An Instrument Scheduler Design for Energy Neutral Coastal Monitoring Systems Deployment*

Yuting Zhang, Thomas D.C. Little

Department of Electrical and Computer Engineering, Boston University, Boston, Massachusetts

{*ytzhang, tdcl*}*@bu.edu*

Benjamen R. Wetherill, Francesco Peri, Robert F. Chen

Center for Coastal Environmental Sensing Networks, School for the Environment

University of Massachusetts Boston

{*Benjamen.Wetheril001, Francesco.Peri, Bob.Chen*}*@umb.edu*

Nov 6, 2014

MCL Technical Report No. 11-06-2014

Abstract–Advances in computing, communications, and sensor technologies are creating new opportunities to exploit low-cost instrumentation for widespread and long-term environmental observation. Because a tethered energy infrastructure is usually not available at these remote locations, localized energy harvesting and power management must be employed for the perpetual energy-neutral operation at low cost with low maintenance. Our strategy is to schedule instruments wisely to execute the sensing mission during the targeted periodic or sporadic events, and to 'sleep' or turn off whenever else for energy conservation. In this paper we present the design of a programmable instrument scheduler that works with an Arduino for power management based on real time clock (RTC). The instrument scheduler allows the duty cycle of power-intensive sensing components at arbitrary schedules in the Arduino software. The current circuit hardware is capable of switching four power channels, including one for itself. This instrument scheduler has been used in several practical deployments to control an ecological observation platform of video cameras and wireless networking equipment. The erosion monitoring platform was implemented at the Thompson Island (Boston, Massachusetts, USA) in October 2012 and at the Jones River watershed (Kingston, Massachusetts, USA) in September 2013. Both systems have been in operation as designed since installation, and are expected to continue operating indefinitely. The deployed systems demonstrate how duty cycling can achieve substantial energy savings on a diverse set of devices through complete shutdown. This approach is expected to have wide applicability for a variety of environmental and ecological studies.

---

1   Introduction

Video sensor networks (VSN) are experiencing exponential growth in the memory capacity, computation and wireless communication capability, at the same time along with dramatic reduce in size and cost. These technological advances provide a vehicle for emerging environmental applications from tracking habitat and wildlife to monitoring climate conditions for crops and livestock, from forest fire detection to water quality inspection [1, 2, 3]. These applications enable unattended observation after deployment to support scientific studies for much longer durations, typically for years or even decades. Archived images and videos can be further processed and analyzed for salient events [4].

Marine and coastal environments are extremely challenging for implementing sensing systems. Because a tethered energy infrastructure is usually not available, energy harvesting and power management are the cornerstones to meet the design goals of lifetime, cost, sensing and transmission tasks [5]. Due to the limited access to the physical fields of coastal studies, remote accessibility is required via long distance wireless communication. The wealth of visual details in still and motion imagery require significant energy resource for recording, communication and storage. Coastal events like erosion are sporadic and infrequent. The short-term shoreline recession in the Northeast of the United States is hypothesized and observed related to high tides, incident waves, ferry wakes, and exposure to storms [6]. Capturing the actual erosion events during high tides is significant to understand the dynamics of erosion and document short-term changes. The VSN system needs to synchronize its 'on' time with high tide in the day time everyday, and 'off' whenever else to save energy.

Commercial devices are often not equipped to support this dynamic scheduling mechanism. Timer relay switches such as CN101 (Cnok, Shenzhen, China) only support stereotype alarm functions. Programmable solar charge controllers also build up the system cost. These conventional solutions are neither designed for ultra low power. To address this limitation, we have developed a programmable instrument scheduler based on the Arduino. The Arduino is a low-cost microcontroller that has been increasingly used in wireless sensor network applications [7], such as temperature monitoring in rabbit chambers [8] and water collection tracking in Ethiopia [9]. The Arduino platform is advantageous in the open-source and easy-to-use hardware and software, and extendable in functionality with multiple 'shield' circuit boards. We designed an ultra-low-power circuit hardware which consists of a RTC module, a state of charge (SOC) monitor and power protection components. A software program is designed to achieve power management for the time-varying observation tasks. We developed a wireless video camera network platform by leveraging this instrument scheduler and commercial modules. The platform is capable of long-term energy-neutral operation at low cost with low maintenance. All devices, including antennas and cameras, are wireless networked and internet-protocol (IP) enabled, to support remote access and live view. This environmental observation platform was deployed on the Thompson Island (Boston, Massachusetts, USA) in October 2012 and at Jones River watershed (Kingston, Massachusetts, USA) in September 2013. Both systems have been operating as designed since installation, and have captured erosion related events. To the best of our knowledge, this is the first deployment of an Arduino-based instrument scheduler for power management in environmental monitoring systems.

The remainder of this paper is organized as follows. Section 2 presents the instrument scheduler in circuit hardware and program software. Section 3 depicts the design of our wireless camera network system. Section 4 describes the practical deployments of this VSN system. In Section 5,
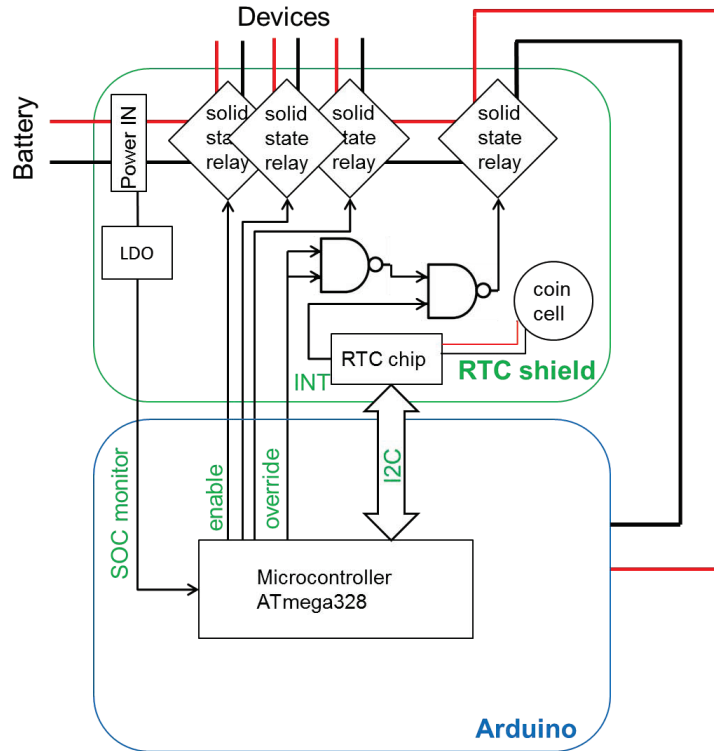
Figure 1: The block diagram of the power management controller.

we provide a result of erosion monitoring and discussion about the system performance. Section 6 concludes this work.

2   Instrument Scheduler

Power management is the key solution to the long-term operation of energy-neutral sensing systems. The primary sensing tasks of these systems should not be sacrificed due to the energy conservation schemes. To support time-varying monitoring applications, we design an instrument scheduler to effectively regulate energy harvesting and consuming, by means of a shield circuit hardware and an Arduino program software.

2.1   Shield Circuit

Considering the overall limited energy resource, we designed an ultra-low-power circuit which consists of a RTC module, a SOC monitor and power protection components. This design takes advantage of the microcontroller ATmega328 (Atmel, San Jose, CA, USA), analog input pins and digital I/O pins on the Arduino. The block diagram of this instrument scheduler is illustrated in Figure 1.

The core of the RTC module is the PCF8563 (NXP Semiconductors, Eindhoven, Netherlands), a low-power CMOS RTC and calendar. It keeps time in year, month, day, weekday, hours, minutes, and seconds. The alarm function can be set on minutes, hours, day, weekday on its internal registers. The PCF8563 supports a two-line bidirectional I^{2}C communication with the Arduino through analog pin A4 and A5. When the targeted sensing tasks are not active, the system energy expenditure is minimized to only keep time and alarm on the PCF8563 by a $3\,V$ coin cell battery cr2032 at $0.25\,\mu A$. When the alarm fires, the RTC module triggers the negative interrupt signal to the NAND gate. One solid state relay AQY272 (Panasonic, Tokyo, Japan) enables the rechargeable battery to turn on the Arduino. The rechargeable battery starts to support the I^{2}C communication and other components. When the Arduino is on, it takes over power switching by applying and holding a digital high override signal to the two-stage NAND gate. The Arduino can enable sensing and communication components by pulling the corresponding digital output pins. Meanwhile, the Arduino also updates the alarm on the PCF8563 for the forthcoming task. When the sensing tasks are completed, the Arduino sets low on these enable pins to turn off the load instruments, then feeds a low override to the NAND gate to shut itself down. The NAND gate ensures the Arduino microcontroller in charge of instrument control once the scheduled sensing task is active as Table 1. The low-dropout (LDO) regulator is adopted to convert $+12\,V$ solar panel and battery to the operation voltage of the instrument scheduler.

Table 1: Instrument scheduling by the NAND gate.

Override	$\overline{\text{INT}}$	Relay	Note
0	1	0	Initial state
0	0	1	RTC alarms
1	0	1	Arduino overrides
1	1	1	RTC alarm is reset
0	1	0	Arduino turns off

Another key element for effective power management is to estimate the SOC of batteries. The battery voltage is widely used as a measure of SOC of batteries. The battery voltage is widely used as a measure of absolute SOC [10]. Particularly, recording and transmitting videos and images are power intensive, and require sustained energy reservoir. The SOC monitor module enables the Arduino to measure the battery voltage on an analog pin. The Arduino then makes the power-cycling decision whether to execute tasks now or to conserve energy for the future. This module also benefits to endure the lifetime of the battery and devices.

The solid state relay AQY272 is used to enable load devices due to the output current on the Arduino pin is limited to $40\,mA$ at $3.3\,V$. It also protects low-power circuitry. Different from a coil relay, the AQY272 uses a semiconductor to eliminate the necessity for the always-on power. When the digital enable pins are high, each relay can control up to $2\,A$ load with $1.5\,mA$ input current. Figure 2 shows the shield PCB with all aforementioned functional modules on the left, and on the right shows the instrument scheduler, i.e., the shield stacked over the Arduino. Currently, four relays are placed on the shield board: one implements power cycling for the instrument scheduler itself; the other three can support up to three loads respectively. More switching channels can be adopted by adding more relays circuity and using more digital pins. A bypass switch is placed
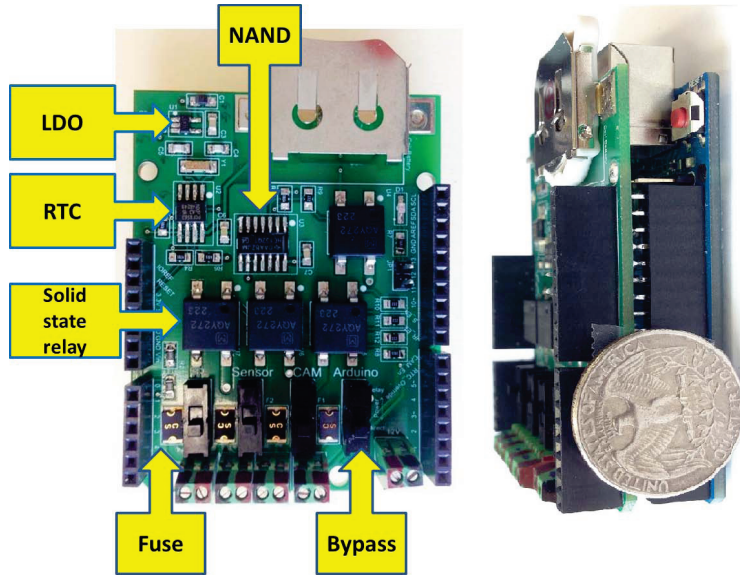
Figure 2: Left: the shield PCB; right: the instrument scheduler, the shield stacked over the Arduino.

along each relay for the convenience of inspection. Fuses are also added for the circuitry and device protection.

2.2 Power Management Software

The Arduino Uno, the lowest at cost, processes $32\ KB$ flash memory with bootloader and $1\ KB$ EEPROM on board. This memory is competent to store a table of daily high tide for more than 6 months. The Arduino offers an open-source integrated development environment (IDE). This software is easy to use, especially for environmental scientists without much intensive coding experience.

The basic structure of an Arduino program runs in at least two parts as follows.

```
void setup(){
        statements;
}
void loop(){
        statements;
}
```

The setup() function is only called once upon powering up. It typically takes care of initializations, such as pin assignments. After the setup() function finishes, the loop() function, precisely as its name suggests, loops iteratively, and allows the Arduino board to execute sensing and actuating on its analog and digital pins.

We design the power management software that takes full advantage of this structure and aforementioned hardware features. The power cycling flow for the erosion monitoring is shown in Figure 3, the green blocks indicates the shield's action, and the blue ones for the Arduino. In the
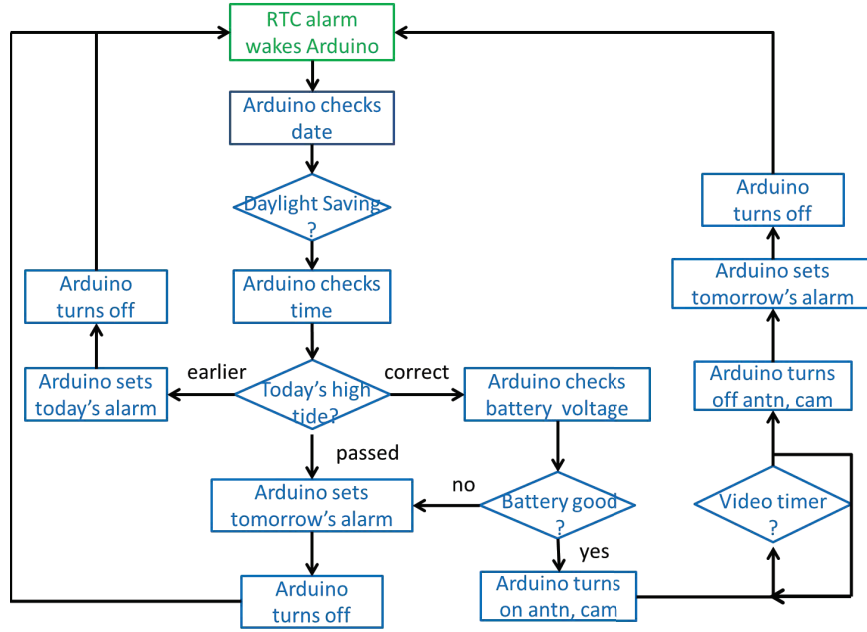
5

Figure 3: The software flow for erosion monitoring.

software script, we first define the aimed monitoring window, for example, 2 hours centered at the exact high tide. During periods outside this window, the Arduino, antenna, and camera are all off; only the PCF8563 runs on the coin cell battery and keeps time for the alarm. When the alarm triggers on the Arduino, the Arduino starts the program and calls the `setup()` function. The Arduino communicates the RTC shield and reads current date. The software compensates the 1-hour shift for the daylight saving time. Then the Arduino reads current time, and compares it to today's high tide schedule in the table. In cases of extremely insufficient energy harvesting during continuous severe weather, this alarm could be out-of-date, either earlier or later than today's schedule. If it is earlier, the Arduino writes today's alarm to the PCF8563, and then turns itself off. If it is later, the Arduino writes tomorrow's alarm and turns off. In both situations, the `setup()` terminates, and the alarm is updated to the forthcoming high tide. If the alarm is right on time for today, the Arduino proceeds to measure the battery voltage in the `setup()`. If the SOC is not competent, the Arduino conserves energy for tomorrow. Only when the battery is sustainable, the Arduino turns on the camera and antenna, and proceeds to the `loop()` function. The `loop()` function keeps video recording and transmission for the predefined length of time window, and takes other actions like periodic SOC measurements. At the end of the window, the Arduino sets tomorrow's alarm and turns off everything. This software flow allows effective power management for arbitrary time-varying sensing tasks.

3 Camera System Design

Practical deployment and implementation of coastal monitoring VSNs pose challenging requirements on the system desgin, including low cost, long term, low maintenance, low power, energy harvesting, power management, remote access and live view, video delivery and storage [11].

6

Table 2: Features of commercial devices in the VSN platform.

Device	Cost	Physical characteristics			Radio performance		Electrical metrics		
		Humidity (%)	Temperature (°C)	Enclosure	Coverage	Angle	Voltage (V)	Surge current (A)	Max power consumption (W)
AXIS camera	$180	20 to 80	0 to 50	Weatherproof case	n/a	n/a	5	0.5	2.2 (including regulator)
Pico2	$50	5 to 95	-20 to 70	Outdoor UV stabilized plastic and die cast metal	150 m	Omni-drectional	12	1	4
Nano2	$80				15 $km+$	30° elevation 60° azimuth	12	1	4
PS2	$130		-40 to 80		50 $km+$	18°	12	1	6.5

3.1 Network Design

Based on a video sensor unit prototype [12], we exploit technological advances of commercial available devices to address these requirements. These devices are well technical supported, and ease the installation and maintenance processes for environmental and ecological scientists. We leverage a network camera from AXIS Communications (Lund, Sweden) and wireless antennas from Ubiquiti Networks (San Jose, CA, USA) into camera nodes, relay nodes, and base stations of the VSN. Table 2 identifies device features in cost, physical characteristics, radio performance, and electrical metrics.

- Camera node. A camera node is comprised of an AXIS M1101 network camera and a PicoStation2 (Pico2) antenna. The AXIS camera provides multiple configurations in video compression, resolution, frame rate and streaming.

- Relay node. A relay node is an optional one. It facilitates the extension of wireless coverage and the establishment of network route when needed. It is composed of Pico2 and NanoStaion2 (Nano2) antennas. When a number of relay nodes are implemented, they can form a distributed mesh network.

- Base station. A base station aggregates video streaming data, and supports high-speed transmission with more communication capability. A PowerStation2 (PS2) can empower long distance wireless link up to $50\ km$.

- Server. We use the AXIS camera station software on the workstation for the video data repository and retrieve.

3.2 System Power Planning

To sustain long-term energy-neutral operation, a VSN node consists of an instrument scheduler, a high-resolution video camera, wireless transceivers, a rechargeable battery, and a solar panel. Fig-
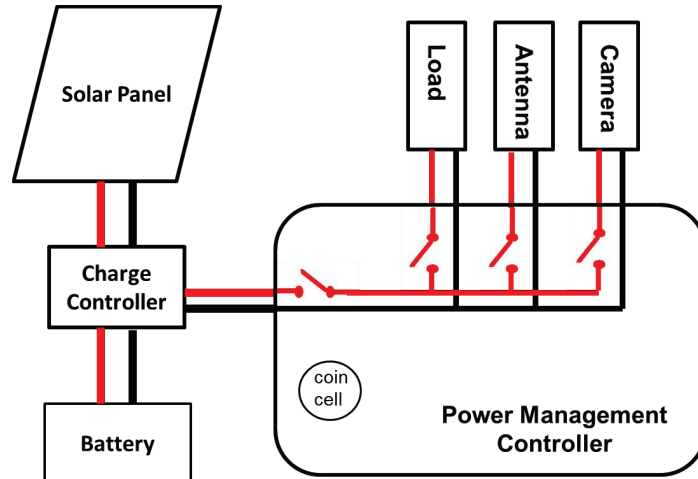
Figure 4: Components connections in a VSN node.

ure 4 illustrates the generalized interconnections among the node components. The power planning accounts for the total power consumption, solar energy harvesting, and battery capacity. The rule of thumb is that solar power in must be greater than the power out. The battery capacity also needs to reach the energy reservation for certain consecutive days when sunlight is not available. The power budget is formulated in the equation array (1). Without loss of generality, we estimated 4 hours of sunlight during winter in the northeast, and targeted for 4 to 5 days on the battery. Based on the device electrical metrics in Table 2, we carefully selected battery and panel for each node. A camera node with $12\ AH$ battery and a $20\ W$ panel is assembled like Figure 5.

4 Camera System Deployment

The site investigation is of crucial importance, because the topographic and geographic features of the site define the practical constrains. The placement of each node must be carefully selected. We prepared and tested all configurations in controlled environment before deployment.

4.1 Bluff Erosion Monitoring

The wireless VSN was first implemented on the Thompson Island in October 2012. The 20-foot bluff at the northeast tip is undergoing rapid erosion; wakes at high tides are able to reach the base of this bluff. A camera node is placed that the bluff is in the camera's field of view. A relay node is sited over the bluff, circumvents hills and trees, and enables the line-of-sight (LoS) wireless links. The base station is located near the salt tidal pond, where the PS2 achieves high-speed wireless connection to the UMASS Boston facility. An experimental camera is added to the base station watching the beach. Figure 6 shows the physical location on the map of Thompson Island. The three links span about $3.5\ km$ distance from the erosion bluff to the facility where the server seats.
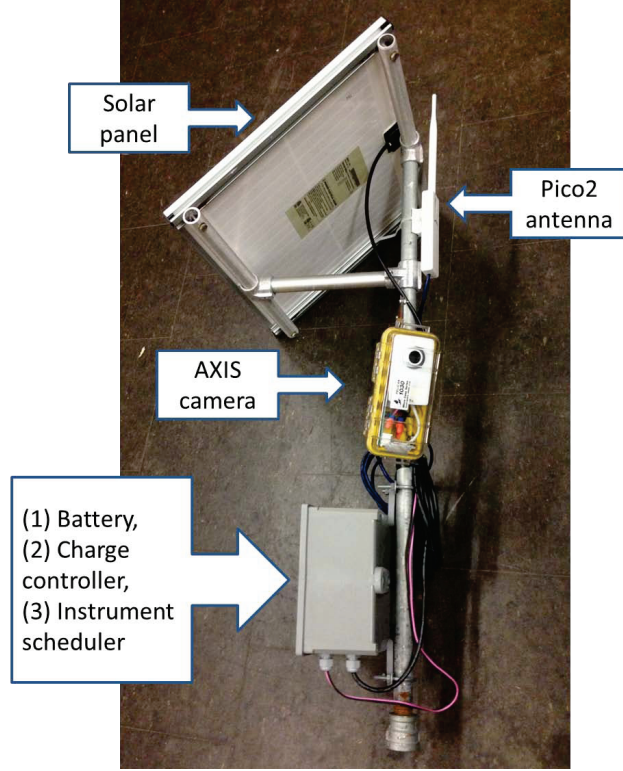
Figure 5: A camera node assemblage.

$$
\begin{cases}
\text{Node consumption (Wh/day)} & = & \sum \text{device consumption (Watt)} \times \text{Node ON interval (hours/day)} \\
\text{Solar supply (Wh/day)} & = & \text{Panel power (Watt)} \times \text{Effective harvesting interval (hours/day)} \\
\text{Battery energy (Wh)} & = & \text{Battery voltage (V)} \times \text{Capacity (Ah)} \\
\text{Solar supply in} & \geq & \text{Node consumption out} \\
\text{Battery energy} & \geq & \text{Node consumption} \times \text{Operating days without sunlight}
\end{cases}
\tag{1}
$$

In November 2012, we tuned the wireless channels to eliminate interference. In January 2013, the instrument scheduler was developed and implemented. Since then, the erosion monitoring system has achieved energy-neutral operation to date.

4.2 Salt Marsh Erosion Monitoring

The success on the Thompson Island evokes more applications of this VSN system. A salt marsh erosion VSN was installed at the Jones River watershed in September 2013. As shown in Figure 7, this site eases the network topology to a single link between a camera node and a base station. The network simplification also leads to robust performance. The cost of this single-link implementation is $820, including all commercial components, the instrument scheduler, and structural
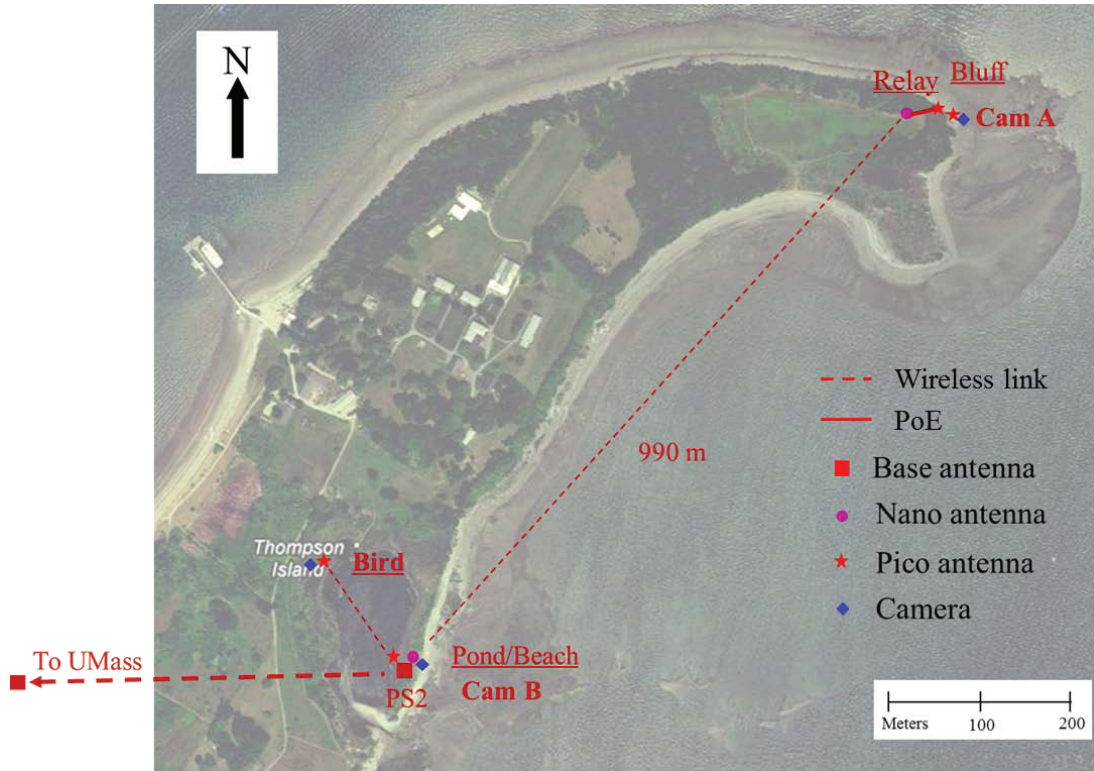
Figure 6: The bluff erosion VSN deployment on the Thompson Island.

hardware. Comparatively, the state-of-art commercial solution is over $7,000$ for outdoor CCTV and approximate $3,000$ for an outdoor router.

In general, the on-site node deployment involves location selection, structure installation, and network adjustment. Due to the current software program memory on the instrument scheduler, semiannual site visits are necessary and sufficient to update high tide table, inspect the equipment and facilitate maintenance.

5   Results and Discussion

Since the initial operation of the VSN on the Thompson Island, several significant erosion processes have been successfully captured. [1] Erosion discoveries during the Hurricane Sandy and winter storms in 2012 has been published in [11]. The daily bluff video in 2013 shows sporadic occasions when extreme high tide and sustained storm waves reach the base, while boat wakes are not prolonged enough. These tidal effects have been corroborated by the wake actions in the beach camera. During winter storms, snow covered the bluff and soil was frozen. Gradual slumping is visible during frost and thaw processes when the temperature fluctuated below and above the freezing point. The most significant frost settling was observed on Feb $24^{th}, 2013$. This discov-

---

[1]Videos and images are all updated on the website of the UMassBoston Center for Coastal Environmental Sensing Networks (CESN). http://www.cesn.org/

Figure 7: The salt marsh erosion VSN deployment at the Jones River watershed.

ery observation encourages further investigation on the driven factors of erosion. Daily images at Jones River also have captured changes of the river bank.

Two key concerns of this energy-neutral VSN have been identified in our practical deployment. The first is the provident power planning. Our instrument scheduler have demonstrated effective switching the devices on during high tide windows and off ortherwise. In 280 days out of year 2013, bluff videos have successfully arrived at the server from the Thompson Island. During 10-month operation to July 2014, images of the Jones River watershed have been archived, merely except for 13 days. The second is the network complexity increases with the number of wireless hops. The LoS links are critical for the delay-stringent video transmission. The more links there are in series, the more susceptible the network is to volatile activities. We further investigated the date distribution of the bluff video. During July, August, September and October, videos arrived in almost everyday. The worst performances were in March and November, only working for 15 and 11 days respectively. The daily network connectivity was statistically hypothesized and tested against the local weather conditions such as rain and wind at the Charles river and Boston Harbor. The VSN performance was not significantly correlated with rain precipitation. There is at high confidence that the failure of video delivery was correlated with wind speed over $0.7\ mph$.

6   Conclusions

The applications of VSNs could advance many scientific pursuits in ecological and environmental studies. To work as a viable modality in most practical conditions, the VSNs must be low-cost, long-term, low-maintenance, low-power, capable of energy harvesting, economized on power cycling, and networked to enable remote access, live view, imagery delivery and storage. Some studies involve time-critical sensing tasks, such as erosion monitoring during the high tide everyday. We developed an instrument scheduler solution, which incorporates the Arduino-based shield

circuit and software. We deployed the energy-neutral wireless VSN with this instrument scheduler and commercial components for erosion studies on the Thompson Island and at the Jones River. Both systems have been operating as designed since implementation. They are expected to continue operating perpetually with little on-site maintenance.

In summary, the instrument scheduler can improve the effectiveness of energy-harvesting and energy-neutral sensor networks. This shield hardware can be directly reapplied or simply customized at very low cost. The software is capable to configure multiple windows of different length based on arbitrary types of time tables. We plan to make the RTC shield PCB files open-source. We expect to further moderate the maintenance by enabling remote programming for the software update. As the cost and availability of this technology continues to improve, we anticipate increasing benefits in a variety of large scale for environmental monitoring studies.

7 Acknowledgments

References

[1] I. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: a survey," *Computer Networks*, vol. 38, no. 4, pp. 393–422, Mar. 2002. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1389128601003024

[2] B. Wetherill, "Modeling Bacterial Water Quality with Networked Real-Time Sensors," 2014. [Online]. Available: http://scholarworks.umb.edu/masters_theses/257

[3] J. Yick, B. Mukherjee, and D. Ghosal, "Wireless sensor network survey," *Computer Networks*, vol. 52, no. 12, pp. 2292–2330, Aug. 2008. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1389128608001254

[4] D. Cullen, J. Konrad, and T. Little, "Detection and Summarization of Salient Events in Coastal Environments," in *2012 IEEE Ninth International Conference on Advanced Video and Signal-Based Surveillance*. IEEE, Sep. 2012, pp. 7–12. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6327976

[5] A. S. Weddell, M. Magno, G. V. Merrett, D. Brunelli, B. M. Al-Hashimi, and L. Benini, "A survey of multi-source energy harvesting systems," pp. 905–908, Mar. 2013. [Online]. Available: http://dl.acm.org/citation.cfm?id=2485288.2485505

[6] E. A. Himmelstoss, D. M. FitzGerald, P. S. Rosen, and J. R. Allen, "Bluff Evolution along Coastal Drumlins: Boston Harbor Islands, Massachusetts," *Journal of Coastal Research*, vol. 225, pp. 1230–1240, Sep. 2006. [Online]. Available: http://www.jcronline.org/doi/abs/10.2112/06A-0005.1

[7] R. Faludi, *Building Wireless Sensor Networks: with ZigBee, XBee, Arduino, and ProcessingÂ (Google eBook)*. "O'Reilly Media, Inc.", 2010. [Online]. Available: http://books.google.com/books?hl=en&lr=&id=xMC69vQJLZIC&pgis=1

[8] J. Pascual and F. Marco-Jiménez, "Technical note: design of a large variable temperature chamber for heat stress studies in rabbits," *World Rabbit Science*, no. 19, pp. 225–231, 2011.

[9] R. Chaudhri, R. Sodt, K. Lieberg, J. Chilton, G. Borriello, Y. Masuda, and J. Cook, "Sensors and Smartphones: Tracking Water Collection in Rural Ethiopia," *IEEE Pervasive Computing*, vol. 11, no. 3, pp. 15–24, Mar. 2012. [Online]. Available: http://www.computer.org/csdl/mags/pc/2012/03/mpc2012030015.html

[10] P. Sommer, B. Kusy, and R. Jurdak, "Power management for long-term sensing applications with energy harvesting," in *Proceedings of the 1st International Workshop on Energy Neutral Sensing Systems - ENSSys '13*. New York, New York, USA: ACM Press, Nov. 2013, pp. 1–6. [Online]. Available: http://dl.acm.org/citation.cfm?id=2534208.2534213

[11] Y. Zhang, B. R. Wetherill, R. F. Chen, F. Peri, P. Rosen, and T. D. Little, "Design and implementation of a wireless video camera network for coastal erosion monitoring," *Ecological Informatics*, vol. 23, pp. 98 – 106, 2014. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S157495411300068X

[12] T. D. C. Little, J. Konrad, and P. Ishwar, "A wireless video sensor network for autonomous coastal sensing," *Proceedings of the conference on coastal environmental sensing networks (CESN 2007), Boston, MA, USA*, 2007.