eCAM: Ultra Compact, High Data-Rate Wireless Sensor Node with a Miniature Camera

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***Abstract*— eCAM is an ultra-compact, high data-rate wireless sensor node (WSN) with a miniature camera. It is constructed by interfacing a VGA quality digital video camera with the Eco node. The purpose of this demo is to show that Eco is not only one of the world's smallest self-contained WSN, but its expansion capability facilitates the construction of new sensing systems over its expansion port. More importantly, Eco pushes the limit on wireless throughput by demonstrating real-time, reliable streaming of VGA quality video. The results show that Eco is not only ultra-compact but also much higher performance than sensor nodes in its class.**

I. Introduction

To reduce efforts of constructing WSNs, *platforms* have been proposed. Platforms are hardware and software systems on which customized extensions are possible. Hardware would involve plugging new modules to an expansion interface, and software would involve programming. Although one can create a smaller, more efficient design by spinning a new custom printed circuit boards (PCBs) and assemble the components, the designer is burdened extra hardware development effort and risking introduction of new errors, not to mention the potential impact on the RF performance. Unfortunately, platforms that have been proposed to date either optimize for expandability but are too bulky, or specialize but forego expandability or configurability. Only a handful of platforms are small enough to be truly wearable without sacrificing expandability and data rates for data-intensive sensing applications. Among them, performance figures are almost always cited in terms of the figures from the data sheets of the components, even though most systems rarely achieve anywhere close to the theoretical peak performance.

In this demo, we propose eCAM, an ultra compact, high data-rate wireless sensor node that is constructed by plugging a VGA video camera [1] to the Eco node [2]. The purpose is to show that high data-rate wireless capability and expandability of a platform can come in a miniature package. The camera module itself already performs compression in hardware and thus represents an optimized subsystem in terms of its power consumption and bandwidth demand.

The purpose of this eCAM demo therefore is to demonstrate that Eco can serve as a suitable platform for many miniature WSNs with similar bandwidth and size requirements. In fact, the complete Eco node itself is only $1cm^3$ in volume, including the microcontroller (MCU), radio, a 3-axial accelerometer and temperature sensor, an infrared sensor, an antenna and a battery. After integration with the camera, eCAM itself is still substantially smaller than a single module in many other sensor platforms. At the same time, eCAM is capable of much higher data rate than most platforms. The theoretical peak bandwidth of eCAM is 1Mbps, four times Zigbee's 250Kbps, and we show that eCAM can actually reliably deliver the live video feed without further compromising video quality. The complete eCAM is also lower power and smaller than some Bluetooth or 802.11b/g modules.

To accomplish this, we analyzed and streamlined the entire chain from the camera and Eco node to the base station. On the eCAM side, we determined performed communication scheduling to eliminate a bottleneck between the camera and the radio. On the base station side, we upgraded the serial/USB link to either Fast Ethernet or WiFi to support the fast uplink to the host computer. By using a much faster yet lower power radio than conventional WSNs, we enable more power management opportunities, and we can also afford to implement more robust communication protocols with the added bandwidth.

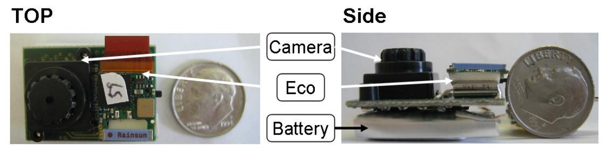

Fig. 1. Photos of eCAM with a US dime coin for scale

II. Related Work

Several recent wireless sensor nodes have been built with image sensors. Although their resolution is much lower than many digital cameras on the market (up to 640×480 vs. several megapixels), low resolution is generally considered acceptable in today's applications. Of course, it is desirable to increase the resolution and frame rate if constraints on the form factor and power can be met.

WiSNAP [3] was developed by researchers at Stanford University. It uses Agilent's ADCM-1670 camera module with a maximum resolution of 352×288 (CIF) at 15 frames per second (fps). It uses Chipcon's 802.15.4 radio (CC2420) whose maximum data rate is 250Kbps. The example applications are event detection or node localization.

Researchers at UCLA [4] built a camera node by adding a similar camera module (Agilent ADCM-1700) to the widely used MICA2 platform. The MICA2 uses Atmega128L 8-bit microcontroller and has a maximum data rate of 38.4Kbps. Also, its camera expansion board has external SRAM (64KB) and flash (512KB) to buffer captured images or run application algorithms such as object detection.

Researchers at Yale integrated a COTS camera module (OV7649) into their XYZ sensor node [5]. OV7649 has higher performance than two previous camera modules from Agilent. It supports VGA and QVGA resolutions. The XYZ sensor node, which contains an ARM7 core running at maximum 57.6MHz, can acquire 4.1 fps at QVGA resolution. However, its radio data rate (250Kbps) appears to be too low to transmit acquired frames in real-time.

These sensor systems have been designed for much more local processing and much less wireless transmission. While suitable for their applications, these systems are insufficient for either high resolution still photos or real-time vision monitoring applications. The main bottleneck is the radio, which is too slow to transmit high resolution image data even with compression. Also, they are all too

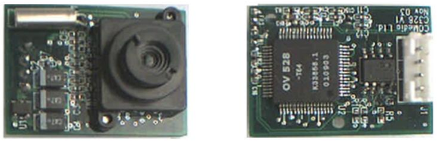

Fig. 2. Photos of Camera Module

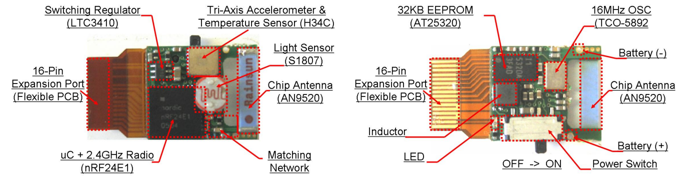

Fig. 3. Photos of Eco Wireless Sensor Node

bulky to unobtrusively monitor many targets especially in wearable applications.

Our eCAM achieves higher efficiency by (1) in-camera hardware compression, which is much more power efficient than software implementations, (2) high-speed, low-power wireless communication interface with a simple MAC, instead of a complex MAC with much higher power, (3) overall streamlined system-level design from the camera, node, and RF to the base station and uplink, and (4) highly optimized board-level system design for very compact form factor.

III. System Design

The eCAM consists of a camera module (C328-7640), Eco wireless sensor node, and 170mAh Li-Polymer battery (PL-052025x1) (Fig. 1). It measures 28(L) $\times$ 20(W) $\times$ 15(H) mm and consumes about 70mA at 3.3Volt in transmission mode. In this section, we detail the camera module and Eco wireless sensor node. Also, we show two kinds of base stations which have 802.11b or 100Mbps Fast Ethernet interface.

A. Camera Module

We use the C328-7640 camera module. It can operate as either a video camera or a JPEG compressed still camera. As show in Fig. 2, it consists of a lens, image sensor (Omnivision's OV7640), and compression/serial-bridge chip (Omnivision's OV528). The OV7640 is a low-voltage CMOS image sensor that supports various image resolutions (VGA/CIF/SIF/QCIF/160$\times$128/80$\times$64) as well as various color formats (4 gray/16 gray/256 gray/12-bit RGB/16-bit RGB). It can capture up to 30 frames per second (fps) and provide complete user control over image quality, formatting and output data transfer.

The OV528 Serial Bridge is a controller chip that implements both a JPEG compression engine and a serial (RS-232) interface to a host controller (in this case, the Eco node). The OV528 implements a set of 11 commands for initialization, taking a snapshot, getting a picture, setting the packet size, etc. It takes 8-bit YCbCR 4:2:2 progressive video data from the OV7640, synchronizes them, and performs down-sampling, clamping and windowing functions with user-defined resolution, as well as color conversion. Its JPEG CODEC with variable quality settings enables users to achieve better image quality with less communication bandwidth by higher compression ratio.

B. Eco: Wireless Sensor Node

Eco is an ultra-compact, high-bandwidth wireless sensor node developed by authors. It measures only 13mm(L) $\times$ 11mm(W) $\times$ 7mm(H) and weights 2 grams. Also, it consumes less than 10mA in transmission mode (0dBm) and 22mA in receiving mode. Its maximum data rate and RF range are 1Mbps and 10m, respectively. Fig. 3 shows photos of Eco hardware. Eco uses Nordic VLSI's nRF24E1, a 2.4GHz RF transceiver with an embedded 8051-compatible MCU (DW8051). The nRF24E1's 2.4GHz transceiver uses a GFSK modulation scheme with 125 frequency channels that are 1MHz apart. The transmission output power is also software-configurable for four different levels: -20dBm, -10dBm, -5dBm, and 0dBm. In addition, Eco has a 3-axial acceleration/temperature sensor (Hitachi-Metal's H34C) which measures acceleration from -3g to $+3$g and temperature from 0 – 75°C. Eco also has an optical sensor (OPTEK's OP591). Eco includes a flexible-PCB type expansion port which has 16 pins. This expansion port includes including 2 digital I/Os, two analog input, SPI, RS232, and voltage inputs for a regulator and battery charging. Eco interfaces with the camera module via this expansion port.

C. Base-Station

We develop two types of base-stations: *Fast Ethernet* and *802.11b*. The Fast Ethernet one uses Freescale's MC9S12NE64, which has an HCS12 16-bit core and a Fast Ethernet interface (100Mbps max). It uses nRF2401 as a wireless transceiver. The 802.11b one uses a PIC18F8720 microcontroller, an nRF2401 transceiver, and Linksys' WCF12 CF 802.11b card (11Mbps max).

IV. Demonstration

We propose to demonstrate an ultra-compact, high data-rate and wireless surveillance system that takes advantage of the distinguished features of our eCAM. This system consists of four eCAMs and one base station. In this demonstration, the activity of the camera module is controlled by ambient events sensed by Eco's sensing devices. In a normal situation, four eCAM keep wirelessly transmitting relatively low resolution (320$\times$240 or 160$\times$128) video streams to the base station. The base station aggregates all data and transmits them to a host computer, which displays the videos in real-time. At 320$\times$240 resolution, our system displays 1.5 frames per second. Once Eco detects any significant changes on its acceleration, temperature, and optical sensors, it immediately takes high resolution (VGA 640$\times$480) still photos and transmits them to the host computer for further analysis. The triggering events can be generated by either over-threshold signal inputs from a single sensing device or a logical combination of them from multiple sensing devices.

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