A 64×64 Pixels UWB Wireless Temporal-Difference Digital Image Sensor

Shoushun Chen[1], Wei Tang[2] and Eugenio Culurciello[2]
[1] School of EEE, Nanyang Technological University, Singapore
[2] Electrical Engineering Department, Yale University, New Haven, USA

***Abstract*— In this paper we present a low power temporal-difference image sensor with wireless communication capability designed specifically for imaging sensor networks. The event-based image sensor features a 64×64 pixel array and can also report standard analog intensity images. An ultra-wide-band (UWB) radio channel allows to transmit digital temporal difference images wirelessly to a receiver with high rates and reduced power consumption. The sensor wakes up when it detects enough scene changes and only communicates meaningful frames. Power consumption is 0.9 mW for the sensor and 15 mW for radio transmission to 4 m with rates of 1.3 Mbps and 160 fps.**

I. Introduction

There is a growing need of autonomous sensors that can sense and communicate images wirelessly for imaging sensor networks. The limited energy capacity and extended lifetime requirements demand that all aspects designed in low power fashion. In an image sensor network, the operation of an imager node consists in events detection, local data processing and data transmission. Power consumption can hence be divided into three components: image sensing, processing and communication. To extend the battery life, in addition to the power minimization of the imager itself [1], [2], special efforts should be made to reduce the power consumed during the wireless data transmission, which further translates into the requirements of reduced amount of data and energy-efficient wireless communication protocol. Smart image sensors must be employed in order to abstract meaningful information out of the raw image data, while, at the same time, trading-off a variety of design parameters such as imager resolution, complexity of on-chip image processing, data encoding strategy (sequential scanning or asynchronous address event (AER) [3], [4] and communication protocol (for instance, Zigbee, Bluetooth, or UWB).

In this paper we present a wireless image sensor that captures compressed motion-based temporal difference digital images, and is capable of wireless data transmission by means of an ultra-low power, high-bandwidth radio based on ultra-wide-band (UWB) pulse radio communication. UWB, compared to other techniques, has the advantage of reporting high data rate transmission and low power consumption [5]. The on-chip UWB transmitter is using ON/OFF keying modulation, while the receiver is built with off-the-shelf components. The imager has a resolution of 64×64, which is ideal for indoor applications for imaging sensor networks [6], Robotic sensors [4], assisted living applications [7], and autonomous cameras [8]. The sensor readout circuitry performs temporal-difference calculations between two frames, while continuously monitoring for photocurrent changes. It responds with an ON or OFF event that represents whether a fractional increase/decrease in intensity that exceeds a tunable threshold (ON) or not (OFF). For clock and data recovery, the ON/OFF events and clock information are first encoded by a Manchester encoder before wireless modulation. In this design, we use sequential scanning, instead of asynchronous AER, to reduce data and thus wireless power. Other interesting features are built-in such as a programmable event alarm generator. A programmable counter will generate an alarm signal based on the number of pixel that changed significantly after each time the array is read-out. Therefore the sensor can sever as an ultra-low power trigger to external high-resolution cameras for taking timely snapshots.

The main innovative contribution of this work is the combination of an UWB radio in a motion detection image sensor design. The rest of paper is organized as follows: Section II introduces the system architecture, pixel design and temporal difference event generation. Section III describes the wireless data transmitter design. Section IV reports the experimental results and Section V concludes the paper.

II. Temporal Difference Imager

A. Imager Architecture

Fig.1 reports the system diagram of the autonomous sensor. It includes a pixels array, global event generator, Manchester Encoder and UWB transmitter. Pixels are organized into rows and columns. The array is synchronously scanned with an internal clock that can be digitally controlled. Each pixel is equipped with an analog memory and the whole array is hence capable of storing the current frame as a reference image. Later, when a pixel is selected for readout, it will output both the new integration voltage on its photodiode and the previous voltage stored on its capacitor. The two voltages are fed into an global event generator circuit which is composed of a global amplifier with a temporal-difference computation circuit based on dual comparison. The event generator computes the difference between the two intensities, and compares it to a positive and negative threshold. A digital event is generated if this difference crosses the thresholds. The event bit stream together with the clock are first encoded by a Manchester Encoder circuit. The encoded digital signal is converted into an impulse sequence in the UWB transmitter. A row of dummy pixels embedded with a special pattern of data is built in the array to synchronize transmitter and receiver. Bias voltages are internally generated and are used to operate the sensor. No external biasing DAC are needed.

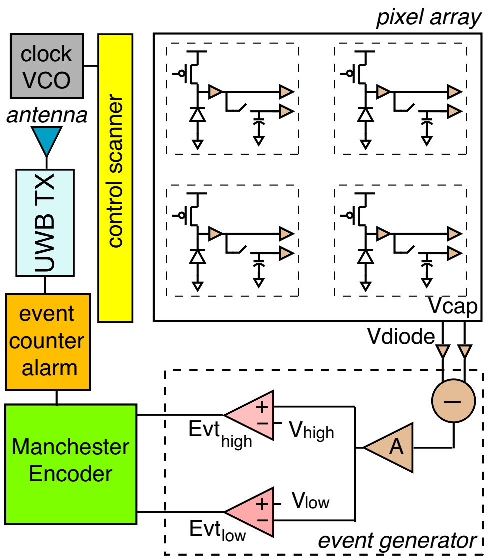

Fig. 1. Block diagram of the wireless image sensor

A simple but efficient wireless power saving scheme is built in the imager. An on-chip 12-bit counter counts the number of events per frame and will generate an “alarm” signal when that number exceeds a programmable threshold. Only when the “alarm” signal is triggered, the UWB transmitter circuit will be enabled to transmit the events of the next frame. Most of the time, the wireless part is in idle mode, saving power.

B. Pixel Design and Timing

Fig.2 shows the block diagram of the proposed pixel. Each pixel includes a photosensitive element (photodiode), a reset transistor ($m1$), a source follower ($m2$), a sample-and-hold path composed of ($m5$,$m6$, C), and two sets of readout circuits ($m9-m10$, and $m7-m8$).

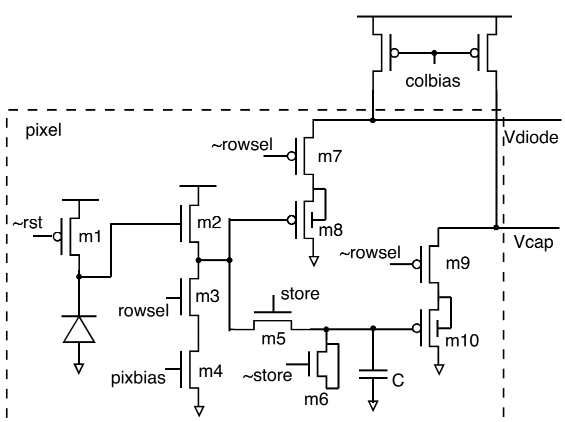

Fig. 2. Schematic of the pixel

The pixel’s operation follows a sequence of “$reset$”, “$integration$”, “$readout$”, “$sample-and-hold$”, “$reset$”. First, a “$reset$” operation is performed and transistor ($m1$) is turned ON, initializing the photo detector to the power supply voltage. Then transistor ($m1$) is turned OFF and the “$integration$” phase starts. At the end of the “$integration$” phase, the pixel is selected for “$readout$” by the ($\sim rowsel$) signal. Both the new integration voltage on the photo detector and the stored voltage on the capacitor will be read. After that, a “$sample-and-hold$” operation will be performed: transistor ($m5$) will be turned ON, and the current integration voltage will be stored on the capacitor overwriting the old value. Transistor ($m6$) is employed as a compensation transistor to reduce charge injection. Transistor ($m3$) is turned on when the row is selected for “$readout$” or the “$sample-and-hold$” operation. This reduces the power consumption of the analog path of follower ($m2$, $m3$ and $m4$). P-type MOS transistors are used in the readout source follower circuits ($m9-m10$, and $m7-m8$) to compensate the DC level shift due the N-type source follower ($m2$).

In the sensor, there are two sets of scanning chains: row-wise and column-wise. Each node of the row scanning chain directly corresponds to the “$readout$” selection signal ($\sim rowsel$) of one row. The control signal for $rowsel$ and $store$, which are activated in “$sample-and-hold$” operation, however, are a combination of the row and column scanners. Transistor ($m3$ and $m5$) may be turned ON simultaneously, but must be turned OFF at a different time. The integration voltage can be copied onto the capacitor (C) when transistor ($m3$ and $m5$) are both ON. Turning OFF transistor ($m3$) before ($m5$) will introduce some charge loss of the capacitor (C) due to the malfunction of the source follower buffer ($m2-m4$). A timing example is shown in Fig.3. The control signal $rowsel30$ is not only active during the 64 cycles when the 30th row is selected for $readout$, but also during the first 3 cycles when the 31rst row is $readout$. This is because the source follower buffer ($m2-m4$) needs to be enabled for successful “$sample-and-hold$” operation for the 30th row. One may note that, during those 3 cycles, the $store30$ signal, is activated only at the moment of $column\_address = 1$.

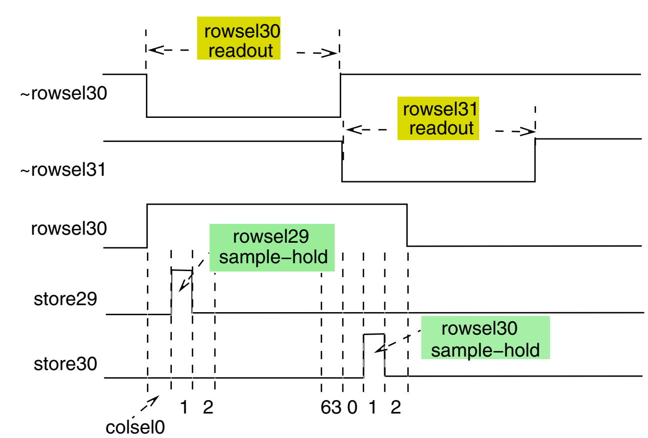

Fig. 3. Example timing diagram of $readout$ and $sample-and-hold$ operation

In our imager, the "$readout$" operation takes place in a column by column manner while the '$sample-and-hold$' and $reset$ operation work in parallel. This reduces pixel size as well as column routing, but at the expense of minor column-based integration time mismatch.

C. Event Generation

The two pixel output voltages, one from the photodiode (V_{diode}) and the other from the cap (V_{cap}), are copied onto two column-wise buses and their difference is computed. As shown in Fig.4, the mixed-signal temporal differencing unit [7] is composed of four stages: 1) unity gain buffer, 2) switched-capacitor based AC amplifier, 3) comparator, and 4) digital signal sampling circuits.

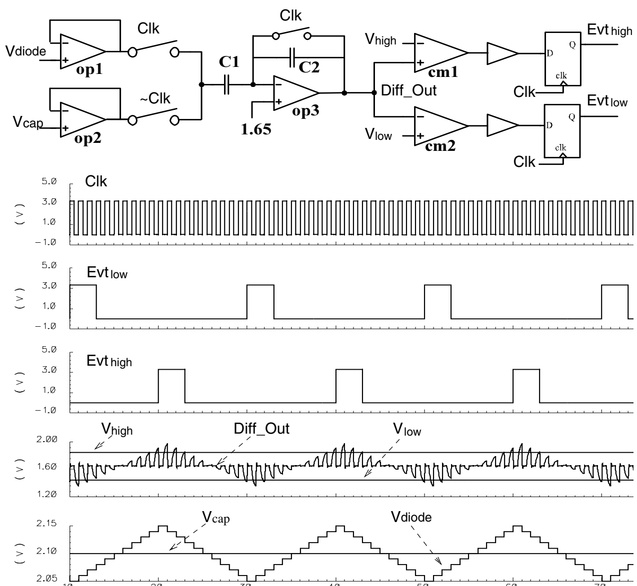

Fig. 4. Event generation circuit and simulation example

The closed loop gain of the switched-capacitor amplifier is A = C2/C1. C2 is large (∼1pF) and therefore the analog signals are first buffered by a unity gain amplifier. The AC amplifier computes the difference of the two signals and amplifies it by C2/C1. The output signal will then be compared with two tunable threshold voltages (V_{high}) and (V_{low}). The comparison results are finally sampled by digital flip-flops and turned into digital events (Evt_{high}, Evt_{low}). Fig.4 also shows the timing diagram of the temporal difference unit.

III. UWB Wireless Transmission

Fig.5 shows the wireless data link for the sensor. The integrated transmitter first communicates the event bit stream and clock to the Manchester encoder circuit. The encoded digital signal is converted into an impulse sequence in the UWB transmitter. The transmitter generates impulses using a voltage controlled oscillator and operates in ON/OFF keying mode. When the input data bit is high, the radio will send a burst of impulses to the external antenna.

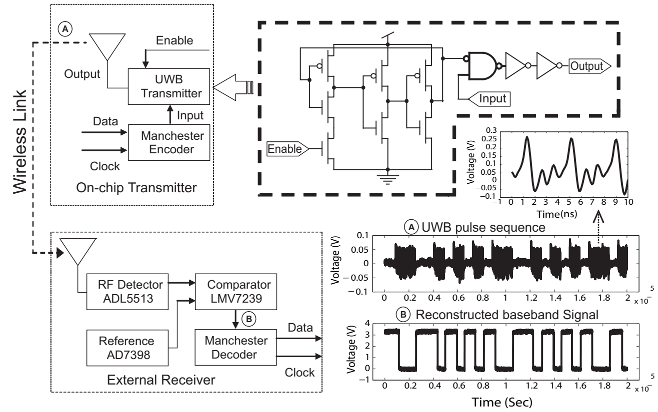

Fig. 5. Wireless data link of the whole system, including clock and data encoding, pulse modulation, pulse detection, clock and data recovery.

At the receiver side, an RF detector (ADL5513) reconstructs the energy envelope from the impulse sequence, and then the output is compared with a tunable reference voltage. The digital output from the comparators is connected to a Manchester decoder, which will recover the event bit stream and clock. Frame synchronization between the transmitter and receiver is implemented by the insertion of a dummy row of pixels embedded with a special pattern of event data.

IV. Experimental Results

The prototype chip was implemented using a 2-poly 3-metal 0.5μm CMOS process, on a 3×3mm^2 die. Each pixel occupies an area of 33×33μm^2 with a fill-factor of 11.5%. An testing platform, as shown in Fig.6, including both the wireless sensor (transmitter) and a receiver was developed.

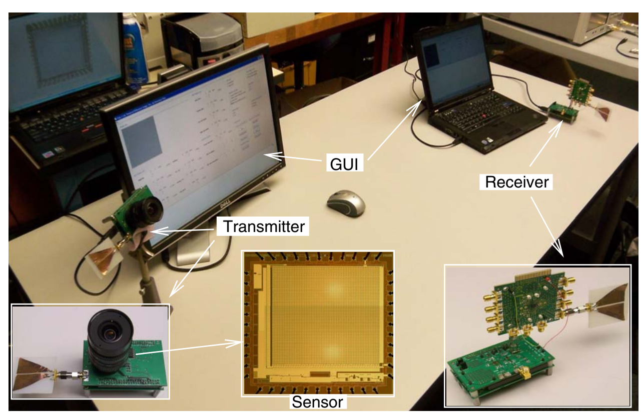

Fig. 6. Experimental Setup of the whole system including transmitter and receiver.

At the transmitter side, the sensor was interfaced with an Opal-Kelly XEM 3001 FPGA board. The FPGA is configured to provide input control signals, temporarily store the baseband data and communicate with a local host PC through USB link. At the receiver side, wireless pulses are first processed by an Analog Device ADL5513 Logarithmic RF detector, and then turned into a stream of digital bits by means of a comparator.

Further baseband processing such as Manchester decoding and frame synchronization was done using another FPGA board. At both sides, the system utilizes a graphic user interface to control the bias voltages and transmission data rate.

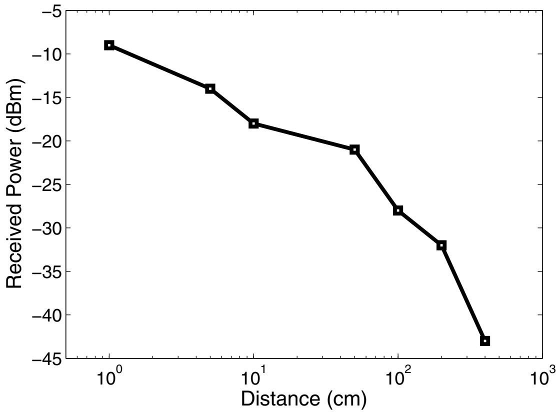

Fig. 7. Received radio power versus the distance between TX and RX antenna.

Fig.7 shows the received power as a function of the distance between antennas. It is converted from the output voltage to received power according to the ADL5513 data sheet. A commercial -80 dBm wide-band RF power detector can receive the signal from our UWB transmitter over 4 m distance.

The photodiode dark current was measured to be around 7.84 fA based on the estimated photodiode capacitance. Fixed pattern noise (FPN) was 3.83 mV when running at 80 fps. The power consumption of the sensor alone is only 0.9 mW, while the UWB radio consumes 15 mW when operating at 160 fps and 1.3 Mbps. Table I summarizes the performance of the imager.

TABLE I

SUMMARY OF THE SENSOR PERFORMANCE.

Technology		2p/3m 0.5μm CMOS
Array Size		64×64
Pixel Size		33×33μm^2
Fill Factor		11.5%
Dark Current		7.84 fA
FPN (under darkness @80fps)		3.83 mV
Power	Sensor	0.9 mw
	Radio UWB (@160fps, 1.3Mbps)	15 mw

Fig.8 reports a few sample images from the wireless sensor, two temporal difference images, and two intensity images, one of each is taken under normal office light condition (400 lux) and outdoor sunny day light condition (20k lux).

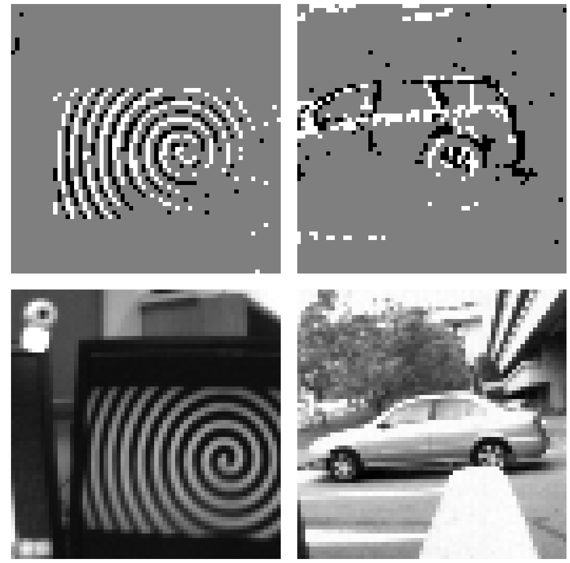

Fig. 8. Sample pictures captured. Top two are temporal difference images and the bottom two are normal intensity images.

V. Conclusion

We report the design of a single chip event-based CMOS image sensor with wireless communication capability. The sensor is capable of delivering frame-differencing (motion detection) at the focal-plane, while consuming less than 1 mW power. On chip UWB wireless radio consumes 15 mW when operating at 160 frames/s and 1.3 Mbps. The proposed design is an ideal candidate of wireless sensor network node, for applications such as assisted living monitors, security cameras and even robotic vision.

Acknowledgment

This work was partially supported by NSF grants ECS-0622133, ECCS-0901742, by ONR grants 439471 and 396490, by Nanyang Assistant Professorship (2009-2012) and the prototype fabrication was supported by the MOSIS Education Program.

References

[1] K.-B. Cho, A. I. Krymski, and E. R. Fossum, "A 1.5-v 550μw 176×144 autonomous cmos active pixel image sensor," *IEEE Trans. on Electron Devices*, vol. 50, pp. 96–105, 2003.

[2] A. Fish, S. Hamami, and O. Yadid-Pecht, "CMOS Image Sensors with Self-Powered Generation Capability," *IEEE Trans. on Circuits and Systems II*, vol. 53, pp. 1210–1214, 2006.

[3] E. Culurciello, R. Etienne-Cummings, and K. Boahen, "Arbitrated address event representation digital image sensor," in *IEEE Int. Solid-State Circuits Conference*, May 2001, pp. 92–93.

[4] P. Lichtsteiner, C. Posch, and T. Delbruck, "A 128×128 120db 15μs latency asynchronous temporal contrast vision sensor," *IEEE J. of Solid-State Circuits*, vol. 43, pp. 566–576, 2008.

[5] T. Opperman, M. Hamalainen, and J. Iinatti., *UWB Theory and Applications*. John Wiley & Sons, September 2004.

[6] N. Massari, M. Gottardi, S. Jawed, and F. B. Kessler, "A 100μw 64×128-pixel contrast-based asynchronous binary vision sensor for wireless sensor networks," *IEEE Int. Solid-State Circuits Conference*, pp. 588–638, 2008.

[7] Z. Fu and E. Culurciello, "A 1.2mw CMOS temporal-difference image sensor for sensor networks," *IEEE ISCAS*, pp. 1064–1067, 2008.

[8] Y. M. Chi, U. Mallik, M. A. Clapp, E. Choi, G. Cauwenberghs, and R. Etienne-Cummings, "CMOS Camera With In-Pixel Temporal Change Detection and ADC," *IEEE J. of Solid-State Circuits*, vol. 42, pp. 2187–2196, 2007.