Energy Consumption Analysis of High Quality Multi-Tier Wireless Multimedia Sensor Network

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ABSTRACT Video surveillance is one of the promising applications of the Internet of Things paradigm. We see heterogeneous deployment of sensor platforms in a multi-tier network architecture as a key enabler for energy optimization of battery powered high-quality video surveillance applications. In this paper, we propose a heterogeneous wireless multimedia sensor network (WMSN) prototype composed of constrained low-power scalar sensor nodes and single board computers (SBCs). Whereas constrained nodes are used for preliminary motion detection, more capable SBCs are used as camera nodes. The camera nodes stream full HD (1080 pixels) video to a remote laptop during occurrence of an event (when motion is detected). We also present a simple power model and simulation results of battery life of the motes for variable event interval and event duration.

INDEX TERMS Energy efficiency, Internet of Things (IoT), multi-tier networks, power consumption, wireless multimedia sensor network (WMSN), video surveillance.

I. INTRODUCTION

Over the past decade wireless sensor networks (WSN) are significantly dominating many varieties of applications in the caliber of sensing and monitoring. Wireless Multimedia Sensor Networks (WMSN) are among the emerging paradigms of Internet of Things (IoT) that provide richer information than traditional WSN by the use of visual and audio sensors.

According to industrial forecasts, future global Internet traffic will be largely dominated by video-traffic emanating from different sources, including mobile devices and video-surveillance networks. Cisco predicts that by 2020, 82 percent of global IP traffic will be dominated by video content; of which video surveillance contributes 3.9 percent, up from 1.5 percent in 2015 [1]. The range of WMSN applications include, but are not limited to, crop monitoring in agriculture [2], monitoring patients in general health-care [3] and accidents in elderly care [4], situation awareness in public safety [5], and emerging Unmanned Aerial Vehicle (UAV)-drone video surveillance in both civilian and military sectors.

Even though there is a growing demand for video-surveillance in many societal, scientific, civilian and military strategic roles, several technical questions arise when dealing with practical deployment of WMSN. The three major challenges of a Wireless-Video Surveillance Network (WVN) are energy consumption, data latency, and data quality [6]. Chiasserni and Magli [6] assert that, energy consumption and image quality are primary factors that need to be taken into consideration when designing a WVN.

Unlike traditional WSN (in which communication dominates most of the energy consumption), in WMSN, the sensing can take major portion of the device's energy reserve than the communication [7], [8]. This is because extracting semantic information from loads of multimedia data is computationally intensive [9]. In our previous work [10], we reported a scenario where motion detection could actually take more power than the actual event recording in a video-surveillance. On the contrary, in most of the surveillance scenarios, the interval of event of interests is considerably long and the devices spend most of their time sensing for motion than transmitting/receiving data. Thus, the idle (i.e, sensing) energy consumption is the dominant factor affecting the operational lifetime of WMSN and needs to take a premium concern during the design of WMSNs.

In general, there are two approaches of designing a WMSN. The first approach is to choose a sensor platform that is capable of doing super-tasks (e.g video processing), and populate each node with the required scalar and visual sensors. This approach yields, a homogeneous single-tier

network of camera sensors that are able to run full-fledged surveillance application. In this approach, the choice of sensor platform is determined by the most demanding task of the surveillance. This design approach renders distributed intelligence which can be relevant in monitoring dynamic environments that are wide in area and with lots of activities. Nevertheless, this approach is expensive—requiring computational more capable devices in larger number. In addition, it is not also energy efficient as it causes simpler tasks to consume more resources than necessary when run on these more computationally capable devices [11].

The second approach is to exploit the availability of heterogeneous sensor platforms with variety of capabilities and power requirements. In this approach, constrained nodes are assigned for simpler tasks (e.g motion detection using scalar sensors) and more computationally capable nodes are assigned for more demanding tasks (such as video streaming and object tracking). This approach can yield a heterogeneous WMSN system with hierarchical power operation that runs at a range of different power levels. The elements can be combined to form one integrated system; or can be tiered wirelessly to form multi-tier network of sensors and cameras.

In this paper, we investigate the possibility of addressing energy efficiency and image quality in a battery-powered wireless video surveillance system using the second design approach mentioned above. We address these issues with the following contributions:

- Propose a prototype of heterogeneous multi-tier WMSN enriched with a full HD camera node using Raspberry Pi (RPi) Single Board Computer (SBC) and Waspmote low-power scalar sensor nodes for real-time video streaming surveillance.
- Implementation of an event driven full HD single-tier WMSN video surveillance application using RPi to be used as baseline benchmark.
- Comprehensive quantitative analysis of the measured power consumption of the live WMSN testbeds.
- Derive a simple power consumption model and battery-life estimation of our proposed prototype.

Furthermore, our prototype involves tiering of nodes both at a device and network levels. At a device level, we combined a constrained low-power sensor node and SBC to create an integrated (hybrid) system that inherits special features from its constituting tiers. A similar design approach (but with a different goal) was presented in Turducken [12], which tiers mobile devices to create an integrated system so as to improve their availability in a distributed system. At a network level, we tired sensor nodes wirelessly to expand range of detection at a lower cost and lower energy consumption.

The remainder of this paper is organized as follows: Section II summarizes the related work. Section III introduces the methodology and experimental setup, including the implementation, hardware used and network architecture. Section IV presents the measurement results and analysis. Section V introduces the power consumption model and

battery-life estimation of the proposed prototype. Finally, Section VI concludes the paper.

II. RELATED WORK

The literature on WMSN, and IoT in general, shows a variety of approaches for optimizing energy consumption. Most common approaches include: design of improved hardware architecture as in [13] and [14], powering-off the motes during idle times and wake them up when needed using wake-on-wireless techniques [15], use of low-power radio (e.g FM radio) as a control signaling to manage the power of higher-power and higher-capacity radio modules (e.g turning on/off Wi-Fi radio module) when the motes are not transmitting or receiving data [16], [17], or a combination of one or more of these techniques.

Tavli *et al.* [18] present an overview of popular visual sensor network platforms named as Cyclops, MeshEye, Panoptes, Meerkats, FireFly Mosaic, MicrelEye, XYZ-ALOHA, CITRIC, and Vision Mote. The authors also overview different WSN platforms, based on their available computational resources to be used as multimedia sensor nodes. The list of WSN platforms considered in the study are Mica2, Mica2Dot, MicaZ, Telos, Imote, Yale XYZ, and Stargate; among which Stargate stands out as the most suitable candidate.

Hengstler *et al.* [13] proposed a smart camera mote architecture, MeshEye, using 32-bit Atmel AT91SAM7S family of microcontroller for distributed intelligent surveillance. In MeshEye, the authors used three image sensors; one of which is used to continuously poll for moving objects in its field of vicinity. Once object is detected, the region of interest is determined from stereo vision of the other two kilopixel imagers.

The authors in [13] continue to state the relevance of a high-degree of in-node processing and distributed reasoning algorithms as key enablers of smart surveillance system. For that, the authors propose a homogeneous deployment of MeshEye nodes communicating over IEEE 802.15.4 wireless link that provides throughput up to 250 Kbps. Nevertheless, it can be argued that this proposal focuses more on intelligence and not much on energy efficiency, cost and quality. Continuously polling of images for motion detection may not be practical in a battery powered surveillance application where event of interest occurs quite rarely. In addition, the AT91SAM7S microcontroller (which can be clocked maximum up to 55 MHz.) and throughput of the wireless link are too low for full HD video streaming applications. Moreover, such homogeneous deployment of costly camera nodes is an expensive design approach.

On the other hand, it has been suggested [8], [11], [19]–[23] that heterogeneous deployment of sensors with different capabilities provides attractive benefits over homogeneous deployment approach.

Kulkarni *et al.* [11] argue that the use of heterogeneous motes in a camera sensor network provides attractive benefits in saving energy over traditional homogeneous

sensor deployment. The authors' assumption seems plausible that employing constrained nodes to do simpler tasks and more capable, high power ones to complex tasks results in fair use of energy resources; especially, in surveillance applications where event of interest occurs quite rarely. In such scenarios, deployment of a mixture of low-cost, low-power motes along with computationally more capable motes (which usually come with more price) is an efficient approach both price and energy wise.

Bhatt and Datta [19] address a similar premise that dense deployment of low-cost audio sensor tiers along with sparsely placed high-cost video tiers can result to low deployment cost and reduction of average energy consumption of critical event surveillance WMSN. The authors propose a two-tier architecture in which the audio nodes perform the preliminary event detection, whereas, video nodes can be woken up on a demand basis.

Similarly, references [8] and [24], advocate a heterogeneous two-tier deployment of scalar and camera sensor nodes for improving lifetime of WMSN in a video surveillance application. Jeličić *et al.* [24] noted that dense deployment of Pyroelectric Infrared (PIR) sensors for preliminary event detection can reduce cameras' active time and prolong the network lifetime by up to 75 percent. The authors in [8] also found that, the use of information from distributed low-power PIR sensor nodes in a video-surveillance application not only reduces the energy consumption of camera nodes but can also minimize the cost of deployment by 50 percent.

Although there exist some literature written in favor of heterogeneous multi-tier WMSN as cost and energy efficient deployment alternatives, to the authors' knowledge, power consumption models and battery-life estimation for a full HD video surveillance have been scarcely investigated. Thus, in our present work, we attempt to fill this gap by introducing a novel heterogeneous multi-tier WMSN prototype based on sleepyCAM power management scheme [10].

III. METHODOLOGY AND EXPERIMENTAL SETUP
A. IMPLEMENTATION
In order to realize a multi-tier WMSN, we broke down the surveillance applications into motion detection and video-streaming modules. Each of these tasks requires different levels of computational resources. While the motion detection can be accomplished using low-power CPU, the video-streaming and video processing requires high-power CPU. We distributed the tasks to a tiered network of devices. We implemented the motion detection module on the front-end tier (tier-1) devices and the video-streaming module at the higher tiers of the network (tier-2). Tier-1 and tier-2 nodes communicate over Bluetooth Low Energy (BLE) link which can provide outdoor coverage up to 100 meters.

At tier-2, we applied our sleepyCAM power management which is device level tiering for optimal power consumption of the visual sensor node. sleepyCAM integrates a low-power microcontroller and a SBC which operate at different power
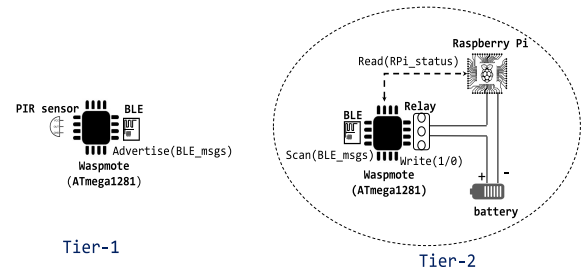

FIGURE 1. Hardware architecture of devices in multi-tier.

levels into single two-tiered (hybrid) device. The resulting device can operate at a power level of either the low-power microcontroller or the SBC. The SBC is used as camera node and the microcontroller is used as power manager of the camera node (thus named controller node).

The camera node is completely powered-off during idle times and has no means of receiving alert messages from tier-1 devices. Thus, in our present work, we upgraded the controller node of sleepyCAM with a BLE module to listen BLE advertisements transmitted from tier-1 node during occurrence of an event.

We used C programming to program tier-1 motion sensor and tier-2 controller nodes. The camera node application is implemented using *Python* programming. In addition, *netcat* utility is used for transmitting the video to a remote computer over Transport Control Protocol (TCP). To display the content on the receiving end, the incoming *netcat* traffic is piped to *mplayer*. In all the measurements, we streamed H.264 video with a resolution of 1920x1080, 17Mbps bitrate and 25fps frame rate.

B. HARDWARE USED
The hardware architecture for the whole multi-tier setup is shown in Fig. 1. The hardware platform used for realizing low-power tier-1 and controller nodes at tier-2 is Libelium Waspmote wireless sensor platform [25]. Waspmote main-board comes with ATmega1281 microcontroller running at 8MHz. The main board has also 8KB SRAM, 128KB Flash and 4KB EPROM memory, built in accelerometer and temperature sensors and a Real Time Clock (RTC). The ATmega1281 has two UARTs (UART0 and UART1), SPI port, I2C communication bus and digital/analog input/output (I/O). The Waspmote platform extends the UARTs to 6 ports using multiplexer: USB connector and Socket0 on UART0, and Socket1, UART1 AUX, UART2 AUX and GPS ports on UART1. In our implementation, all BLE modules at tier-1 and tier-2 Waspmote motes are mounted on Socket0.

Tier-1 nodes are normally in sleep mode until the MCU is alerted with an interrupt from a motion sensor. Parallax Rev. B PIR sensor is used for motion detection and is attached on one of the digital I/O pins of the Waspmote. We turned off the I2C bus of the MCU to save power, as we do not have any sensors communicating with the MCU over I2C.

At tier-2 level, we used RPi-3 Model B SBC as camera node. RPi-3 has 1GB RAM memory, BCM2837 System

on Chip (SoC) with a 1.2 GHz 64-bit quad-core ARM Cortex-A53 processor, built in Wi-Fi and Bluetooth 4.0 chips, Ethernet, 40 General Purpose Input/Output (GPIO) pins, full HDMI, microphone and display interfaces. We mounted a 5MP high resolution camera module and a PIR sensor on RPi. The PIR sensor is used to detect motion during the uptime of RPi. Compared to tier-1 nodes, RPi can do more advanced and complex computational tasks, and thus consumes more energy. The key idea of multi-tier WMSN is to conserve the energy of high-power consuming visual sensor nodes by keeping them in low-power mode when there is no motion in the area. RPi, however, does not have any low-power states due to lack of Advanced Configuration and Power Interface (ACPI) support. It is possible to do some tweaking, such as under-clocking the CPU, disabling the unused peripherals and optimizing the operating system. That does, however, not bring a pronounced effect as sleepCAM does on the total power consumption.

C. MEASUREMENT AND DATA POST-PROCESSING

The power consumption of the nodes at each tier was measured using Monsoon power monitor tool [26]. Monsoon can provide power to the device under measurement at voltage output between 2.1-4.55V. The maximum sampling rate of the tool is 200MHz. Monsoon provides different levels of details of the measurement data with fine adjustment of the granularity, such as, saving all samples, every 10th samples, 100th samples, etc. The measurement setup is illustrated in Fig. 2.

The measurement data can be saved to a workstation in csv file format for post-processing. We analyzed the data using MATLAB to generate the graphs, compare and model the battery-life estimations. Moving average filter is also applied, when necessary, to improve readability of the graphs.

D. NETWORK ARCHITECTURE

1) SINGLE-TIER ARCHITECTURE (BASELINE)

The baseline setup used to validate our work is a single-tier multimedia sensor network. In this setup, both the motion detection and event capturing functionality are performed by the camera sensor node. Hence, this node needs to be running

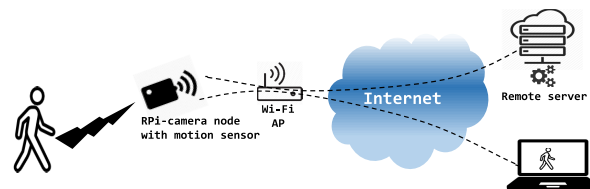**FIGURE 2.** Monsoon measurement setup of tier-2 devices.

FIGURE 3. Single-tier network architecture.

throughout the surveillance application time. The hardware composition of this setup includes RPi-3 model B with a 5MP high resolution camera module and a motion sensor.

There are two motion detection alternatives for this setup: using software algorithm that process video frames, or using scalar sensors such as PIR motion sensor. The software based motion detection rigorously takes video frames of few seconds of the past and compares them against the present stream. If the difference passes a certain threshold, then it is considered as motion and the camera starts streaming video to the receiving end. These two techniques are thoroughly analyzed in our previous paper on sleepyCAM [10]. Accordingly, the hardware motion detection using scalar sensors is more energy efficient and is thus used as a benchmark in the present paper. We selected Parallax rev B PIR sensor for motion detection. The PIR sensor has three connector pins: output, power, and ground pins. The ground is connected to ground, power pin to 3.3V, and the output pin to a General Purpose Input/Output (GPIO) pin of RPi. The output pin is a digital low or high, depending on whether motion is detected or not. For saving the power consumption of the camera node in idle mode, we make use of interrupts in our program instead of polling the GPIO pin.

The network architecture of the baseline setup is shown in Fig. 3. When an intruder is in the proximity, the change in infrared thermal heat turns the PIR sensor output from low to high. This triggers an interrupt signal to the MCU of RPi to launch a function in the program that activates the camera module and starts streaming to the laptop. The stream can be also directed to a remote server which can transcode the video data to various playable formats.

2) MULTI-TIER ARCHITECTURE

Fig. 4 and Fig. 5 illustrate the network architecture of our multi-tier WMSN and communication flow between nodes, respectively. At tier-1, we used low-power sensor nodes that are capable of detecting motion using PIR sensor in the location that is under surveillance. When motion is detected in step-1, tier-1 nodes send BLE advertisement to tier-2 controller nodes.

In step-2, the controller receives the advertisement, turns off its BLE radio module and powers-up the camera node by latching the relay switch. The reason for turning off the BLE radio at this step is to save power of the controller when the camera node is up and running.

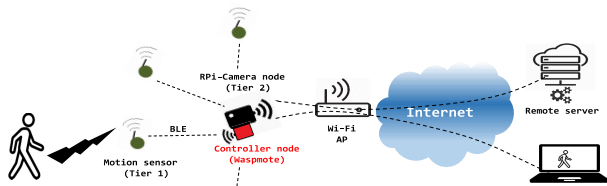In step-3, the camera node starts streaming video to the remote computer over TCP. It is up to the camera node
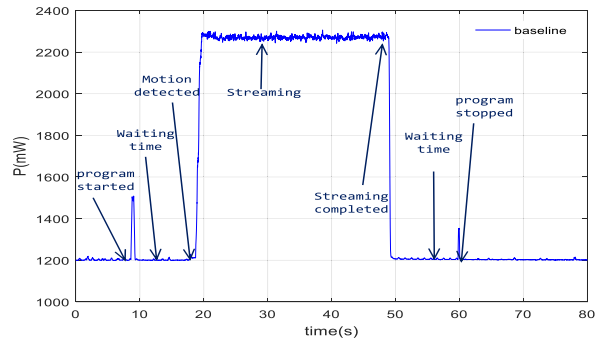
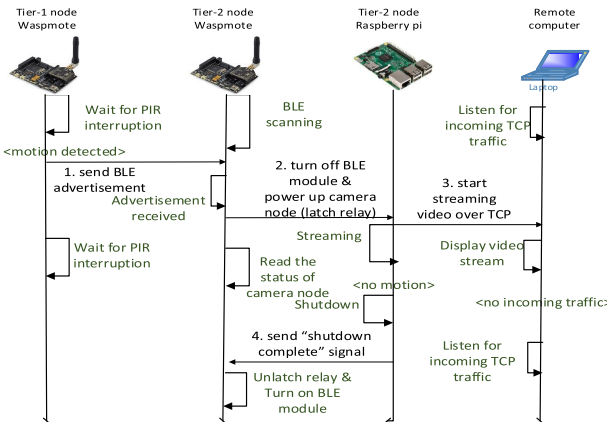**FIGURE 4.** Multi-tier network architecture.

FIGURE 5. Multi-tier node communication flow diagram.

to decide when to shut down after it wakes up. Since the controller does not listen BLE messages from tier-1 during this session, we mounted a PIR motion sensor on the camera node to detect the continuity of motion when it is up and running. In the present prototype, the camera node by default streams video of 30 seconds, and if its PIR sensor is active, it continues the stream for another 30 seconds, and so on. When streaming is completed and there are no further movements, the camera shuts down itself.

In step-4, a graceful shutdown completion message is signaled to the controller. The controller unlatches the relay switch and turns-on its BLE radio for the next coming events. It is important to detect a graceful shutdown of RPi before unlatching the relay to avoid the corruption of micor SD card inside RPi. The status of the shutdown process can be read by the controller node on a GPIO pin of RPi that is configured for this purpose.

IV. MEASUREMENT RESULTS AND ANALYSIS

In this section, we report the measurement results gathered from our empirical study of the benchmark setup and our proposed WMSN prototype. The power transients due of specific tasks of the surveillance are highlighted in each graph.

A. POWER CONSUMPTION IN SINGLE-TIER ARCHITECTURE

Fig. 6 depicts the power transients of the baseline setup. The graph presents the power consumption of a standby RPi surveillance camera node at different phases: before the

FIGURE 6. Power consumption of a single-tier architecture.

surveillance program is launched and when only basic operating system tasks are running, after the surveillance program is launched and when the system is in idle mode, when motion is detected and streaming begins, when streaming is finished and the device goes back to waiting mode, and finally when the program is terminated.

A short spike is observed when the program is executed and the device goes to waiting (idle) mode. In the waiting phase, the program is ready to receive interrupt signals that would be fired by the activation of the PIR sensor due to change in infrared radiation in the area. The PIR sensor normally consumes very little power as compared to RPi and has thus no pronounced effect on the overall power consumption of the device. During video-streaming, the average power consumption of the camera node jumps from $1209.9mW$ to $2251mW$ (refer tables 1 and 2).

TABLE 1. Idle (waiting) time power consumption of camera nodes.

	Single-tier	Multi-tier
	Power (mW)	Power (mW)
Controller node	NA	101.2
Camera node	1209.9	0
Total	**1209.9**	**101.2**

TABLE 2. Streaming power consumption of camera nodes.

	Single-tier	Multi-tier
	Power (mW)	Power (mW)
Controller node	NA	253.5
Camera node	2251	2230.7
Total	**2251**	**2484.2**

B. POWER CONSUMPTION IN MULTI-TIER ARCHITECTURE

In this section, we present the power consumption of tier-1 motion sensor, tier-2 controller and camera nodes. Fig. 7 illustrates the power consumption transients of a tier-1 node. When the device is powered-on for the first time, it enters to idle mode after a brief initialization. We programmed the Waspmote main board to be in a sleep mode until it receives external interruptions. Most of the circuitries
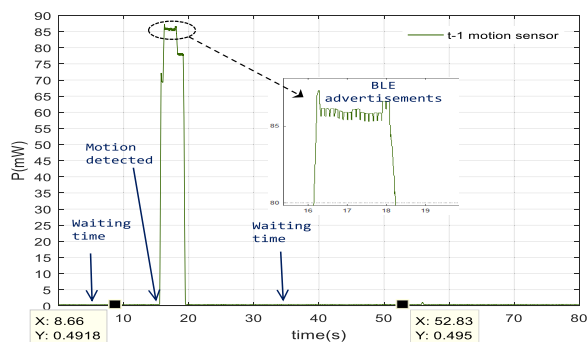
FIGURE 7. Power consumption of tier-1 motion sensor node.

of this node are powered-off, and only the absolute necessary circuitries for receiving external interrupt from PIR sensor are on.

When motion is detected, the device will transit to its active state. The BLE radio module will be turned-on and starts broadcasting advertisement to tier-2 controller node for 3 seconds. During this time, the average power consumption rises to $76.4mW$ from $0.5mW$ in idle mode.

Next, in Fig. 8, we present the power transients of tier-2 nodes. While the graph on the top presents the power consumption of the controller, the bottom one presents that of the camera node. During idle time, the controller is scanning BLE advertisements and camera node is completely powered-off. During this phase, the average power consumptions of the controller and the camera are $101.2mW$ and $0mW$, respectively (refer table 1). Upon receiving advertisement messages from a known tier-1 node, the controller latches the relay and turns off its BLE module. The average power consumption of the controller rises to $253.5mW$ when the relay is latched. It stays in this power state until it detects a graceful shutdown of the camera. The camera boots-up and starts streaming
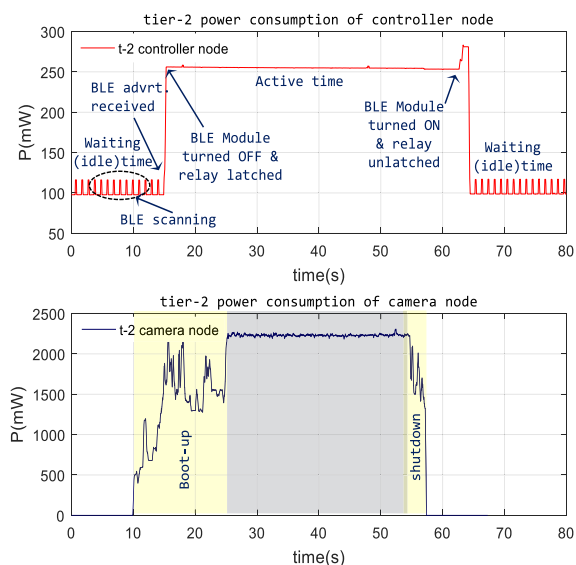
video. The average power consumption of the camera during streaming jumps to $2230.7mW$. Thus, the average power consumption of tier-2, controller and camera combined is $2484.2mW$ (refer table 2).

It should be noticed that, we did not consider power consumption of tier-1 node in the tables for two reasons: At first, it belongs to a different tier and by the time camera begins streaming, the device is already in sleep mode. Secondly, the number of tier-1 devices per a tier-2 device can vary depending on the area of the place under surveillance. For a given amount of area, a single-tier architecture would normally require more power consuming camera nodes compared with a multi-tier. So, it is to the benefit of single-tier architecture that we ignored tier-1 devices at this point.

To sum up this section, we present the power transient graphs of single-tier and our multi-tier camera node prototype in Fig. 9. The graph of the multi-tier represents the combined power consumption of the controller and camera nodes. The graphs are time synced based on starting time of streaming to better visualize the relative power gains and losses. From Fig. 9 we observe:

- 91.64 percent power reduction in the waiting time of multi-tier camera node compared to single-tier, as the result of power management of the camera node using sleepyCAM approach.
- 10.4 percent power increase during streaming phase due to the overhead of controller node that needs to keep the relay switch latched during the up-time of camera node.
- Energy overhead of the camera due to boot-up and shut-down latencies.

Boot and shutdown energy costs are unavoidable but can be greatly reduced with custom design of an embedded Linux distribution. Using open-source embedded Linux build systems, such as buildroot [27] and yocto-project [28], the process of generating a custom embedded Linux distribution
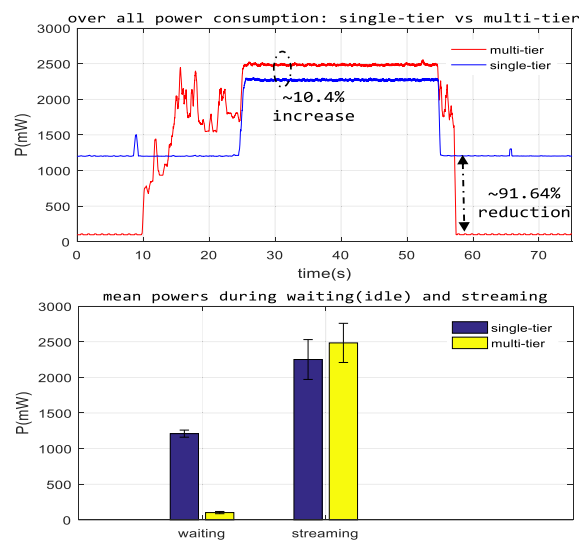

FIGURE 8. Power consumption of tier-2 nodes.

FIGURE 9. Power consumption: single-tier vs multi-tier.

is much more simplified and automated. Thus, it is possible to create a custom embedded OS, that boots fast and contains only the absolute necessary tools for running the surveillance application. In addition, the type and read/write speed of micro SD card also affects the boot and shutdown latencies. However, these are beyond the scope of this paper and we did not try to address them here.

Note that, the boot-up and shutdown energy consumptions are fixed energy expenditures for each event occurrences and their effects would be invisible if the camera node stays awake for longer period of video streaming (see Fig. 10).
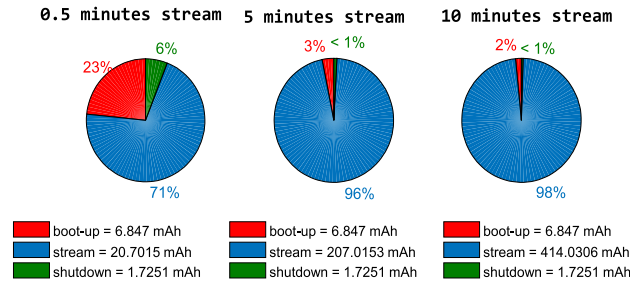

FIGURE 10. Camera boot and shutdown energy overhead with respect to video stream length.

V. ENERGY CONSUMPTION MODEL AND BATTERY-LIFE ESTIMATION

The amount of time it takes for a device to drain a full battery can be estimated by measuring energy consumed during one cycle of an event. One cycle of an intrusion detection by our WMSN prototype is represented by Fig. 11.

To model the energy consumption of the nodes, we measure the average power consumption of each individual node in idle mode (waiting time) and active time, and amount of time each node stays in active state. The active time of tier-1 node is the amount of time it broadcasts BLE advertisement when motion is detected.

The active time of the controller node is the amount of time it keeps the relay latched after receiving a BLE advertisement from tier-1 node. For the camera node, the active time is the total time it takes to boot, stream, and shutdown. Thus, tier-2 nodes (controller and camera) have equal amount of active time that depends on the length of the streaming.

Note, however that, the idle duration can vary depending on application scenario and is unpredictable. The duration which
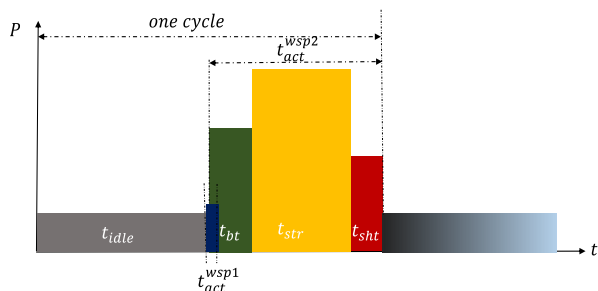
the devices stay in sleep mode depends on the specific field of application: the chance that an intruder crosses a protected area, occurrence of a landslide in mining industry, or a natural disaster in a city. For each device, we simulate the battery-life for different lengths of event intervals (duration of idle time).

Taking into account the cycles of active and idle states, total energy consumption of a device, in mWh, can be expressed in terms of the average power consumptions as:

$$E_{total(mWh)} = n(E_{idl} + E_{act})$$
$$= n(P_{idl}t_{idl} + P_{act}t_{act}) \quad (1)$$

Since battery-life is expressed in mAh, we can normalize the last equation over the supplied voltage.

$$E_{total(mAh)} = n\left[\frac{1}{V}(P_{idl}t_{idl} + P_{act}t_{act})\right] \quad (2)$$

Thus, the number of cycles for a given battery capacity $C(batt) = E_{total}$ is:

$$n = \frac{C(batt)V}{(P_{idl}t_{idl} + P_{act}t_{act})} \quad (3)$$

Similarly, battery-life of a device can be expressed as the gross sum of the idle and active time durations:

$$t_{batt} = n\left(t_{idl} + t_{act}\right) \quad (4)$$

Inserting the right side of equation 3 into equation 4, we get:

$$t_{batt} = \frac{C(batt)V}{(P_{idl}t_{idl} + P_{act}t_{act})}\left(t_{idl} + t_{act}\right) \quad (5)$$

Battery-life of a node can be determined by inserting the parameter values provided in table 1, 2 and 3 into equation 5 for each respective node.

TABLE 3. Model parameters .

	Parameter definition
C(batt)	battery capacity
t_{batt}	battery-life of a device
n	number of cycles
V^{rpi}	voltage supplied to RPi (4.5V)
V^{wsp}	voltage supplied to both Waspmotes (3.7V)
p_{idl}^{rpi}	multi-tier camera average idle power
p_{bt}^{rpi}	multi-tier camera average boot-up power.
p_{str}^{rpi}	multi-tier camera average streaming power.
p_{sht}^{rpi}	multi-tier camera average shutting down power.
p_{idl}^{wsp1}	Tier-1 Waspmote average idle power
P_{act}^{wsp1}	Tier-1 Waspmote average active power
p_{idl}^{wsp2}	Tier-2 Waspmote average idle power
P_{act}^{wsp2}	Tier-2 Waspmote average active power
P_{act}^{sngl}	Single-tier average active power
P_{idl}^{sngl}	Single-tier average idle power
t_{bt}^{rpi}	multi-tier camera boot time ($\sim 15.2sec$)
t_{str}^{rpi}	multi-tier camera streaming time
t_{bt}^{rpi}	multi-tier camera shutdown time ($\sim 2.5sec$)
t_{act}^{wsp1}	Tier-1 Waspmote active time ($\sim 3.9sec$)
t_{act}^{wsp2}	Tier-2 Waspmote active time $= (t_{bt}^{rpi} + t_{str}^{rpi} + t_{sht}^{rpi})$

FIGURE 11. One cycle of an event.

(a) Battery-life of single-tier (baseline)

(b) Battery-life of tier-1 motion sensor node

(c) Battery-life of tier-2 controller node

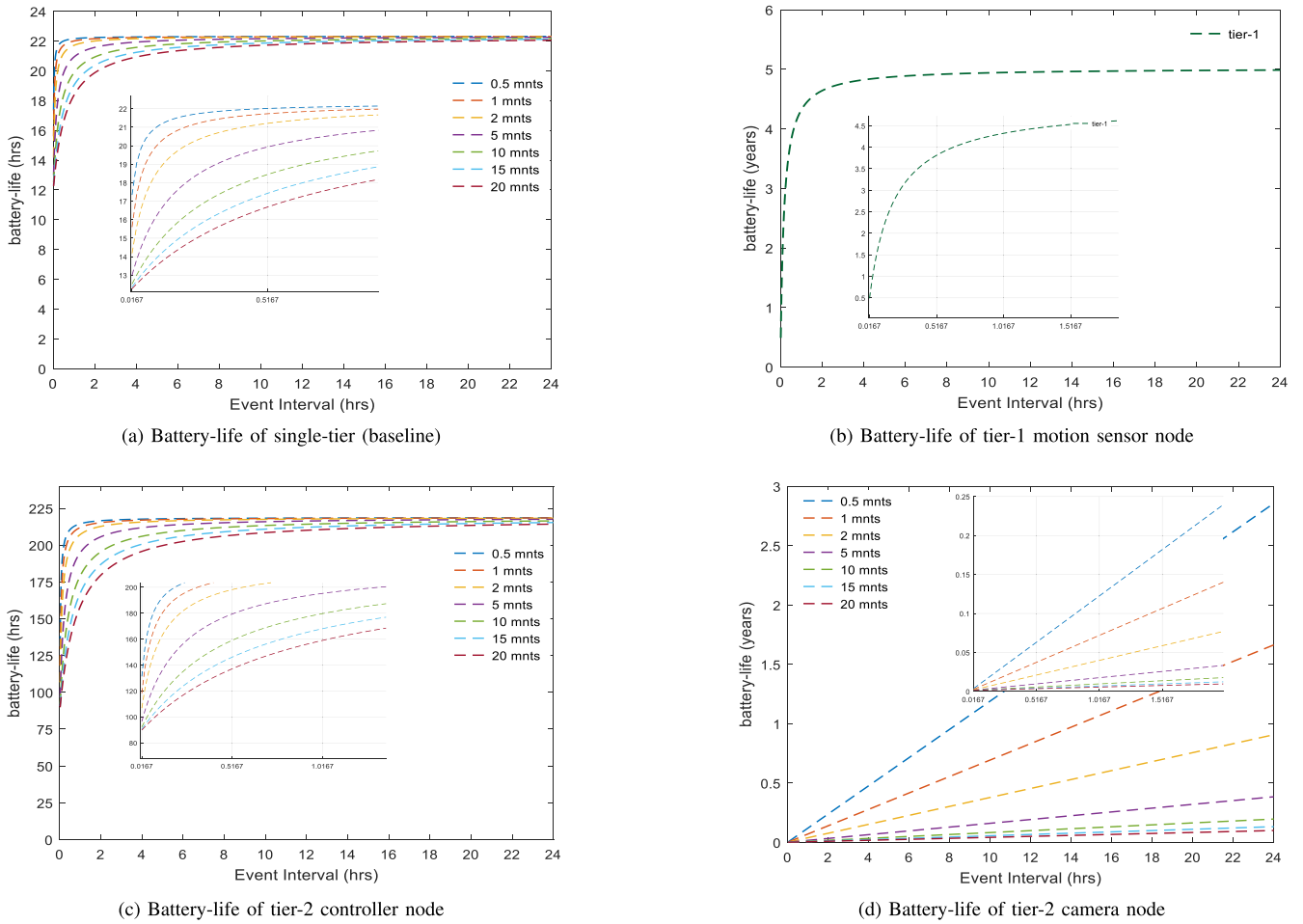(d) Battery-life of tier-2 camera node

FIGURE 12. Battery-life of each node based on equations (6-9).

Thus, the battery-life of our benchmark single-tier camera node is:

$$t_{batt}^{sngl} = \frac{C(batt)V^{rpi}}{(P_{idl}^{sngl}t_{idl} + P_{act}^{sngl}t_{act}^{sngl})}\left(t_{idl} + t_{act}^{sngl}\right) \quad (6)$$

For tier-1 motion sensor node (Waspmote-1):

$$t_{batt}^{wsp1} = \frac{C(batt)V^{wsp}}{(P_{idl}^{wsp1}t_{idl} + P_{act}^{wsp1}t_{act}^{wsp1})}\left(t_{idl} + t_{act}^{wsp1}\right) \quad (7)$$

Similarly, for tier-2 controller node (Waspmote-2):

$$t_{batt}^{wsp2} = \frac{C(batt)V^{wsp}(t_{idl} + t_{bt}^{rpi} + t_{str}^{rpi} + t_{sht}^{rpi})}{\left[P_{idl}^{wsp2}t_{idl} + P_{act}^{wsp2}(t_{bt}^{rpi} + t_{str}^{rpi} + t_{sht}^{rpi})\right]} \quad (8)$$

In the same way, we can derive battery-life of tier-2 camera node. Recall that, tier-2 camera node is powered-off during the idle time. Hence, in a strictly practical sense, the idle power consumption can be equated to $0mW$. Thus, the battery-life of tier-2 camera node is:

$$t_{batt} = \frac{C(batt)V(t_{idl} + t_{bt}^{rpi} + t_{str}^{rpi} + t_{sht}^{rpi})}{\left[P_{act}^{rpi}(t_{bt}^{rpi} + t_{str}^{rpi} + t_{sht}^{rpi})\right]} \quad (9)$$

The simulation results of equations (6-9) are illustrated in Fig. 12. Fig. 12a shows that, single-tier camera node battery can last up to $\sim$ 22.3 hours. If events occur every minute and the camera streams 0.5 minutes video, the battery-life of single-tier camera is about 17.3 hours.

Fig 12b shows that, tier-1 motion sensor of multi-tier architecture can run up to $\sim$ 5 years. If events occur every minute, the battery-life of this node is about 0.5 years. In a similar manner, the controller node at tier-2 can run up to $\sim$ 218.6 hours (refer Fig. 12c). If events occur every minute and controller node has to stay active to power-up the camera node for 0.5 minutes of video stream, its battery-life is about 131.3 hours. More interestingly, the battery-life of tier-2 camera node (Fig. 12d), increases linearly with event interval as there is no idle consumption that would limit the battery-life to a limited maximum. Note, however, that external factors such as temperature may affect the slope of the curves. In the case of 1 minute event interval and camera wakes-up for a 30 seconds video stream, its battery-life is about 31.2 hours.

The last two equations (equation 8 and 9) and simulation results in Fig. 12 are based on the assumption that tier-2 devices (controller and camera nodes) are powered from

different battery sources. That is also the reality in our present prototype (since both Waspmote and RPi have different voltage ratings). But, practically speaking, if the controller battery dies the camera node is unreachable. Thus, to evaluate the battery saving potential of our solution, we combine the controller and camera node energy consumption and compare it against the benchmark.

The energy consumption of tier-2 nodes combined as a system can be found by rewriting equation 1 as:

$$E_{total(mWh)} = n\Big[P_{idl}^{wsp2}t_{idl} + P_{act}^{wsp2}(t_{bt}^{rpi} + t_{str}^{rpi} + t_{sht}^{rpi}) + (P_{bt}^{rpi}t_{bt}^{rpi} + P_{str}^{rpi}t_{str}^{rpi} + P_{sht}^{rpi}t_{sht}^{rpi})\Big] \quad (10)$$

Rearranging equation 10 and inserting the resulting n into equation 4, where t_{act} this time is the sum of t_{bt}, t_{str} and t_{sht}, we obtain the combined battery-life of tier-2 devices presented by equation 11, as shown at the bottom of this page.

We are certainly justified in stating that, the battery-life estimation of tier-2 nodes as integrated system is conservative, as integrated system can use more power efficient communication links between constituting hardwares and components [12].

Fig. 13 and Fig. 14 illustrate estimated battery-life of single-tier vs multi-tier, formulated by equation 11. The graphs show a significance battery-life enhancement using multi-tier over single-tier architecture. The battery-life of multi-tier integrated camera for a 0.5 minutes video-stream can reach up to 216.7 hours, whereas that of single-tier is limited to 22.3 hours (about 194 hours improvement, or equivalently ∼ 870 percentage increase). In a scenario where events occur averagely every minute, multi-tier provides battery-life of about 25.2 hours, whereas single-tier provides about 17.3 hours of battery-life (45.6 percent improvement).
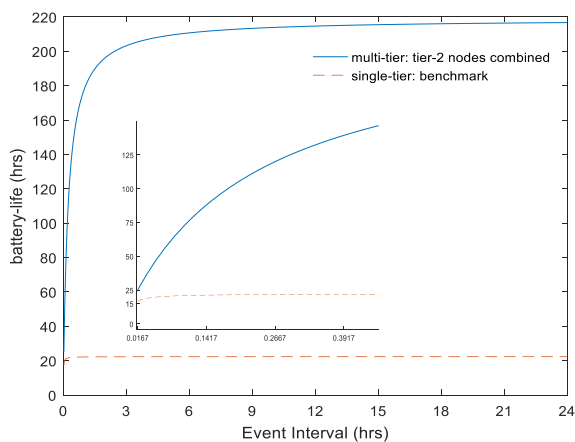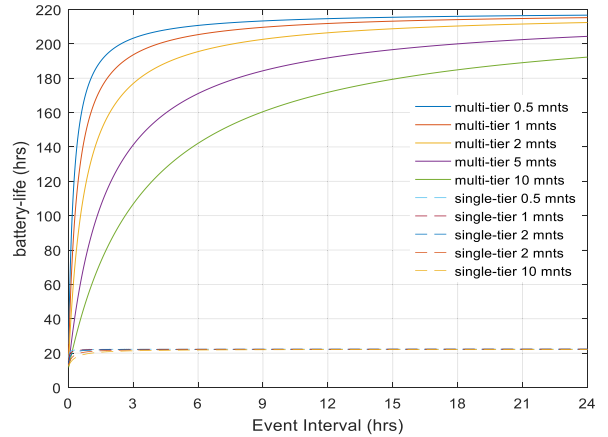

FIGURE 14. Battery-life single-tier vs multi-tier for different lengths of video stream. As the interval of events increases, multi-tier provides longer battery-life.

Finally, it is important to highlight the impact of the controller on the battery-life of tier-2 nodes integrated as a system. Inevitably, from Fig. 9, the reader would assume that battery-life of tier-2 nodes combined as a system can be less than that of single-tier camera node if the video streaming is too long and the idle time duration is too short. Using simulations, we estimated crossover points of events of intervals for variable lengths of video streams as depicted by Fig. 15. The overhead of the controller causes a diminishing battery-life for idle time durations below the crossover points. We found that, for short video streaming (0.5 minutes and so), the overhead does not have negative impact even when the device has to wake-up for events that occur quite frequently (i.e, every minute). As shown on the graphs, we observe a diminishing return on the battery-life of multi-tier
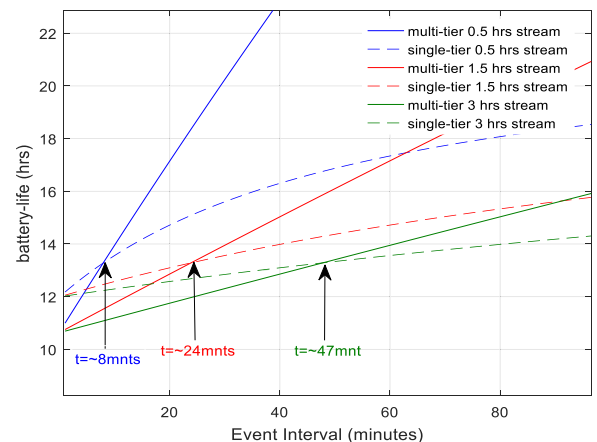

FIGURE 13. Battery-life single-tier vs multi-tier for 0.5 minutes length of video stream.

FIGURE 15. Points of diminishing returns.

$$t_{batt} = \frac{C(batt)\Big(t_{idle} + t_{bt} + t_{str} + t_{sht}\Big)}{\frac{1}{V^{wsp}}\Big(P_{idl}^{wsp2}t_{idl} + P_{act}^{wsp2}(t_{bt} + t_{str} + t_{sht})\Big) + \frac{1}{V^{rpi}}\Big(P_{bt}^{rpi}t_{bt} + P_{str}^{rpi}t_{str} + P_{sht}^{rpi}t_{sht}\Big)} \quad (11)$$

if camera has to wake-up every: ≤ 8 minutes and stream a 30 minutes video, ≤ 24 minutes and stream a 90 minutes video, ≤ 47 minutes and stream a 180 minutes video.

VI. CONCLUSION

In this paper we introduced a multi-tier low-power WMSN for real-time high-quality video surveillance applications. Our prototype is based on heterogeneous deployment of constrained low-cost simple sensor platforms for preliminary event detection and more computationally capable SBC as camera nodes for streaming HD (1080p) video to a remote computer. The underlying communication between motes at different tiers and power management of the high-power camera node are discussed. The power consumption transients at different state transitions are also illustrated in graphs. More importantly, we presented the power consumption model which estimates lifetime of battery-powered motes under varying event intervals and event duration (video-streaming length). The results show that, using our proposed power management and heterogeneous multi-tier architecture, battery-life of a full HD camera can be 194 hours longer than a single-tier architecture (~ 870 percentage improvement).

There are several dimensions to continue this work. The controller node we proposed in our prototype is a modest design that can be optimized with better power switches. The wake-up and shutdown latencies of the camera can also be optimized by creating a custom embedded Linux. More broadly, orchestration of the camera nodes in the edge network for dynamic reconfiguration is an important feature in video-surveillance. These are deferred to future work. We are currently in the process of investigating orchestrated version of the surveillance camera nodes; using additional low-power node that is ideally located in the edge infrastructure of operators. In addition, we are exploring the relevance of virtualizing the camera software using container technologies and investigating the energy overhead of doing so.

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