT are generally not efficient in software implementations because they lead to greater energy consumption than the transmission of the uncompressed image. That is due to the resource limitation of the software-based platforms in terms of processor speed. In the case of the Cyclops camera for example, where the software runs in TinyOS operating system environment, the processing time of the 2D-Discrete Wavelet Transform (DWT) on an

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8-bpp image (128×128), for the case of the 5/3 filter bank, is around 8 s. In the same way, the processing time of the Loeffler 2-D 8-point Discrete Cosine Transform (DCT) is around 7 s. As a result, hardware-based solutions are greatly sought after.

This paper is then a contribution in this field. Its main scope is to present a hardware solution for image compression at source node. This solution, presented as a CMOS circuit, is intended to be embedded in the camera sensor node. It will be considered as a coprocessor for tasks related to image compression and data packetization, which unloads the main microcontroller so that it will spend less time in active mode [11,12]. The proposed image compression scheme is designed to be robust against packet loss so that image communication could be achieved using a lightweight protocol without any error-correction functionality (i.e., without any kind of ARQ or FEC-based mechanism). This yields a significant reduction in energy consumption for the radio transceiver unit. Performance of our hardware solution is evaluated considering FPGA and ASIC circuits.

This paper is organized as follows. In Section 2, we discuss the related work and present our contribution. Section 3 describes the key features of the proposed image compression scheme and gives detail about the application-level performance. Section 4 provides the hardware specification of the proposed CMOS circuit and the analysis of its architecture, which is designed for WCSNs. Section 5 presents the synthesis results of our proposal using FPGA and ASIC circuits. Section 6 provides performance comparison between our solution and others found in the related literature. Finally, the last section provides concluding remarks and directions for future work.

2. Related work and contribution

There is a big concern among the research community about the implementation of image compression schemes on resource-constrained wireless camera nodes. The relevant parts of these researches aim to optimize both physical resources required at the node and networking constraints.

In Ref. [13], Yu et al. proposed an energy efficient JPEG 2000 image transmission system for WCSNs. JPEG 2000 is a DWT-based image compression standard which provides some error resilient coding schemes. The proposed system aims to minimize the overall processing-and-transmission energy consumption, given the expected end-to-end distortion constraint. However, the wavelet transform and the EBCOT coding process both require high computational resources and huge available memory size.

Lecuire et al. in Ref. [14] proposed to combine a DWT-based image coding scheme with a semi-reliable transmission scheme to achieve energy conservation. The DWT allows for image decomposition into separable subbands for multiresolution representation and packet prioritization purposes. The semi-reliable transmission scheme enables nodes located between the source camera sensor node and the sink to drop some packets in accordance with the packet priority and the batteries' state-of-charge. Such an image transmission approach provides a graceful tradeoff between the reconstructed image quality and the lifetime of the nodes forwarding data packets but it is not very efficient for the source camera sensor due to the computationally intensive DWT.

In Ref. [4], Lu et al. presented a low-complexity image compression scheme for WCSNs. This scheme is based on the Lapped Biorthogonal Transform (LBT), zerotree coding, and Golomb and Multiple Quantization (MQ) coders. The LBT is more suitable than the DWT because it requires much less calculation and memory space. For the same reasons, the Golomb and MQ coding algorithm fits more than Huffman coding or arithmetic coding. A distributed implementation scheme of the image compression algorithm is also proposed to overcome the computation resources and energy limitation of individual nodes by sharing the processing tasks among multiple wireless sensor nodes. Certainly, collaborative in-network processing fits well the needs of resource-constrained wireless camera sensor networks. However, enabling scalable and dynamic cooperation among sensor nodes inevitably requires a lot of communication between them whereas this kind of communication is usually not very robust against loss.

Wu and Abouzeid presented in Ref. [15] a hop-by-hop reliability algorithm based on the generation and multiple copies sending of the same data bit stream after encoding it using Reed–Solomon (RS) codes. The data transits through cluster heads and other relaying nodes that are randomly chosen within every cluster. RS encoding and decoding algorithms are done at each relaying node, which chooses the strength of the RS code according to the estimated channel error probability. This scheme increases error robustness. However, it does not optimize the end-to-end performance, but rather makes additional energy cost and delay due to the extra processing performed at the relaying nodes.

Makkaoui et al. in Ref. [16] presented a zonal JPEG-based scheme which reduces the number of DCT coefficients to be computed, quantized and encoded. As a result, this scheme reduces the computation time and the energy consumption at each stage of the whole compression chain. This approach is attractive but the performance evaluation has been performed for a software implementation only.

In Ref. [17], Panigrahi et al. have developed a hardware/software architecture in order to optimize the energy consumption in WCSNs. This is based on JPEG compression algorithm which can be dynamically adapted to wireless communication. However, this compression scheme needs to be enhanced against packet error transmission.

It has been proved through these related works and others which are not cited here that the software implementation of image compression schemes is not suitable for WCSNs since it requires long processing time and leads to high energy consumption. These restrictions do not play in favor of many WCSN-based applications.

From these considerations, we believe that a hardware-based image compression solution will resolve the problem of the required energy and time processing. In fact, the solution that we propose is a specific hardware embedded circuit which has to relieve the main microcontroller of the node from the image processing tasks, and consequently which will spend less time in active mode and thus will decrease its energy consumption. Although several works exist on hardware-based image compression [19–23], the interest of our solution is twofold. First, compression settings can be changed at runtime (upon reception of a request message sent by an end user or according to the internal state of the camera sensor node). Second, the image compression chain includes a (block of) pixel interleaving scheme which significantly improves the robustness against packet loss in image communication. Our proposal is described in the following section.

3. The proposed image compression scheme

The image compression scheme that we propose lies on the <transformation-quantization-codeword assignment>conventional structure. Our goal is to have a low-complexity and low-memory scheme for meeting the hardware implementation requirements. The key features of our image compression scheme are:

- The transformation stage is based on the 2-D 8-point DCT algorithm, i.e., the image is divided in blocks of 8×8 pixels and each block is encoded independently. 2-D 8-point DCT is very popular in image compression but this transform is computationally intensive, and hence is energy consuming. Several fast DCT algorithms can be found in the literature. In the 1-D DCT domain, the Loeffler–Ligtenberg–Moschytz (LLM) algorithm [24], with 11 multiplications and 29 additions, is the most efficient (11 multiplications is the theoretical lower bound). In order to reduce the computational complexity of the DCT, some algorithms such as BinDCT [25], Cordic DCT [26] and Cordic–Loeffler DCT [27] approximate multiplications