Towards Efficient Wireless Video Sensor Networks: A HW/SW Cross Layer Approach to Enabling Sensor Node Platforms

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1. Introduction

Wireless sensor networks (WSNs) capable of capturing video at distributed video sensor nodes and transmitting the video via multiple wireless hops to sink nodes have received significant interest in the recent literature. The video capture, processing, and communication in wireless video sensor networks (WVSNs) critically depends on the resources of the nodes forming the sensor networks. This letter introduces our comprehensive literature review of wireless video sensor node platforms (WVSNPs). We concluded that existing WVSNPs could be divided into three main architectural categories: General-purpose architectures, heavily coupled architectures, and externally dependent architectures [1]. A thorough survey and contrast of these architectures led to a cross-layer focused hardware/software (HW/SW) design approach we named Flexi-WVSNP. This node design includes dual-radio communication, a middle-ware for sensor operation and communication control, as well as a cohesive HW/SW design that enables a highly adaptable low cost wireless video sensor (WVS) deployment. The design's target applications range from the less demanding low duty cycle video acquisition, to more demanding surveillance and internet-wide distributed video acquisition and delivery. A novel baseline adaptive video acquisition and delivery application is also proposed. This is intended to demonstrate the capabilities of the node design and how it fits in the nascent Internet of things framework, without violating the core requirements of WVSNPs defined in [1].

WVSNs target applications include computer vision, video tracking, video surveillance, remote live video and control, and assisted living. Many aspects of wireless video sensor networks have been extensively researched, including multi-tier network structures, multi-sensor image fusion, image and video compression techniques, wireless communication protocols, distributed algorithms, light-weight operating systems, middleware, and resource allocation strategies. Generally, a large portion of the research has focused on software-based mechanisms. Past surveys such as [2], [3] collected a subset of the generic sensor nodes typically used in the sensor network community. We specifically surveyed wireless video sensor node platforms (WVSNPs) [1] by considering the HW/SW components required for implementing the WVS node functions. That is, all cross-layer aspects, ranging from video capture, filtering, compression, to wireless transmission and forwarding to the sink node. The node/platform's HW/SW design governs, to a large extent, sensor network performance parameters, such as power consumption (which governs network lifetime), sensor size, adaptability, data security, robustness, cost [4] and computation capabilities. An in-depth understanding of the state-of-the-art in WVSNPs is therefore important for essentially all aspects of cross-layer WVSN research and operation. To the best of our knowledge, there is no prior survey of the field of WVSNPs. Closest, related to our survey are the general review articles on the components of general WSNs (data), e.g., [4]–[6], which do not consider video sensing or transmission, and other general surveys on multimedia sensor networks, e.g., [2], which include only very brief overviews of sensor platforms.

We summarize the insights gained from our detailed survey, including the key shortcomings that cause existing WVSNPs to fail the ideal practical requirements. Building on these insights, we proposed a novel Flexi-WVSNP design that addresses the shortcomings of existing WVSNPs through a number of innovative cross-layer architectural features. We also outline a baseline application that is designed to be a benchmark for revealing the capabilities of a cross-layer highly-adaptable WVSNP. This will be used to demonstrate objectively how our design could be compared to future and existing WVSNPs candidates.

2. Selection and organization of wireless video sensor node platforms for review

We first outlined the sensor node requirements and defined our ideal, yet reasonable and practical requirements for a WVSNP (Pronounced Wave-Snap). From detailed reviews of the requirements for WVSNPs [1], we identified three core requirements, namely power consumption, throughput, and cost. The power requirements are influenced by a wide range of design choices, including power source type, component selection, power management HW and SW, and importantly node and network management algorithms, such as implemented by a real time operating system (RTOS) or sensor network duty cycling schedules. We defined the desirable power consumption of an entire node platform to be less than 100 mW when idle (also referred to in the literature as standby or deep sleep mode). We also require that a WVSNP have an instantaneous power consumption of less than 500 mW. These requirements are based on rule of thumb calculations: a node running on two AA batteries lasts a year if it consumes, on average, less than 0.2 mA. A cell phone typically consumes more than 4 mA. To satisfy these stringent power consumption requirements, a sensor node has to provide most, if not all, of the power modes defined in [1]. That is On, Ready, Doze, Sleep, Idle, and Hibernate. Power modes enable a cross layer node design and control that trades off the power savings achieved by duty cycling through these power modes with the transition costs and frequency of checking the radio channels. Other key cross-layer design points defined in [1] are source to sink throughput. Minimum throughput is defined as at least fifteen common inter-frame format (CIF, 352 x 288 pixels) frames per second (fps). 15 fps is an acceptable frame rate for human perception of natural motion.

From the review, we concluded that 32-bit MCUs consume typically two orders of magnitude less power than an 8-bit MCUs for the same work load [1], [2], [7]. Therefore cross-layer design optimization should target 32-bit based MCUs. Radio communication and the image acquisition components are other major throughput limiting factors in a design. Field programmable gate arrays (FPGAs) have advantages for highly specialized tasks such as routing, Forward Error Correction (FEC), Cryptography and Digital Rights Management (DRM) algorithms [8], [9]. Popular use of hardware acceleration modules on recent multimedia SoCs have eroded this advantage. FPGA based designs, therefore, fail the cost rule due to very limited off-the-shelf economies of scale. FPGAs have low computation performance relative to power consumption [10], [11]. They also have limited standardized intellectual property (IP), which often requires vendor specific tools to program. These increase their cost given the unrivaled open source community support for SoCs. The cost of a node depends primarily on the technology chosen for the architecture, the type and maintenance cost of the selected components, the intellectual accessibility of the SW/HW components, and the scalability, manufacturability and upgrade ability of the architecture. A low-cost platform generally has very few, if any, proprietary components. It should be possible to substitute components based on competitive pricing in a modular manner. Such substitutions require cross-layer in-depth knowledge of the functions and limitations of each HW/SW component, which is rare for proprietary platforms. Therefore, standardized HW/SW components and well architected open source SW and open HW cores that benefit from economies of scale are important for meeting the low-cost objective.

A WVSNP can be designed to use minimal physical and middle-ware-level input from its environment. e.g., a surveillance node can use low power motion sensors to decide when to capture a frame. We call a node with this capability a smart node. Smart nodes further reduce power consumption and improve effective throughput beyond the manufacturer's stated hardware capabilities for a specific application. Our comprehensive review found that none of the existing nodes met the outlined ideal set of requirements. To conduct an insightful survey that uncovers the underlying structural shortcomings we relaxed our requirements. We organized the platforms that satisfy our relaxed selection criteria into architectural classes: General Purpose Architectures: MeshEye [12] and WiSN Mote [7], Panoptes [13], XYZ [14], and NIT-Hohai Node [15]; Heavily Coupled Architectures: eCAM and WiSNAP [16], Cyclops [17], Smart Camera Mote [18], and CMUcam3 [19], and Externally Dependent Architectures: DSPCam [20], Stargate [21], Imote2/Stargate 2 [2], [22], CITRIC [23], Scatter-Web [24], FleckTM-3 [25] and Fox node [26].

3. Flexi-WVSNP Design

Most of the existing nodes have some image acquisition capability but lack the necessary cross layer integration to achieve commensurate processing and wireless transmission speeds. The

HW/SW integration and performance considerations have not been consistently examined across all major stages of the video acquisition, processing, and delivery path. Further, consistent attention to power management has been lacking. We designed Flexi-WVSNP as a video sensor node capable of wireless video streaming via both Zigbee and Wi-Fi. Such a dual-radio system (i) integrates well with other Zigbee sensors, and (ii) provides gateway access for the sensors to the Internet. The Flexi-WVSNP design is highly adaptable and cost flexible. In its barest form, it may consist of only a SoC with the requisite swappable HW/SW modules. We believe that a WVSNP design needs to be application-targetable within a few days if it is to cover a wide array of cost-sensitive applications ranging from low-cost surveillance to remote instrument monitoring and distributed computer vision.

The Flexi-WVSNP architecture [1] introduces a design concept that (i) eliminates the hard choices of anticipating a specific application scenario and (ii) initially bypasses the tedious process of designing a comprehensive WVSNP. The design assumes that hardware and semiconductor processes will continue to improve, and that power savings will depend on the main components added for the specific application. The design is centered on a powerful yet efficient SoC that satisfies essentially all requirements for a WVSNP. Each module within the SoC is independently controlled from active power state all the way to off. The SoC has hardware supported coprocessor module capability and accelerators useful for video capture, encoding, and streaming. Flexible connectors can achieve application functionality. Each HW module has a corresponding SW module which can be turned off/on based on payload content. Neither exists if its other layer counterpart does not exist, which saves storage and power.

Core components of the Flexi-WVSNP design are (i) a dual WiFi-Zigbee radio for flexible video streaming and low power network management, (ii) a middle-ware layer that transparently controls the novel HW/SW module match architecture, and (iiii) dynamic SW co-driver modules in full control of HW modules. We are in the process of implementing a client driven video acquisition and dynamic delivery application that differs radically from a traditional synchronized server-client source sink scheme, while mapping well to WSN algorithm implementations.

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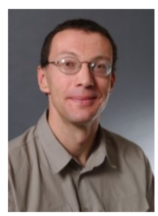

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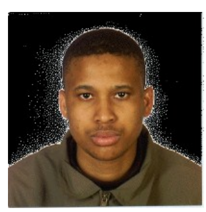

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