A Low-Power Wireless Image Sensor Node with Noise-Robust Moving Object Detection and a Region-of-Interest Based Rate Controller

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Abstract: *This paper presents a low-power wireless image sensor node for military surveillance, with a noise-robust moving object detection and region-of-interest based rate controller. The improved robustness to noise from both environment and hardware further reduces the transmission energy with negligible computation and memory overhead. The rate controller minimizes memory requirement by dynamically tuning the coding parameters for the constant encoding rate.*

Keywords: Wireless image sensor, Moving object detection, Region-of-interest, Rate control

Introduction

In wireless image sensor nodes for moving object surveillance, energy efficiency can be enhanced through moving object detection that reduces data transmission while preserving the information. In many applications, the sensor nodes are exposed to noisy environment such as snow or rain, and noise can also be induced by a sensor array or ADC during image sensing. Even under such noise, reliable moving object detection is required to avoid unnecessary transmission of background scenes [1]. Transmission energy can be further reduced by region-of-interest (ROI) based coding that allocates more bits to the ROI by degrading the non-ROI quality [2]. One of the major challenges of ROI coding is to match the encoding rate with the available transmission rate under the variations in channel bandwidth and input video content, since the mismatch will result in random drop (quality degradation) or buffering (increase in memory requirement) of data.

In this work, we present a low-power wireless image sensor node with a noise-robust moving object detection and region-of-interest based rate controller [Fig. 1]. The moving object detection technique is improved to have robustness noise from both image sensor hardware and dynamic environment, with small memory/computation overhead. We also present an on-line rate controller that minimizes the buffer requirement by modulating the ROI coding parameters for keeping the encoding rate under the transmission rate. Simulation results show that the system with the proposed approach consumes significantly lower energy than existing complex moving object detection methods or rate controllers at the same ROI quality.

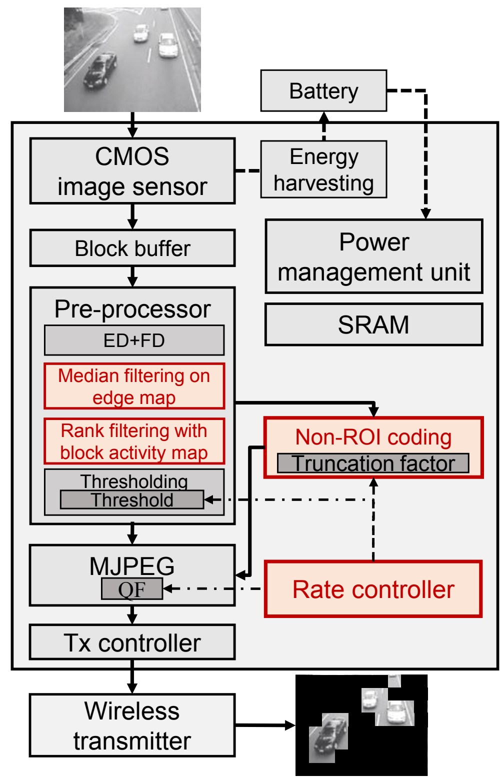
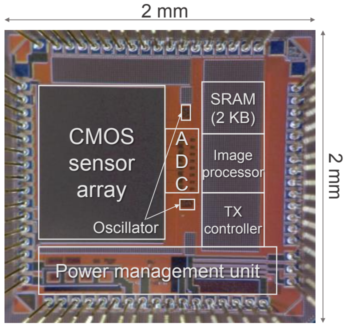


Fig. 1. Block diagram of the proposed system. Red boxes indicate newly-designed blocks.

First Prototype of a Self-Powered Image Sensor

In our previous work [3], we have presented a self-powered wireless image sensor node for moving object surveillance [Fig. 2]. It incorporates the energy harvesting image sensor array and a low-overhead pre-processor for moving object detection. The sensor array can harvest 2.1μW of peak power at 200klx luminance, which can self-power the system at the frame rate of 7 seconds per frame.

In this paper, we focus on its image sensing and motion detection performance. As Fig. 3(a) shows, the image captured by the sensor node has high level of random and fixed-pattern noise with very limited dynamic range. Even with the noisy image input, the pre-processor performs the expected function of object detection. Fig. 3(b) shows that more blocks are transmitted in frames with objects, and the number of transmitted blocks fairly matches with the

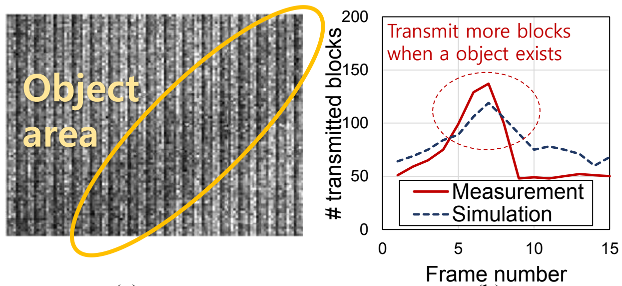


(a)

Specification	Value	
Technology	IBM 0.13um	
Area	2 x 2 mm²	
Supply voltage	1.2 V	
Max. frame rate	230 frames/sec	
Energy consumption per frame (uJ, @230fps)	Sensor array	0.07
	ADC, peripherals (from simulation)	5.7
	Image processor	3.0
	Tx Controller	4.5
	SRAM	0.24
Energy harvesting	2.1uW @200klx	

(b)

Fig. 2. (a) Die photo and (b) key performance parameters of the first prototype of our image sensor node.



(a) (b)

Fig. 3. (a) Image captured by the sensor node, (b) number of transmitted blocks with a moving object.

simulation result. However, due to the random noise at the background, around 1/3 of the total blocks are unnecessarily transmitted even when there is no moving object. Therefore, there is a need for improving the noise robustness of moving object detection to further reduce the transmission energy. We also add a simple rate controller with a low-overhead ROI coding method to further optimize the memory requirement.

Noise-robust moving object detection

Fixed-Pattern Noise: Fig. 4(b) shows an image with FPN with Gaussian distribution of variation=0.05. Although FPN creates vertical lines in the original image and edge map, their locations do not change over frames. Therefore, frame differencing of two consecutive edge maps removes most of the lines generated by FPN. As a result, increase in the activity levels at the background due to FPN is not significant, generating similar distribution of the activity map as the original image. Therefore, it can be claimed that certain level of FPN can be effectively handled by the nature of ED+FD method.

Random Noise: If the pixels in an input image are affected by the random noise, their boundary pixels will be determined as edges in an edge map. As the location of noisy pixels changes frame by frame, the edge locations also change, resulting in large activity level at the background due to noise [Fig. 4(c)]. We propose removing the edges generated by impulse noise in each edge map, instead of filtering the original image. To remove impulse edge pixels

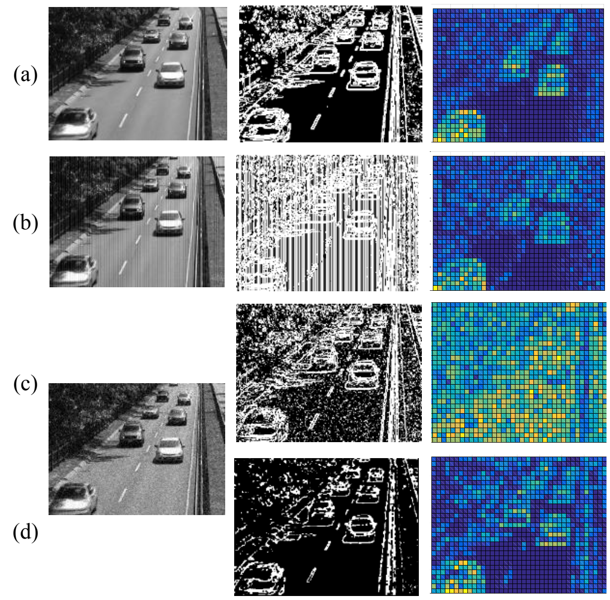


Fig. 4 (left): input images, (middle): edge map, (right): block-level activity map with (a) original video, (b) with FPN, (c) with random noise using the original ED+FD method. (d) images with random noise using the proposed noise-robust method.

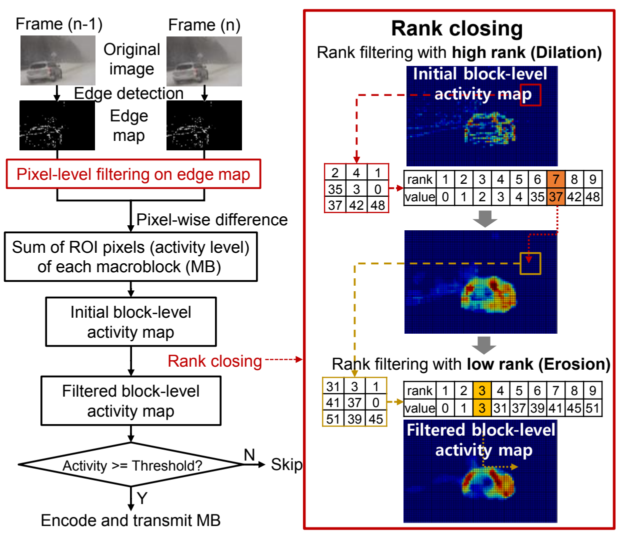


Fig. 5. Diagram of (a) noise-robust moving object detection and (b) rank closing.

in the edge map, we use a simple median filter with 3x3 kernel size. Median filtering on an image generally requires sorting elements in a kernel, which needs computation of *O(nlogn)*. However, as we perform filtering on a bit-map of edges, it can be implemented simply by adding the bits in the kernel and comparing the value with the threshold (5 for median filter). Fig. 4(d) shows the edge map after the proposed filtering process. It shows that most of the small group of edges generated by random noise are removed, resulting in the similar activity map as the original video.

Noise from dynamic environment: The noise from dynamic environment (e.g. snowflakes) usually cover a group of

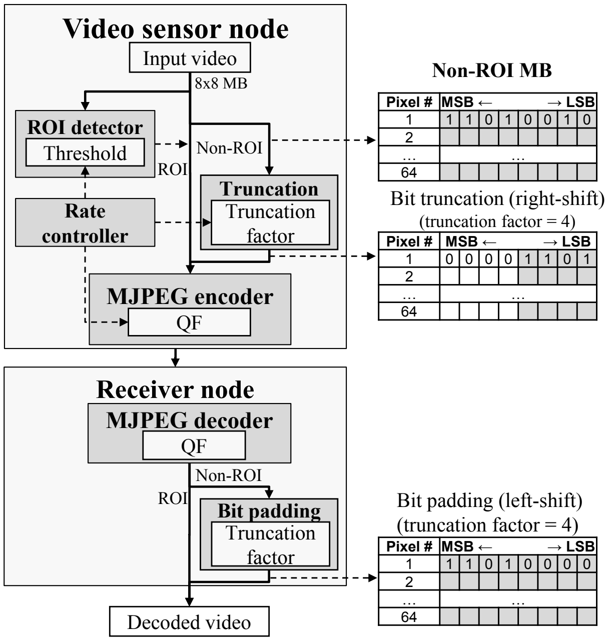


Fig. 6. Diagram of the proposed non-ROI bit truncation method.

pixels (1-2 blocks), and cannot be eliminated by the pixel-level filtering. Therefore, we propose to apply morphological filtering to the block-level activity map generated by edge detection and frame differencing (ED+FD) [Fig. 5]. For low-overhead filtering, we utilize rank closing, a series of simple filtering operations with high/low order values. With the rank closing operation, noisy blocks with high activity levels are removed, while the regions with low activity levels inside the object are filled.

ROI-based rate control

Once the ROIs are determined, energy-efficiency can be further improved by assigning more resources to ROI. Since dropping non-ROIs leads to overall quality degradation and loss of context, we consider transmitting non-ROIs with smaller size. For higher compression of the non-ROI at MJPEG, we reduce the pixel value variance in non-ROI blocks using bit-truncation [Fig 6]. Bit-truncation also reduces the energy dissipation of MJPEG. To match the encoding and transmission rates, we design an on-line rate-controller that tunes the three parameters (the ROI detection threshold, the truncation level of non-ROI blocks, and the QF of MJPEG) [Fig. 7]. Fig. 8 shows that the rate controller with truncation provides higher ROI quality under a given target data rate.

System Design and Energy/Performance Analysis

An image processing engine with the proposed approaches is synthesized with the IBM 130nm technology [Fig. 9] for energy/area analysis.

We first compare performance and energy consumption of the proposed rate controller with the existing complex rate controllers in H.264/AVC. Fig. 10 shows that the proposed approach requires more data transmission to achieve the same quality. However, with its significantly low computation energy and reduced buffer overhead, it consumes less system energy than other approaches at the same ROI quality.

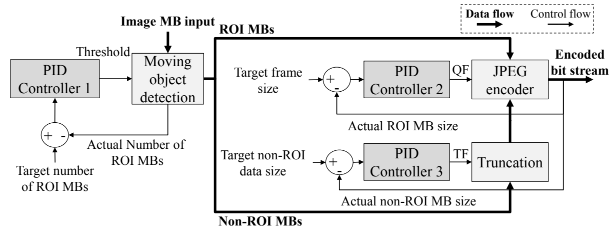


Fig. 7. Diagram of the proposed rate controller.

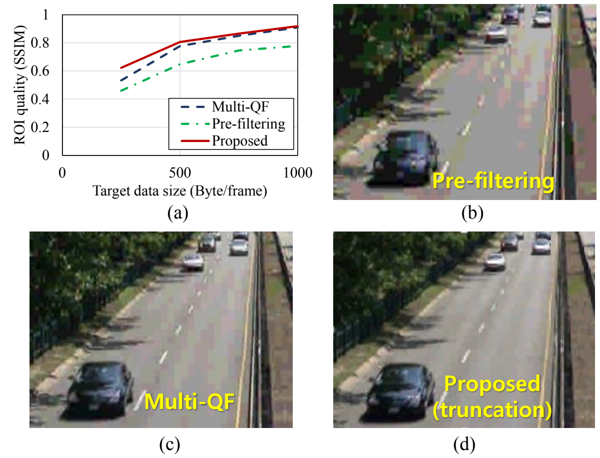
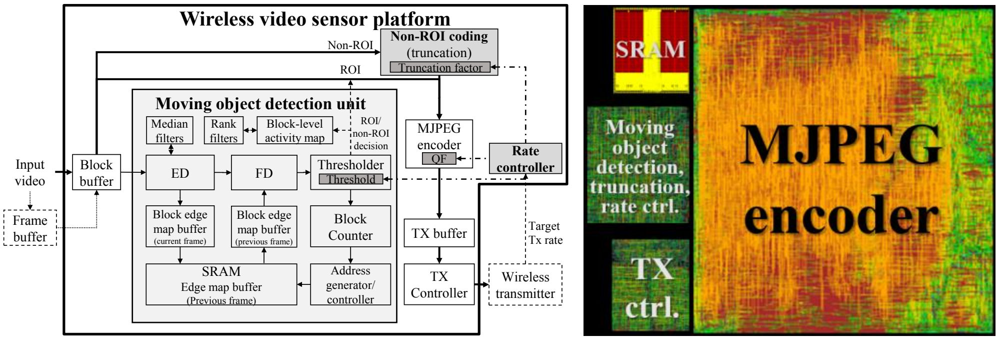


Fig. 8. Performance and quality of different ROI coding methods.

For analysis on noise robustness, we compare the detection performance with existing complex moving object detection methods based on Optical Flow (OF) [4] and Gaussian Mixture Model (GMM) [5]. Fig. 11 shows data reduction and system energy consumption at ROI delivery=0.8 under various types of noise.

With FPN, the moving object detection method based on ED+FD shows comparable noise-robustness to the complex methods such as OF and GMM. However, in presence of random noise, the performance of the original ED+FD method significantly degrades since random noise increases activity level (movement of edges) at the background. However, after performing edge map filtering, the non-ROI activity level significantly decreases, thereby reducing false detection. For videos with environmental noise (snow), the proposed filtering scheme on the block-level activity map improves detection performance of ED+FD. However, the proposed method does not always outperform the complex methods in detecting ROI, resulting in higher transmission energy in some cases.

Although OF and GMM consumes less transmission energy due to higher data reduction, they require significant memory size (OF: 200 bit/pixel, GMM: 120 bit/pixel). As a result, the leakage power of the SRAM for these methods (OF: 84 uW, GMM: 50 uW) is much higher than the harvested power at the maximum brightness (2.1 uW).



(a) (b)

Area and Energy in 130nm CMOS

Module		Area (mm^2)	Energy (uJ/frame)
Moving object detection	Computation unit	0.28	0.55
	SRAM (2 KB)	0.14	0.264
ROI coding	Truncation unit	0.0002	0.0051
	Rate controller	0.03	2.8
MJPEG		2.1	18.8
Tx controller		0.15	3.8
Total		**2.63**	**26.2**

(c)

Fig. 9. (a) Block diagram, (b) layout, and (c) area/energy of the proposed wireless image sensor system.

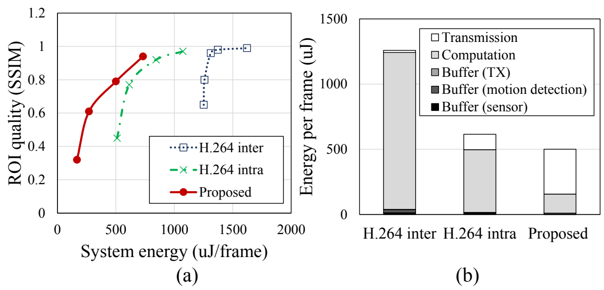


Fig. 10. (a) Quality-energy and (b) energy @ROI quality=0.8 of different rate controllers.

Therefore, the system with those high memory demand moving object methods cannot be self-powered by energy harvesting. A low memory requirement (storage: 1 bit/pixel, access: 2 bit/pixel) of the proposed moving object detection method enables the self-supported operation with a wireless transmitter at frame rate of 95 seconds/frame when FPN exists. In case of random and environmental noise, the self-power performance of the original ED+FD method significantly degrades because of the large transmission energy consumption due to the false detection. By reducing false detection by noise robustness, the proposed approach can be self-powered at much higher frame rate than ED+FD.

Conclusion

We have presented an energy-efficient wireless image sensor with noise-robust motion detection and ROI-based rate controller. Its improved robustness to both environmental and hardware-induced noise reduces the transmission energy with the reliable ROI delivery. The rate controller modulates coding parameters to keep encoding rate constant under variations in channel and input video, thereby reducing the buffer size. The improved noise- and variation-robustness will enhance reliability and energy-efficiency of the system, which are the key requirements of the military applications.

Acknowledgements

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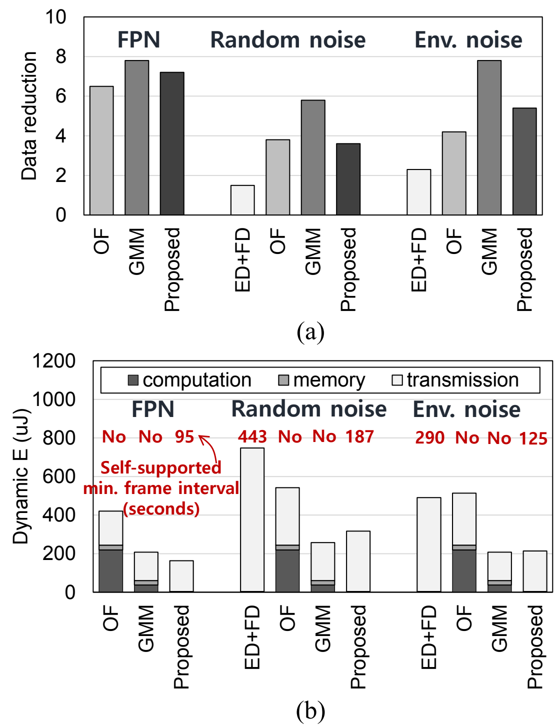

Fig. 11. (a) Data reduction and (b) system dynamic energy consumption through different moving object detection methods under noise.

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