Ecological Monitoring Using Wireless Sensor Networks—Overview, Challenges, and Opportunities

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Abstract. Wireless sensor networks (WSNs) offer a powerful feasible integration of distributed sensing capability, real-time data analysis, and remote surveillance due to the combined result of miniaturization of electronic devices and availability of powerful computational capability, larger information storage, and ubiquitous Internet connection. With these advances, WSNs are starting to be translated into a new ecological knowledge. They are providing a new insight into the observation of the world in new ways of extended spatial and temporal scales. Through WSNs, more unexpected phenomena can be obtained, and new paradigms can be developed. Recently, more and more ecological WSNs have been established, and lagre WSNs are deployed to monitor habitats with different scales. The research in the temporal scale ranges from the evaluation of soil moisture dynamics at several minutes to daily precipitation. Spatial measurements, on the other hand, range from the evaluation of global climate change to those related to the monitoring of forest and riparian environments in the range of a few meters. Although we are seeing more use of ecological WSNs, opportunities and challenges begin to be realized, including newly better design of software and hardware, formulation of new questions, discovery of previously unobservable phenomena, and development of new sensors, etc.

1 Introduction

Before 1980s, the scientist must deploy sensors such as thermometers, hygrometers, precipitation collectors to record in situ measurement. And they periodically visit the places where the instruments were set up to manually record sensed data [1]. With the advent of microprocessors and the advanced technology of very large scale integration (VLSI) on IC design in the 1980s, sensors were then connected to a microprocessor-based data logger through which the sensed data could be recorded electronically and an observation with a much frequent sampling rate would be achieved. The sensed data could be obtained with a lower frequent manual visiting. Meanwhile, some data loggers were connected to the modems with the remote communication capability based on phone wire. By doing so, the

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sensed data could be retrieved by the remote control center automatically. Recently, because wireless transmission technologies began to revolutionize personal communication networks, brand-new applications have rapidly developed to this point such as weather information update on cellular phones, GPS navigation in vehicles and cellular phones, file share in Internet cloud services, and wireless Internet access at hotspots in modern cities. Therefore, there is a growing trend of applications involving with connecting humans to the surrounding environment, plants or animals, such as landslide detection [2], pest population detection [3-4], structural health monitoring of bridges [5] using wireless remote monitoring technologies, and animal tracking using Radio Frequency Identification (RFID) technologies. A key to the advances is the development of cyberinfrastructure presented by National Science Foundation (NSF), U.S. [6], which is a technological solution that support advanced data storage, access, inquiry, mining, visual representation, and computing over the Internet.

New ways of processing and recording collected data, new types of sensor, and new methods of data communication are leading to the growing use of WSNs [7]. With new sensing technologies, the measurement is not restricted within a few variables, such as general meteorological variables, but is extended to a variety of variables, such as the concentration of carbon dioxide (CO_2) and nitrogen dioxide (NO_2) in air, soil moisture, and other types of chemical materials [8-9]. Coupled with cyberinfrastructure, WSNs provide a powerful combination of distributed computing capability, sensing capability, Internet connection, wireless access, and self-configuration that can be applied to countless various ecological applications. The scientific imperative of multi-point observation also drives the adoption of advanced WSNs by biologists. Moreover, WSNs allow an near-real-time observation based on the incoming sensed data stream from remote fileds. With the characteristics of high-frequency and large spatial scale sampling, the use of WSNs is offering a better understanding of ecological systems by showing the previously unobservable phenomenon. Hart and Martinez [10] have concluded that WSNs will become a standard research tool by reviewing more than 50 examples of WSN applications.

To date, the environmental science community, which is supported by the National Science Foundation (NSF, U.S.), National Oceanographic Partnership Program (NOPP, U.S.), etc., has begun designing and implementing some new observing systems, including the National Ecological Observatory Network (NEON) [11], the Collaborative Large-scale Engineering Analysis Network for Environmental Research Network (CLEANER) [12], and Global Lake Ecological Observatory Network (GLEON) [13]. For example, the mission of NEON is to increase the understanding of how ecosystems and organisms respond to the variation in climate and changes in the use of land in US. Figure 1 demonstrates the infrastructure regarding the regional distribution of sensors and data transmission nodes in the NEON program. Through the combination of WSNs and wireless/cable communication technologies, the important feedbacks related to the change of territorial use among atmosphere, geosphere and biosphere could be

Fig. 1. The NEON's infrastructure to advance ecological monitoring (created by Nicolle Rager-Fuller, National Science Foundation, 2007) [11]

measured, and a further investigation could also be conducted. Similarly, Rundel et al. [14] have indicated that Southern California faces many challenges in managing the environment, so examining how the ecosystem is affected by human activities, e.g. change of land use, is crucial. On the other hand, how the human living is influenced by the ecosystem structure and climate also needs to be investigated. The researchers concluded that the combination of new sensing and communication technologies as the NEON program did is a promising way to explore such information. Furthermore, NASA has developed the Integrated Earth Observation System (IEOS) [15] to integrate the data from ocean buoys, satellites, weather stations and in-situ earth observing instruments into advanced decision support tools and science numerical models that will offer new outcome benefiting worldwide science research. In addition, the research team of Texas Environmental Observatory (TEO) [16] aims at providing near-realtime data of environmental conditions in the state of Texas based on the wired/wireless ground sensors, which were built by other research teams or governmental organizations. The data includes rainfall, water quality, weather information, and soil moisture. The ecologists expect to build the hydrologic model by analyzing and synthesizing the valuable sensed data provided by TEO. More importantly, TEO also offers cyberinfrastructure to make the data available to the public.

Because the automated WSN-based systems could extend the scales of observation, they could cooperate with the ecological models and theories. A better understanding of ecology would be achieved when spatial, temporal, quantitative data could be easily compared. If the data is collected daily at a few monitoring sites, but the ecological model is built resting on the hourly scale of a large range observation, it does not make sense to perform the analysis. In general, WSNs provide an appropriate scale and accuracy of observation that is sufficient to build an ecological model, thus allowing a wider and detailed verification. However, although WSNs offer a improved capability of performing automatic ecological observation, they generate a vast amount of data needs to be further identified, mined, and analyzed. In order to deal with such a data richness problem, Collins et al. [17] have presented a conceptual strategy to reduce the scale of WSNs and their associated cyberinfrastructure to three main components that are common to the field ecological experiment: 1) the sensors which are specific for unique measurements; 2) a WSN that gathers and transfers the sensed data; and 3) the end user analyzes and interprets the data with a particular question. The sensors and end users were problem-specific, whereas WSNs are generalized across different applications. Understanding the relations among the three components would lead to more efficient WSNs. Practically, there have been many existing studies developing the potential ability of WSNs to function beyond the acquisition of large amount of complex sensed data. That is, the WSN itself is able to produce and transmit the particularly important information in a usual form from the sensed data rather than directly transmitting the raw data [18-20]. On the other hand, a technology called Sensor Web Enablement (SWE) [21], developed by OGC based on the notion of Sensor Web first proposed by NASA's Jet Propulsion Laboratory [22-23], allows more end users to manipulate the sensed data from WSNs and control data quality via Internet.

Although employing the WSN technology could facilitate the ecological observation, there have been many challenges that need to be overcome, including the issues of data gaps caused by sensor failure or energy depletion of sensor nodes, stability of operation, housing process in a wild environment, constrained energy source, reliability of wireless communication, etc. Fortunately, more and more ecologists, scientists, and engineers have presented new solutions of hardwares and approaches to deal with these issues in order to optimize sensor fidelity, data completeness, and system operating performance.

In this article, we will investigate the characteristics of ecological WSNs by reviewing and summarizing the existing studies involved with terrestrial, soil, and aquatic surveillance, etc. Meanwhile, combing with our more than five years experience of implementing the near-real-time WSN-based pest monitoring system [3-4], we also address the possible challenges and opportunities for using ecological WSNs.

2 New Advanced Sensors Allowing New Ways to Conduct Ecological Monitoring

Due to the advance of Microelectromechanical Systems (MEMS), a variety of sensors with a very small size have been well developed. Theses sensors are capable of converting real world physical/analog values such as temperature, stress, strain, pressure, etc, into an electrical signal. In general, sensor modalities can be categorized into three types, 1) physical sensors; 2) chemical sensors; and 3) biological sensors [24]. Firstly, physical sensors are common ones and may include the sensors used to measure temperature, relative humidity, lead wetness, wind speed, wind direction, cup anemometer, 2-D/3-D sonic anemometer, and soil moisture. These physical sensors are usually, reliable and with low power consumption, but not expensive. Secondly, chemical sensors may be used to measure soil carbon dioxide, soil nitrate, phosphorus, but they are expensive and deployed under a reliable environment. Finally, the minirhizotron image sensor, sap flow sensors, and acoustic sensors belong to the biological sensors, which are expensive and need a control system.

Coupled with a communication component and a microprocessor, sensors are able to carry out a unobtrusively successive observation at a distant place where people cannot easily arrive at. These individual entities with capabilities of sensing and communicating are called sensor nodes in this article. Further, through the data received from the network configured by these sensor nodes, ecologists can study animals behavior, oceans, and rare dangerous events that cannot be directly observed. In some cases, the rates of ecosystem processes can be estimated as coupled with ecological models. In Table 1, we will show the examples of utilization of advanced sensors in ecological observation ranging from ecology surveillance of pests to in-stream temperature monitoring, we also provide some discussions regarding the insights drawn from ecological observation.

In addition to these sensors mentioned above, the advent of low power digital cameras allows automatic in-situ photography. The in-situ images could be captured and then compressed into a digital file with a smaller size by a compression IC chip. These images are wirelessly transmitted to a remote control center to be restored into a database. Further, due to the smaller size of images, a series of images collected during a short time frame, i.e., a short film, could also be produced to achieve a complete and detailed record for complicated dynamic ecological behavior. For example, Chen et al. have deployed a solar-powered remote visual surveillance system to monitor the Chinese Crested Tern (*Thalasseus bernsteini*), which is one of the least known and possibly the rarest seabirds [34]. Through these images sent back to the remote base station every 30 minutes, ecologists could study the brooding and breeding activities of these seabirds, as well as the population dynamics. Wawerla et al. [35] have used solar panels, a battery, and a camera to build a ecological monitoring system for grizzly bears at the Ni'iinlii Njik (Fishing Branch) Park in Canada. The captured video was periodically forwarded to the control center/base station and was stored in hard drives via a radio signal. Such a visual system aids ecologists in investigating the behavior of grizzly bears. Due to the observation was conducted in an arctic region, how to maintain an normal operation under such a severe climate and environment is crucial for the remote visual surveillance. Figure 2 shows some practical photos of these ecological applications.

Table 1. Summary of ecological monitoring using various advanced sensors

Example	Sensor modality/ technology	Property	Insights or comments
Landslide detection [2]	Geologic sensors (geophone and dielectric moisture sensor)	C, G	Studying the relations between the occurrence of landslide and the environment
Ecological monitoring for pests [3-4], Figure 1(a)	Pest number (detected by a particular sensor) meteorological parameters	A, C, G, H	Studying the population dynamics and distribution of pests and its ecology, and providing pest outbreak forecast
Hydrologic monitoring [25], Figure 1(b)	Soil moisture, meteorological parameters	C, H	Understanding the vegetation distribution and response to flooding
Cattle trajectory tracking [26], Figure 1(c)	GPS devices affixed to WSN motes	A, B, F	Discovering animal-landscape interaction
Avian activity around the entrance to burrow [27], Figure 1(e)	RFID, temperature/ humidity sensor, PIR (Passive Infrared) sensors	C, E, F	Understanding the bird's breeding, arrival/departure to burrow activities
Desert shrub microclimate [28]	Air/soil temperature, light sensor	C, F	Finding the relation of shrub species and microclimate
Carp tracking in a lake [29]	Robotic sensor, radio tag	C, F	Studying carp migration behavior and distribution in the lake
Diurnal fluctuations of pH, dissolved oxygen, and temperature by photosynthesis nia lake[30]	Water quality sensors (pH, dissolved oxygen, water temperature)	C, F	Exploring how an aquatic environment is influenced by the algal blooms
Dynamics of phytoplankton in a lake [31-32]	Water temperature, in situ chlorophyll fluorescence, robotic mobile sensing boat	C, G	Studying the seasonal changes in structure of the lake and phytoplankton assemblage

Table 1. *(continued)*

Example	Sensor Modality/ technology	Property	Insights or comments
Predict a increase of peak stream temperature under various riparian covers [33], Figure 1(d)	In-stream temperature (distributed temperature sensing, DTS), meteorological parameters	C, F	Investigating the impact of various riparian covers on stream temperature, higher stram temperature that causes a kidney disease of fish

Note: A: a wide range observatoin; B: an extra-high frequency observation (second level); C: a high frequency observation (minute level); D: a mediate frequent observation (hour level); E: an event-driven observation; F: a low-frequency radio (MHz); G: a high-frequency radio (GHz); H: a deployment with a larger amount of sensor nodes (> 100).

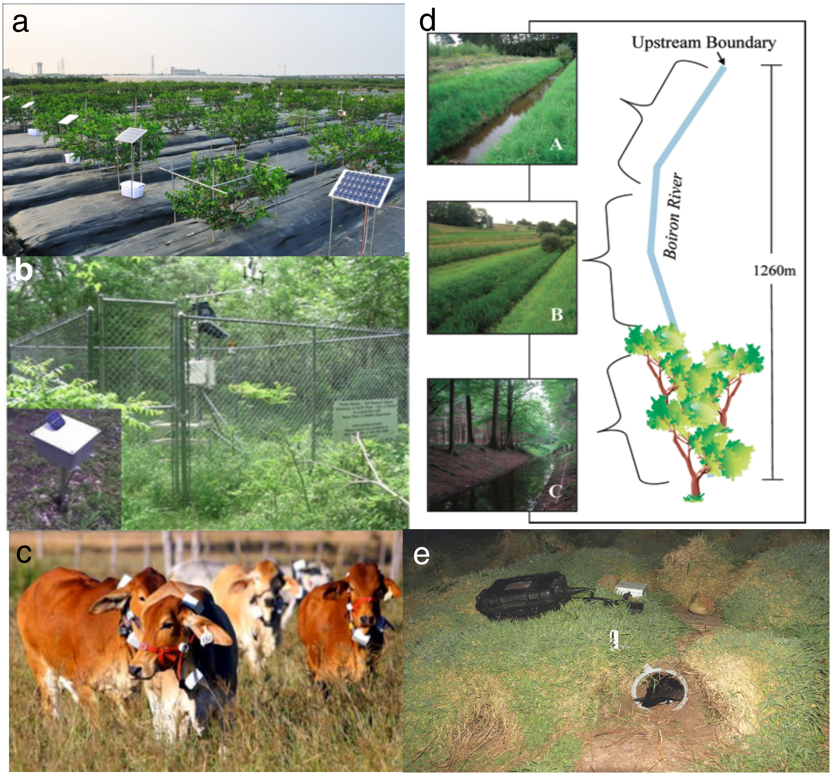

Fig. 2. Illustration of several WSN-based ecological systems. (a) Ecological monitoring system targeting pests in Taiwan [3-4]; (b) Environmental monitoring station and installed waterproof box of WSN mote in Texas [25]; (c) Cattle wearing GPS receivers and motes in Australia [26]; (d) In-stream temperature monitoring and environmental parameter measurement under three kinds of riparian covers (A, B, C) along of the Boiron de Morges Rive in Switzerland [33]; (e) Habitat monitoring using RFID and WSN technology on Skomer Island, UK [27].

On the other hands, acoustic sensors have also been developed nowadays. Acoustic sensor network can offer a non-intrusive approach to observe animal behavior by passively listening to the animals' vocalizations [36-37]. In the domain of ecological observation, microphone is one kind of the pervasive means in acoustic sensor networks. Through the collection of acoustic data, ecologists and biologists can determine the occurrence of specified animal species [38] using feature extraction methods. In addition, ecologists have been pursuing the goal of passive acoustic acoustic localization because of its merit of non-intrusiveness. For example, a study [39] has presented a localization approach coupled with some signal processing technologies that can simultaneously estimate the localizations of acorn woodpeckers using the acoustic sensor networks equipped with microphone arrays. Further, with the utilization of acoustic WSNs, the interaction of multiple individuals can be simultaneously observed. In practice, although we can benefit from the acoustic sensor networks in ecological observation, it is inevitable to involve more complicated front-end (sensor nodes) pre-processing to deal with the larger amount of collected data [36-37] (e.g. data compression and feature extraction) due to the limited wireless communication bandwidth. Thus, both the difficulty and cost to implement the acoustic sensor networks in ecological monitoring may rise because of the processing requirement.

3 Extending Spatial and Temporal Sacles of Ecological Observation

Distributed embedded sensing devices, including imaging devices, can provide a high-resolution spatio-temporal data of observation to complement the conventional sensing products that are very coarse in spatial and temporal scale. WSN technologies drive the ecological observation to a new domain in which researchers can explore new model of ecosystems, and the technologies also can support them to resolve compelling scientific questions related to ecology, biology, and nature. Despite ecological research benefits from WSN technologies, there is barrier emerging in the extending spatio-temporal scale.

Due to the expensive high cost of installations and maintenance of WSN devices, most of WSN-based ecological studies merely deployed the sensing instruments at specific points. Moreover, a successive observation is required for ecological monitoring, because modeling the ecological behavior or phenomenon may face some problems if a large amount of data is missing. Energy-harvesting instruments are adopted in the practical monitoring field in order to last a longer system lifetime. Such a requirement of energy harvesting is often a necessity in the visual surveillance systems because of the power-hungry image processing and wireless data transmission [34-35]. One of the pervasive schemes satisfying the requirement is the solar energy harvesting technology, which is utilized in the ecological studies [25-26, 34-35, 37]. Solar energy is the cleanest, most abundant, renewable energy source, and it can be conveniently transformed into electricity through solar cells. In many studies involved with ecological monitoring [27, 29-32], the research results indicated that a better way to charge the batteries and power the instruments is to use solar panels. More importantly, redundant electricity can be stored into batteries so that the system can maintain normal operation when sun lights are unavailable, such as in the night. These energy-harvesting devices usually have an installation location contraint, e.g. it is best to place the solar-harvesting system in an open space without any veils like trees. Therefore, for automatic ecological monitoring systems deployed in a remote field, some constraints that obstruct any extension of a spatial scale may still exist.

Much early WSN-related literature claimed that wireless sensor nodes could be randomly scattered into an interest of area for monitoring purposes, even can be dispersed from an aircraft [40-41]. Such a statement or assumption cannot be easily applied to the WSN-based ecological monitoring applications because only some of ecological phenomena that take place in certain areas need to be observed. The location-specific observation also has similar constraints on extension of spatial scales. Although freely deploying WSNs in ecological monitoring is not feasible, an appropriate location arrangement for sensor node deployment that takes network connectivity into account can offer a better quality of service.

In general, the deployment of WSNs mainly considers as a 2-D deployment. Although the physical environment where the WSN is settled is a 3-D space (i.e., sensor nodes can be regarded as the different points in a 3-D coordinate), most studies still took a more simple 2-D horizontal plane model into consideration for convenience. A typical application of 3-D WSNs in ecological monitoring is underwater WSNs [42-43]. In addition to the networks formed by the sensor nodes floating on the water, there is another type of networks formed by the sensor nodes located under water. By a connecting bridge or gateway, both of the networks can be integrated into a underwater WSN. More specifically, the sensor nodes locate at different depths under water can be viewed as the third vertical axis of a 3-D WSN deployment. For example, Bondarenko et al. have proposed a underwater WSN coupled with the Niskin bottle method [42], which aims at monitoring the sea temperature at various depths and collecting the plankton (e.g., *Trichodesmium* cyanobacteria), to examine the interaction between cold water intrusions, originating from the coral sea and upwelled on the reef, and coral growth in the Great Barrier Reef Australia (GBR). In this study, each sensor node is composed several temperature sensors and Niskin bottles, which are fixed in a hydraulic cable. The signal between each sensor and the mote (Unode) that is in charge of managing the sensed data and transmitting them to the base station, is propagated in a wireline. Figure 3(a) displays the study sites at Nelly Bay, Magnetic Island, Australia. Moreover, Figer 3(b) shows the system architecture of another 3D scale underwater observation system [43]. A observation result regarding the sea surface temperature is shown in Figure 3(c) [43].

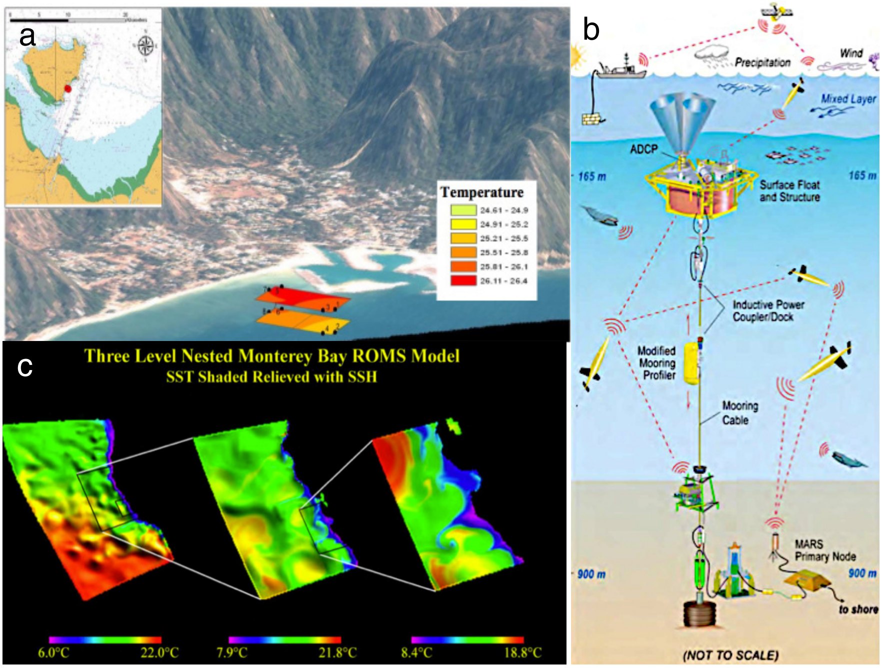

Fig. 3. Illustartion of 3-D WSNs. (a) Observation sites at Nelly Bay, Magnetic Island, Australia [42]; (b) A underwater mooring WSN system based on the acoustic communication technology [43]; (c) The simulated sea surface temperature distribution using nested ROMS models [43].

In the past, ecological/biological observation was conducted in manual ways, which may lead to a high cost and could not provide a better sensing fidelity as well as a high-resolution observation. Fortunately, WSNs can fill in the areas of spatio-temporal continuos sampling in ways that could not be done in the past. In terms of the scalability of a temporal scale, depending on various ecological phenomena to be observed, the sampling rate of WSNs can be flexibly adjusted to satisfy different requirements. According to the survey result as shown in Table 1, it is obvious that most of ecological studies using WSN technologies have a minute-level temporal scale of observation. Note that the temporal scale of sampling/observation refers to the practical frequency of sensed data sent to a database (i.e., the sampling rate of WSNs) rather than the physical sampling rate of sensors. In general, the sampling rate of WSNs are smaller than that of sensors, because of the limited transmission bandwidth and energy. In order to realize the spatio-temporal characteristics of WSN-based ecological applications, we show the distribution of spatio-temporal characteristics of ecological research in Figure 4, based on Porter et al.'s analysis results in 2005 [44]. After adding several recent ecological studies mentioned in this article to the research outcome provided by Porter et al., we create a new statistical result. Figure 4 shows that the temporal scale ranges from seconds to several hours, and the spatial scale ranges from several meters to 100 km. The spatio-temporal sampling of most WSN-based ecological applications falls within such ranges. For temporal scales, obviously, it appears that the minute scale observation is widely adopted by many studies. On the contrary, the conventional methods usually offer a larger temporal scale observation ranging from several hours to years. Specifically specking, the new observation methods using WSN technologies have a smaller temporal scale that cannot be applied to the conventional methods.

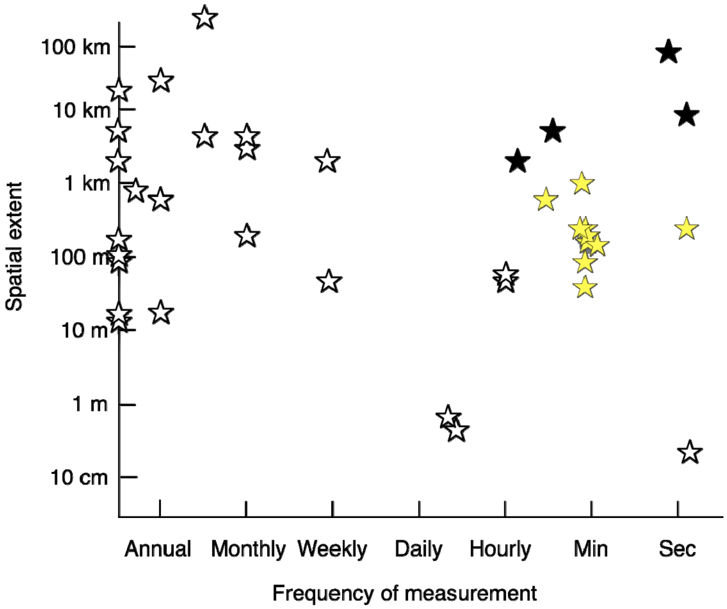

Fig. 4. A distribution of spatio-temporal scales of ecological observation based on the analysis result [44], and which is comuped with several recent ecological studies mentioned in this article. Conventional monitoring methods are marked by open stars, and WSN-based monitoring approaches are marked by black filled stars (surveyed by Porter et al. [44]) and yellow ones (surveyed by this article).

On the other hand, a new paradigm of designing WSNs is multi-scale sensing that can be used to spatially and temporally dynamic phenomena. The basic concept of multi-scale sensing is to employ low-resolution sensor nodes to carry out a wide-range observation. Thus, by doing so, the points (areas) of interest can be identified and then higher-resolution sensor nodes will be used to replace original lower-resolution ones at these points of interest. Our research team has developed an ecological monitoring system for pests using the WSN technology for a long period of time while deploying hundreds of sensor nodes into the fileds [3-4]. Each sensor node can provide the number of its captured pests through an specifically designed pest deciton sensor, and the micro-climate parameters are collected every 30 minutes. The practical deployment sites of our developed system are shown in Figure 5(a). Figure 5(b) illustrates the predicted plane of pest distribution in a monitored orchard using a hot spot analysis approach. After the areas of interest are found, the pest population dynamics and the interaction between pest's behavior and micro-climate (or micro-environmental) variables can be further studied by deploying higher-resolution sensor nodes in the areas. Meanwhile, the cost of providing infrastructure to perform monitoring tasks can be drastically reduced. Hence, indeed, there is a great promise when using WSNs in ecological studies. Nevertheless, there are a number of challenges in developing ecological WSNs. We will discuss this in the following section according to our practical experience of designing and implementing a long-term ecological monitoring system for pests.

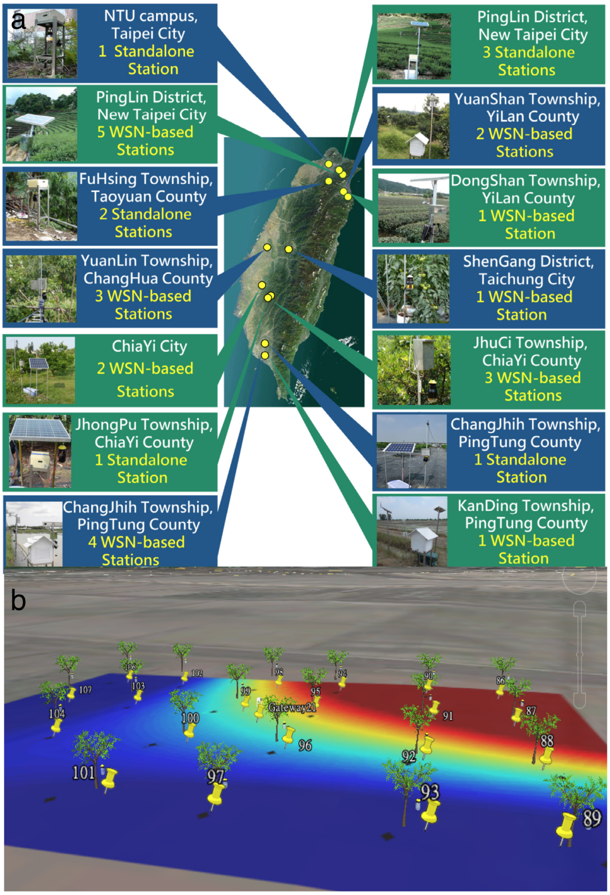

Fig. 5. An illustration of multi-scale sensing. (a) WSN-based ecolgocial monitoing system for pests in Taiwan [3-4]; (b) Red region indicates the hot spot of trapped pest distribution, which suggests that this area of interest should be monitored.

4 Challenges and Opportunity for Sensor Network Development in Ecological Monitoring

4.1 Data Management and Preservation

Ecological WSNs are able to generate a large amount of data due to the characteristics of high-resolution and wide-range sensing. However, the challenging problem is to preserve the fidelity of sensed data while reducing the size of data and transmit it to the remote base station using an energy-efficient way. A larger amount of sensed data to be transmitted will rapidly consume the energy of sensor nodes, and this problem should be addressed especially in ecological monitoring. To overcome such a problem, the data aggregation technology is a prevalent approach [45-48]. The main idea of the data aggregation technology is gathering the sensed data from a number of sensor nodes and sending it to a head node. The gathered data is pruned, compressed, or fused. Thus, the data amount can be reduced. Meanwhile, the fidelity of data can also be retained. For example, video/image sensor networks applied to ecological observation use the image compression technology in order to decrease the data amount to be transmitted [35].

For ecological WSNs, gaps in data flow present a serious and pervasive problem, which will influence the ecological modeling — such as time series analysis — if such observed data is used. In general, data gaps may be caused by many factors, such as outage of power, device failures, poor communication quality, animal destruction, harsh climate, etc. Figure 6 shows some practical photos regarding the problem that WSNs may encounter in a wild environment according to our actual field experience in building the ecological monitoring systems for pests [3-4]. Thus, maintaing a successive observation seems to be a difficult goal to achieve. Even in some sophisticated WSNs, only 50–83% of measurements can be accepted [49-50]. Moreover, a wireless visual surveillance system established by our research team shows that 76% of images have pixel loss rates below 20% in the best case [34]. To date, there are many related schemes proposed to avoid data gaps and guarantee the survival and persistence of sensed data, e.g., energy-harvesting approaches, optimal energy-efficient routing protocols, etc. Among these methods, robust in-network distributed storage mechanisms are a new feasible ones [51-53]. Previous studies generally rely on external storage devices. However, in-network distributed storage mechanisms are more efficient for ecological WSNs, because the sampling rate of sensor nodes may be much higher than the rate that the sensor nodes can upload data to the external storage drive in some high duty cycle observation applications. Furthermore, when the connectivity of sensor nodes breaks down, the sensor nodes with the in-network storage capability can ensure a complete recording. For example, the research team of Light Under Shrub Thicket for Environmental Research (LUSTER) [51] has developed an automatic sensor node with in-network storage capability using SD/MMC flash storage cards affixed to the sensor nodes. The designed sensor nodes support that both redundant in-network storage of data to eliminate data loss and an online query mechanism to recover the missing data. Figure 7 shows the physical photos of the sensor node with a

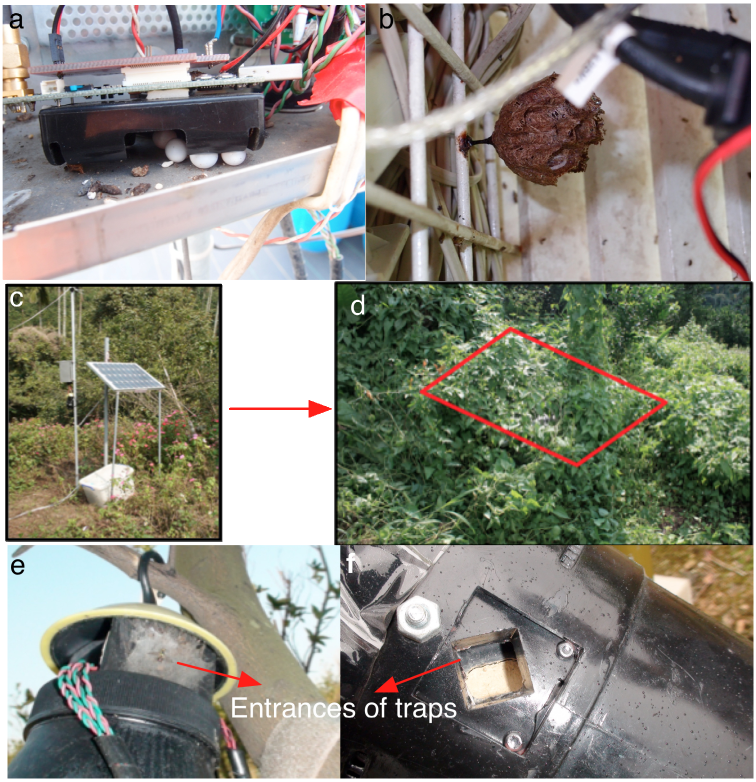

Fig. 6. The problems that WSNs encounter in wild areas [3-4]. (a) the intrusion of geckos, and they laid eggs near the sensor nodes inside the waterproof protection case; (b) a beehive is built inside the waterproof protection case, which implies that the activity of wild bees is present in the case; (c) The initial deployment scene of the solar panel used to power the sensor node; (d) The scene after the monitoring system has been deployed for one year, and the solar panel was covered by these thick leaves; (e) Entrance of the pest trap equpped with automatic infrared sensors is cobwebbed, whcih prohibits the pests (for the oriental fruit fly) from being attractted into the trap; (f) Entrance of the pest trap for the tobacco cutworm is jammed with the beehive.

Fig. 7. The sensor nodes capable of in-network storage using an external SD/MMC storage device, which is implemented based on the MICAz mote [51]

in-network storage device, which is developed by the team of LUSTER[51]. Hence, it is obvious that ecological WSNs have an urgent need of developing preservation strategies to avoid data loss or missing, because they face many challenging problems in wild environment than in a stable indoor environment.

4.2 Energy-Efficient Operation and Energy-Harvesting

Many investigation locations of ecological WSNs are difficult to arrive at, which suggests that the battery change (batteries are the power source for most WSN systems) is not easy to do. Therefore, another challenging problem is to allow ecological WSNs operate normally for a very long time with sufficient electrical power. Two main approches are 1) energy-efficient operation and management of WSNs; and 2) enrichment of power. The majority of existing literature focuses on how to design an energy-efficient WSN. The possible strategies include developing optimal routing protocols, using optimal scheduling strategies for sensor node (i.e., determination of turning-off or turning-on for all sensor nodes), employing the above-mentioned aggregation methods, etc. We will not discuss these strategies in this article due to their prevalence. The second way to prolong network lifetime is to provide additional power to WSNs using energy-harvesting technologies. Energy harvesting is a technique that capture or harvest unused ambient energy (such as thermal, wind, solar, etc.) and convert the harvested energy into the usable electrical energy that can be stored and used for performing sensing tasks. Thus, energy harvesting is increasingly gaining notice in ecological WSNs since it is a potential solution to maximize the system lifetime.

Some energy harvesting prototypes that harvest various energy have been developed. In this article, we focus on discussing the energy-harvesting technologies suitable for the ecological WSNs deployed in wild areas. Generally, energy harvesting can be categorized into three types depending on various sources, including 1) thermal energy; 2) radiant energy; and 3) mechanical energy. Thermal energy can be derived from animal heat and some external heat. Radiant energy can be generated from solar energy and RF waves, and mechanical energy can be derived from vibration, air flow, or heel strikes. Although there are many existing ways to harvest ambient energy, the gathered energy is general small. For example, the power density produced by thermoelectric generators ranges from 100 μW/cm^2 (at 5℃ gradient) to 3.5 mW/cm^2 (at 30• gradient). The power density produced by vibrational generators, by contrast, is very small ranging from 4 to 800 μW/cm^2. The power density produced by wind turbine generators vary from 35 μW/cm^2 (< 1m/s) to 3.5 m W/cm^2 (at 8.4 m/s) [54-56]. However, the power density yielded by solar radiant generators is quite high, reaching 100 mW/cm^3 (exposure to direct sunlight). In addition to the energy-harvesting methods mentioned above, scientists have developed sound energy harvesting systems. When noise comes into an acoustic collector, electrical power will be produced. For example, the noise of a jet plane of 160 dB can produce up to 100 kW power. Recently, they have also devised a prototype of magnetic energy harvesters to collect magnetic energy everywhere on the earth. We expect these technologies can be practically applied to the domain of WSNs in the future.

After surveying the literure related to automatic ecological observation systems, we found that the majority of these observation systems adopted solar energy as their primary power source [25-26, 34-35, 37]. This is because that the solar energy harvesting has a better performance in generating higher electrical power, which matches the demand of long-term ecological monitoring. Although solar energy harvesting systems offer a good way to power WSN-based ecological observation systems, not all of the applications involved with ecological observation need such a energy harvesting system. For example, for cattle behavior observation systems [26], placing solar panels and batteries on cattle to maintain the operation of monitoring systems does not make sense. Thermal energy harvesting systems exploiting natural temperature difference between different materials may be a better solution in this case. In summary, it is worth noting that the selection and design of energy harvesting systems for ecological WSNs may vary due to different requirements of deployment locations and system loading. There is no doubt that energy harvesting systems will become an important component of self-powered ecological WSNs.

4.3 Fault Detection Technology

Because sensor nodes are often deployed in an uncontrolled or even a harsh environment, they are prone to have faults. Thus, it is important to identify the faulty sensor node, locate them, and exclude them from a normally-operating WSN. If available, they can only serve as relaying nodes in charge of transferring sensed data after they are identified as faulty ones. Since ten years ago, fault detection and fault tolerance in WSNs have began to be investigated. Basically, they used the concepts in data mining to discover the necessary information among neighboring nodes and then compared the information with the possible faulty node to determine the abnormal condition. Related to the SOM technology, a number of studies have applied the technology to anomaly detection [57-60]. Siripanadorn et al. [60], for example, have proposed an anomaly detection algorithm using self-organizing map (SOM) coupled with the discrete wavelet transform (DWT) to accurately detect anomalies. By employing DWT, the size of input data to SOM can be efficiently reduced. Moreover, Sharma et al. have employed four anormal detection technologies to detect different types of faults [61]. The Bayesian fault recognition algorithm was also presented to solve the fault-event identification problem in WSNs [62]. In addition to fault detection, some research has further proposed some self-healing strategies for the faulty sensor nodes to recover from the malfunction [63–64]. In addition, Bokareva et al. have proposed a hybrid sensor network structure [64], which is capable of recognizing various types of faults and responding to these possible faults. The basic concept is to use another monitoring node to supervise a number of sensor nodes in a local area. The monitoring nodes are able to survey sensor readings and ensure their correctness. When faults are detected, they can notify the faulty nodes to take an appropriate action.

In a wild field, ecological WSNs are much susceptible to the faults from overheating, low power battery, chemical fouling of sensors, or physical damage, which will result in degradation of sensor accuracy. Furthermore, given that the quality of wireless links easily vary, fault detection or and healing technologies pose an opportunity to improve the effectiveness of ecological WSNs. With such technologies, the invalid sensed data can be found, even be modified or interpolated in advance to ensure that the sensed data is complete. This will be a promising way for ecological WSNs, because ecologists can get a reliable, accurate, and useful data for further analysis.

5 Conclusion

Wireless sensor networks have great potential in ecological and environmental monitoring. Ecologists can use WSNs to collect multiple-point sensed data related to ecological variables at a high temporal scale across broad geographical areas. Sensor nodes equipped with different kinds of sensors are able to monitor various parameters in real world. Ecologists can conduct comparative analysis on some unexplored phenomena based on high spatio-temporal resolution data, if they use WSNs as their research tool. Nevertheless, many challenging questions are emerging from the implementation of the WSN technology in ecological monitoring, including limited energy, inevitable data gaps, sensor degradation, faulty sensors, etc. To date, these issues could be addressed by developing new hardware/software suitable for ecological observation. For example, energy-harvesting technologies have been employed to power WSNs. Some anomaly detection algorithms have been used to identify and locate sensor faults. Ecological WSNs, therefore, have benefitted from the useful technologies.

Although the development of ecological WSNs is promising, ecological WSNs are not insufficient to have a quick answer to some complicated scientific questions in nature. We need to increase the cooperation among research areas including biology, ecology, electrical engineering, information technology, statistics, etc. Only making an effective integration of these research areas can facilitate studies aiming to explore the unobservable and unexpected phenomena in the past.

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