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# Near-lossless energy-efficient image compression algorithm for wireless capsule endoscopy

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ABSTRACT

New near-lossless algorithm for energy efficient image compression in wireless capsule endoscopy (WCE) is proposed. The designed compressor operates directly on data from CMOS image sensor with the Bayer Color Filter Array (CFA). By optimal combining transform-based coding with predictive coding, the proposed compressor achieves higher average image quality and lower bit rate as compared to significantly more complex JPEG-LS based coding schemes. For typical WCE images, the average compression ratio is 3.9, while the PSNR is 46.5 dB, which means that very high image quality is achieved. The designed image compressor together with 1 KB FIFO (first-in, first-out) stream buffer and a data serializer was implemented in Verilog and synthesised with the UMC 180 nm CMOS process as an intellectual property (IP) core. Integrated FIFO and data serializer facilitate low-cost interface to an RF (radio frequency) transmitter. The silicon area of the core is only 0.96 × 0.54 mm. The IP core, operating at clock frequency as low as 5.25 MHz, is able to process 20 fps (frames per second). It consumes only about 44 μJ per a single 512 × 512 image frame. As such it is very suitable for integration with RF transmitter to form a compact, ultra low-power image processing system for WCE application.



## 1. Introduction

Wireless capsule endoscopy (WCE) was introduced to the market by Given Imaging Inc. in 2001 [1]. This revolutionary tool was built primarily to enable painless visual examination of the small bowel, which is the most inaccessible part of the gastrointerstinal (GI) tract. Now, WCE is considered a disruptive technology enabling examination of the entire GI tract including the esophagus and the colon [2].

However, there is an evidence, that WCE may omit a significant number of lesions detected on enteroscopy [3–5]. The main reasons include a limited visual field, lower picture resolution, and lower frame rate in comparison to push endoscopy. These limitations were addressed by many research groups [6–8,10].

In [11] a robotically-driven colonoscopic capsule platform was proposed to achieve higher quality and reduced invasiveness of colon exploration. Olympus Endoscopy in collaboration with Siemens Healthcare [10] produced a modified endoscopic capsule controlled by magnetic flux for the examination of upper GI tract. Although active locomotion enables remote controlling and directing the capsule toward suspicious area, such system is both expensive and bulky. Moreover, its use may be further limited by the problems with compatibility with other medical equipment, low performance in obese patients and high cost of the procedure. It seems, that a preferred approach to obtain a larger visual field may be based on the use of more cameras [8,9] with better optics inside the capsule.

In the study [12], a PillCam ESO sending images at a rate of 4 fps was compared to a new device sending images at a rate of 14 fps. It was concluded that a higher frame rate ensures superior visualization of the entire esophagus. Shortly after this research, the second-generation capsule, the PillCam ESO2, capturing 18 fps was introduced. Increased frame rate, automatic light control, and widened angle of view of the PillCam ESO2 ensures high rates of detection of suspected Barrett's esophagus and esophagitis [13]. The latest PillCam ESO3 has two optical heads and can provide up to 35 fps (total).

High frame rate is also extremely important to cover whole mucosal surface of the colon. Therefore, the new capsule designed for the colon (the PillCam COLON2) offers frame rate from 4 fps in quiescence to 35 fps in motion [14] and two cameras at both ends.

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Unfortunately, the coin batteries inside the WCE do not have sufficient capacity to support the high frame rate regime longer than for a few minutes [2].

The power consumption of a typical WCE has been analysed in [15]. It has been found, that in WCE incorporating ultra-low power CMOS image sensor with ability to capture images in low light [16], the most power hungry component is the RF transmitter. Because of this, a flash memory was proposed [8,9] for storing captured images. However, with higher image acquisition rate, the power consumption of the flash memory also increases.

Spectral and power restrictions of MICS band (401-406 MHz) considerably limit the achievable data rate [17]. ZL70102 the commercial implantable RF transmitter [18] supports only 800 kbps, and RF transmitters designed for WCE [19] offer data rate from 2.7 Mbps in (PillCam SB) to 5.4 Mbps (in the PillCam COLON2). As a result, image compression is not only a feasible method of increasing frame rate and image resolution, but also the necessary component supporting image acquisition at higher frame rate for longer time period.

To resolve the data transmission bottleneck and reduce the total power dissipation of the capsule, a dedicated, efficient and computationally simple image compressor for WCE is required. Moreover, high-quality images are required for accurate diagnosis of GI tract disease. Designing of image compressor with high performance, low-power and low-silicon area is a challenging task.

Most of low-complexity image compressors for WCE proposed so far, rely on prediction and encoding of residuals with Huffman [20] or Golomb-Rice codes [21–24,26,27]. They are designed to operate on 8-bits CFA data [20–22,25–27] or on 24-bits full-color images [23,24].

Efficiency of predictive coding depends on the correlation between neighbouring pixels. Full-color images exhibit strong inter-pixel correlation. However, CMOS image sensor captures CFA data only. Unfortunately, medical grade image sensors [28,29], in contrary to consumer ones [30], do not include color interpolation processor to recover 24-bits full-color image from 8-bits CFA data. It is because on-chip color processor increases power consumption. It is due to the complexity of demosaicing operation, which is related to the size of a local window around interpolated pixel. High-quality demosaicing algorithms [31,32] operate on 5 × 5 pixel window. To support data access in such a window a memory storage for 4 image lines is required.

High cost of demosaicing and low power requirements drives research on direct compression of CFA images. However, inter-pixel correlation in CFA images is lower than in full color RGB images, which makes predictive coding of CFA image less efficient and more difficult. Therefore, in this paper, we propose to combine discrete cosine transformation (DCT) and predictive coding to efficiently exploit inter-pixel correlation in CFA image. Presented results show, that the proposed approach offers higher compression ratio and better image quality in comparison to the previous schemes. Furthermore, its implementation cost, in terms of logic gates and memory size, is significantly lower when compared to JPEG-LS based schemes dedicated to WCE [21,22,26]. The presented solution demonstrates also very high energy efficiency.

## 2. System description

A simplified block diagram of low-power image processing system for wireless capsule endoscopy is presented in Fig. 1. It consists of a Bayer CFA CMOS image sensor, a LED-based illumination module and a VLSI chip integrating image compressor, interfaces, system controller, stream buffer, and a radio data transmitter (RF). Captured images are transferred from the CFA sensor to the compressor serially. The serial interface, contrary to the parallel one, requires only one data input pad (*pxi*) instead of 8, which significantly reduces silicon area of the chip and simplifies the PCB. It also enables generation of required clock signals (*pclk*, *xclk*) by division of the serial pixel clock (*sclk*). Serially received data are converted to parallel (S/P) and compressed using a novel image compressor. The data rate of the compressed bit stream depends on an amounts of fine details in the compressed image. Since the transmitter (TX) operates with a constant rate, a FIFO is used for data rate averaging. To drive a binary RF transmitter the parallel-to-serial (P/S) converter is used at the FIFO output.

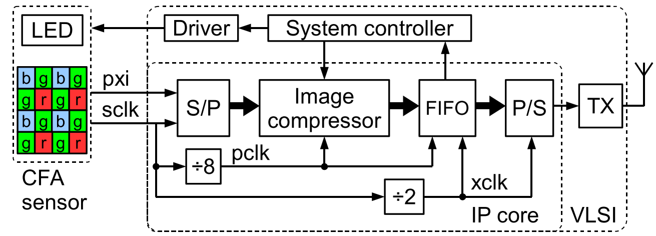


**Fig. 1.** Block diagram of image processing system for WCE.

## 3. Algorithm description

WCE uses CMOS image sensor with a Bayer color filter array to capture color images of GI tract. The captured CFA image (see Fig. 1) consists of 2 × 2 repeating patterns with two green (*g*), one red (*r*) and blue (*b*) pixel. Therefore, to produce full-color image, the two missing color components at each pixel location of the CFA image have to be recovered by demosaicing [31,32].

Inter-pixel correlation in CFA images is lower than in full color ones, which in turn makes CFA images compression challenging. Recently many high performance algorithm for encoding CFA images have been presented [33–35]. However, their computational complexity is too high to be adopted in WCE application.

JPEG-LS is the ITU/ISO standard for lossless/near-lossless continuous-tone images compression. It relies on median edge detection prediction, residual modelling and context-based coding of the residuals with Golomb-Rice encoder. JPEG-LS offers good compression performance, relatively low complexity and low storage requirements. However, JPEG-LS is not efficient in compression of CFA images. It is due to poor spatial correlation of adjacent pixels in CFA image. Therefore, in [21,22,26] a suitable modification was proposed to improve the situation. Although the modified JPEG-LS offers higher compression its hardware complexity is quite high.

Low inter-pixel correlation in CFA images makes predictive coding of CFA image less efficient and more challenging. Therefore, in this paper we propose to combine predictive coding with discrete cosine transformation. DCT ensures excellent efficiency in exploiting inter-pixel correlation to pack pixel energy into very few transform coefficients. To reduce memory requirements of the proposed compressor, DCT is applied row-wise to incoming pixels of the compressed image. However, since the image is 2-D signal, a non negligible correlation exists also along columns. This residual correlation is exploited by column-wise predictive coding followed by an adaptive Golomb-Rice [36] entropy encoder. The details of spatial decorrelation and entropy encoding process are discussed in the following two sections.

### 3.1. Spatial decorrelation

The proposed image compressor is presented in Fig. 2. Incoming pixels, from the CFA image sensor, are grouped into 4-elements vectors

$$\mathbf{x} = [x_0, x_1, x_2, x_3]^T, \quad (1)$$