Rapid Prototyping for Wildlife and Ecological Monitoring

Jyh-How Huang, Ying-Yu Chen, Yu-Te Huang, Po-Yen Lin, Yi-Chao Chen, Yi-Fu Lin, Shih-Ching Yen, Polly Huang *Member, IEEE* and Ling-Jyh Chen *Member, IEEE*

***Abstract*—Wildlife tracking and ecological monitoring are important for scientific monitoring, wildlife rehabilitation, disease control, and sustainable ecological development. Yet technologies for both of them are expensive and not scalable. Also it is important to tune the monitoring system parameters for different species to adapt their behavior and gain the best result of monitoring. In this paper, we propose using wireless sensor networks to build both short term and long term wildlife and ecological monitoring systems. For the short term system, everything used is off-the-shelf and can be easily purchased from the market. We suggest that before establishing a large scale wildlife/ecological monitoring network, it is worthwhile to first spend a short period of time constructing a rapid prototype of the targeted network. Through verifying the correctness of the prototype network, ecologists can find potential problems, avoid total system failure and use the best tuned parameters for the long term monitoring network.**

I. Introduction

Technologies for wildlife tracking and ecological monitoring progressed slowly in decades until recent years when GPS receivers can be embedded into tracking collars. In general, modern wildlife tracking and ecological monitoring solutions require three core components: 1) a *Global Positioning System (GPS) receiver* to track animals' movements; 2) a *wireless communication* network to transmit data collected by the GPS; and 3) a *battery* to prolong the lifespan of the system. For some specialized applications, the system may also incorporate additional sensors to record information of interest about the tracked target, such as the light intensity, humidity, and temperature of its living environment. GPS technologies have matured and can now provide a resolution of several meters. Meanwhile, wireless communication networks generally favor *long range* (i.e., several miles) wireless technologies, which are either proprietary (e.g., UHF/VHF) or standard (e.g., Argos [2] and GSM [4]) systems. However, conventional wildlife tracking and ecological monitoring solutions share the following limitations.

1) Battery power is usually a bottleneck since a battery's capacity depends, to a large extent, on its shape and size, which are constrained by the size and weight of the tracked animal's body.
2) The equipment and operating costs are both very expensive and thus limit the scale of the deployment and the experiments conducted.
3) Current solutions only provide per-animal information, i.e., not inter/intra-species interaction information.

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J.-H. Huang, P.-Y. Lin and P. Huang are with the Department of Electrical Engineering, National Taiwan University.

Y.-Y. Chen, Y.-T. Huang, Y.-C. Chen, Y.-F. Lin and L.-J. Chen are with the Institute of Information Science, Academia Sinica.

S.-Y. Yen is with the Department of Life Science,National Taiwan Normal University .

To overcome the above limitations, recent advances in mobile and wireless networks have demonstrated the feasibility of using *short-range* wireless communications (such as WiFi and ZigBee) in such network scenarios [10, 12]. In fact, this kind of applications can be regarded as a type of challenged networks, where network contacts (i.e., short-range communication opportunities) occur intermittently, data transmissions are likely to experience unacceptably long delays, and the reliability of transmissions can not be guaranteed. While traditional Internet and MANET techniques can not be applied directly to networks in this category, recent studies have reported that data transmission is feasible and can be improved significantly by proper exploitation of the network's mobility [19] (i.e., in a *store-carry-and-forward* fashion [38]).

The recent advances in wireless communications have not brought any improvement to the wildlife/ecological monitoring society. So far using GPS enabled collars with UHF/VHF uploading link is still the most popular way to track wildlife. However, after talking to several biologists and ecologists, we discovered that this is not the ideal solution to track wildlife, since different animals have very different activity patterns. For example, cattle usually move around to graze during the day and lay down to ruminate during the night. Instead of using fixed time duration to sample GPS locations of monitored animals, we can sample more frequently during their moving periods and less when they are resting. Also, we can turn off the GPS when some conditions are met, e.g., when the temperature reaches 30 degrees Celsius, turtles will move into their caves which will shield all GPS signals so we can turn all GPSs off. These fine tunes can save GPS power thus prolong the system lifetime.

To achieve this, we suggest that a prototype of the real large scale ecological monitoring system is needed, because the monitoring duration is usually 2 to 5 years long, and the capturing of wild animals is very labor intensive and difficult. Even just one failure in the system design may cause the whole monitoring system to fail. Thus, like large software engineering projects, prototypes are important for large scale wildlife monitoring. One very good tool to build a prototype of the ecological monitoring system is the programmable GPS enabled wireless sensor network.

After validating the correctness of the whole system through prototyping, we need a system that can dynamically changes the GPS sampling frequency as well as radio waking up periods to best utilize the limited energy or use the saved energy to get better GPS resolution.

Inspired by the success of the *YushanNet* system [21], which we recently deployed in Taiwan's Yushan National Park for hiker tracking and rescue operations, we developed an opportunistic network-based system, called *EcoNet*, to demonstrate the feasibility of using wireless sensor networks to build a prototype for wildlife tracking and ecological monitoring system. In this study, we report the results of two field experiments conducted to evaluate the proposed EcoNet system.

The remainder of the paper is organized as follows. Section II contains an overview of related works on wildlife tracking and ecological monitoring systems. In Section III, we describe the design and implementation of the *EcoNet* system. Section IV discusses the significance of behavior observation and prototyping. Section V provides details of the conducted experiment and the measurement results. Then, in Section VI, we consider the lessons learned from the experiment and summarize our conclusions.

II. Related Work

Scientists have used a variety of methods to track animal species [1, 7]. Before the 1960s, it was common practice to capture a small number of subjects, attach identifiers (i.e., tags or bands) to them, and release them back into the wild so that they could be tracked. Eventually, the animals were recaptured, or their remains were found, and the identifiers were retrieved. Generally speaking, this approach is cheap and can provide baseline information about the observed wildlife; however, the recovery rate is low and the accuracy is poor due to inevitable observation errors.

The first breakthrough in tracking technology occurred with the advent of radio telemetry [14, 17]. A radio telemeter, which consists of a *Very High Frequency* (VHF) transmitter, an antenna, and a power cell, is attached to the subject by a harness, a collar, glue, subcutaneous prongs, or surgical implants. Signals emitted by VHF transmitters are detected by using receivers with homing techniques [29] or by applying triangulation-based techniques [20]. Although these approaches can collect much more accurate information than previous methods, the radio telemeter system causes two additional problems: 1) the maximal lifespan of the system is limited by the battery capacity, which is also a common problem in the methods discussed below; and 2) the tracking range is limited by the radio range, which makes wildlife tracking extremely labor-intensive.

To resolve the second problem, Buechner *et al.* [18] proposed employing a satellite telemeter, which utilizes a *platform transmitter terminal* (PTT) attached to the target and sends *ultra high frequency* (UHF) signals to satellites. In addition to relaying the received data to receiving/interpreting sites on the ground, the satellites can calculate the target's location based on the *Doppler Effect*. Currently, the US/French Argos system [2] is the only functional satellite telemeter system, and it has been widely applied by many wildlife tracking projects [8, 11]. However, to transmit signals to satellites, the Argos system consumes much more power than radio telemeter-based systems and thus has a shorter lifespan. Moreover, the operating cost is quite high - about USD 500 per animal per month.

Global positioning systems are also widely used in wildlife tracking. Some approaches (e.g., [23, 30, 36, 40]) store GPS and sensing data in the devices, which are subsequently retrieved after an automatic or remotely triggered drop-off mechanism releases them from the tracked animals. All the data is then downloaded from the device in a single operation. In general, these types of devices are smaller and consume less energy than previous methods, since an additional radio transmitter is not needed; however, the data cannot be accessed in real-time. To overcome this, in recent years there are GPS collars with UHF links for ecologists to download data collected in the collars[3]. Ecologists need to get into the UHF reception range to download data manually from the GPS and UHF enabled collars. Though convenient, this method is still labor intensive and not scalable.

To monitor wildlife automatically in real time, long-range wireless technologies have been applied to GPS-based tracking systems. Peter Richards [35] developed the *Automatic Packet Report System* (APRS) to relay GPS data from the tagged kangaroos and dingoes in the Australian outback. Mcconnell *et al.* [28] attached phone-tags to seal pups on the Isle of May (Scotland). The tags automatically sent GPS data via SMS text messages once every two days. Instead of using GPS, Pendock *et al.* [32, 33] implanted RFID tags into bats and monitored the arrival/departure of the bats using wireless nodes attached to their nesting boxes. However, the three projects have a common problem in that the tracking area is restricted by the coverage of the radio access points and/or RFID readers. McCarthy *et al.* [8] resolved the problem by using satellites to transmit GPS data from collars fitted to snow leopards in Pakistan's Chitral Gol National Park, but the solution is very expensive, as mentioned earlier.

Since full wireless coverage is impossible in most wilderness environments, the advances in wireless sensor network technology provide an alternative to relaying GPS and sensor data. For example, ZebraNet [24, 27, 41] equipped zebras with customized sensor nodes, and applied an epidemic routing protocol to forward data to a mobile base station (e.g., a car or a plane) on a daily/weekly basis without assuming the presence of fixed base stations. However, since every node in the network has to store data from every other node, the routing protocol leads to the buffer overflow problem and thus limits the scalability of the system. TurtleNet [9, 13] is a similar system that focuses on energy management and hybrid sensor networks. The first energy-aware programming language *Eon* was designed to manage harvested energy effectively. In addition, to adapt to the environment where turtles live, the designers of TurtleNet developed *Underwater Wireless Hybrid Sensor Networks* (UW-HSNs), which use radio communications for sustained traffic and acoustic methods for small amounts of data.

Thiele *et al.* [25, 31, 39] used wireless sensor networks to monitor the behavior of rats. Since radio communication in a rat burrow was limited, the sensor nodes attached to the rats were only connected sporadically and the network topology was highly dynamic. The project proposed a routing protocol comprised of two strategies: 1) a utility strategy that assigns different priority levels to packets based on whether they contain data of interest; and 2) a social network strategy that forwards packets to the node with the highest number of neighbors in its meeting history. The project is still a work in progress in the controlled environment.

Sikka *et al.* [37] improved the radio transceiver, power supply architecture, and solar charging mechanism of Mica 2, a commercial product, to provide a better hardware design for animal tracking. The proposed platform, called *Fleck*, will be deployed in Sweden's Lycksele Zoo to monitor animals' movements and allow visitors to see what the animals see from the attached cameras [5].

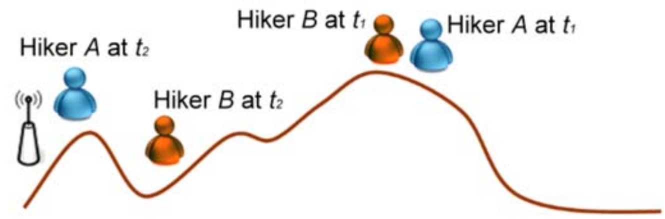
The above projects are similar in two respects. First, they only target a single species at a time; and second, when GPS is used, the GPS data must be retrieved in a real-time fashion via expensive solutions (e.g., satellite connections) or in an all-at-once fashion by labor-intensive solutions (e.g., manually collecting devices that have dropped off animals). A feasible wildlife tracking solution that can provide multi-species monitoring at an affordable cost and acceptable delay is thus highly desirable. Also materials and methods to build a prototype of the real system rapidly is also very important. To address these needs, we developed the EcoNet system, which utilizes short-range wireless technologies and exploits the mobility of wildlife to increase network capacity. As a result, it is affordable, scalable, flexible, and reliable; moreover, the delays are acceptable and all tools used are off-the-shelf. We present the design details and experiment results in the following sections.

III. EcoNet

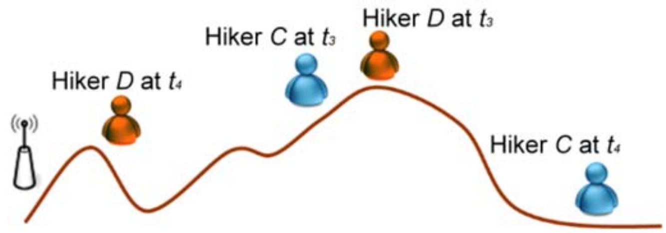
A. Basic Concepts

EcoNet was inspired by one of our previous projects called YushanNet [21], which is a delay-tolerant wireless sensor network deployed in Taiwan's Yushan National Park. The objective of YushanNet is to provide a reliable and robust system for tracking hikers in the national park. The aggregated information also helps the park's administrators to provide various services to tourists, such as maps and the locations of sightseeing spots, toilets and pavilions. Moreover, the collected hiking traces can provide more precise information to professional rescue teams if hikers get lost in the mountains.

Since full wireless coverage is impossible in wilderness environments, network communications in YushanNet are inevitably intermittent and thus very challenging. To overcome this difficulty, YushanNet applies a delay/disruption tolerant network technique and makes use of opportunistic, ad hoc, and short-range wireless communications to disseminate data over the network in a *store-carry-and-forward* fashion. More precisely, in the YushanNet system, each hiker is required to carry a device, called *Taroko mote* [26], which has a GPS receiver, a Zigbee radio, and 10KB of memory. When hikers encounter each other on hiking trails, the motes automatically exchange their IDs and record the encounter information (i.e., the time and location) in their respective memories. The devices continue exchanging their stored data as long as possible (i.e., depending on the encounter time and the wireless bandwidth). Then, when a hiker reaches one of the base-stations installed at frequently visited spots in the park, all the information stored in his/her device is uploaded to an Internet server from the base station via GPRS or Wi-Fi.



(a) Hikers moving in the same direction



(b) Hikers moving in opposite directions

Fig. 1. General Scenarios of YushanNet

Figure 1 shows two typical scenarios in YushanNet. Suppose the entrance of the trail is on the right-hand side of the figure, and the base station is deployed on the left-hand side. Figure 1a shows the scenario where two hikers, A and B, are hiking in the same direction. Suppose B is ahead of A initially, but A catches up with B in the middle of the trail at time t_1. A and B's devices record the encounter information and exchange their stored data. Subsequently, A hikes faster than B and reaches the next base station at time t_2. A's device uploads its stored data to the Internet via the base station, and B's whereabouts become accessible even though he is still on the way to the base station. In Figure 1b, two hikers, C and D, are hiking in opposite directions on the same trail, and they encounter each other at time t_3. After the encounter, C and D continue hiking in their respective directions, and D reaches the next base station at time t_4. D's device uploads its stored data to the Internet, and thus makes C's whereabouts available even though C is still on the trail.

The results of the YushanNet project are not specific to hiker tracking and rescuing applications. In fact, they can be generalized to a variety of applications, such as wildlife tracking, scientific monitoring, landslide and debris flow monitoring, and disaster monitoring networks. We present the details of one of the extended systems, called EcoNet, in the next subsection.

Fig. 2. A General Scenario of EcoNet

B. EcoNet Design

The design of the EcoNet system is based on the four observations: 1) since wildlife habitats are usually extremely large and uninhabited by humans, it is costly and infeasible to deploy a wireless network with full coverage in such environments for wildlife tracking and monitoring; 2) there are common places that animals are likely to visit on a regular basis, e.g., creeks or lakes for drinking water; 3) different species may encounter each other opportunistically in the wilderness area; and 4) a prototype for the large wildlife monitoring system is necessary to prevent errors in design. Clearly, network scenarios that involve wildlife tracking and monitoring are similar to the scenarios encountered by YushanNet. In the EcoNet system, GPS-enabled sensor nodes are carried by wildlife, Internet-enabled base-stations are deployed at spots usually visited by the wildlife, and data communication over the network can be implemented in a *store-carry-and-forward* fashion, as implemented in the YushanNet system.

Figure 2 shows a general scenario of the EcoNet system. In the scenario, buffalos, sheep, and eagles live in the observation area. Suppose each animal carries a client device, and a base station is deployed on a tree next to a lake. While the buffalos and sheep may encounter each other when wandering in the grass or drinking around the lake, the eagles may encounter other animals while flying or resting on the tree. Since data communication starts automatically when any two tracked objects move into each other's transmission range, the EcoNet system can record the inter/intra-species encounters and upload the recorded data to the base station, so long as some of the animals pass by the tree. The data can then be uploaded to the Internet directly via a long-distance wireless communication network (e.g., 3G/GPRS) or retrieved by *message ferries* periodically [43, 44].

Note that, even though EcoNet shares many design concepts with the YushanNet system, it has four distinguishing characteristics. First, EcoNet tracking devices must be customized for the animal of interest. For instance, biologists advise that a sensor node should not weigh more than 5% of the tracked animal's body weight. Since the client device for each hiker in YushanNet weighs about 100 grams, it can only be used in the EcoNet system if the animal weighs more than 2kg; hence, it can not be used for small animals, such as squirrels and turtles.

Second, EcoNet client devices must have a much longer battery life than those used in the YushanNet system. The client device is only required to be *alive* for one week in the YushanNet system (hikers usually take less than a week to finish a trip). In contrast, several months of battery life must be provided in the EcoNet system, since it is extremely labor-intensive to recharge/replace batteries after the network is deployed. However, as the battery's capacity depends to a large extent on its shape and size, which are constrained by the tracked animal's body size and weight, energy management is one of the most important issues in the EcoNet system. In the developed system, we employ a simple energy management protocol that controls the duty cycle of the GPS receiver. The process could be enhanced by controlling the CPU and radio duty cycles, or by applying modern battery technologies (e.g., solar panels and fuel cell batteries). We defer a detailed study/evaluation of this aspect to a future work.

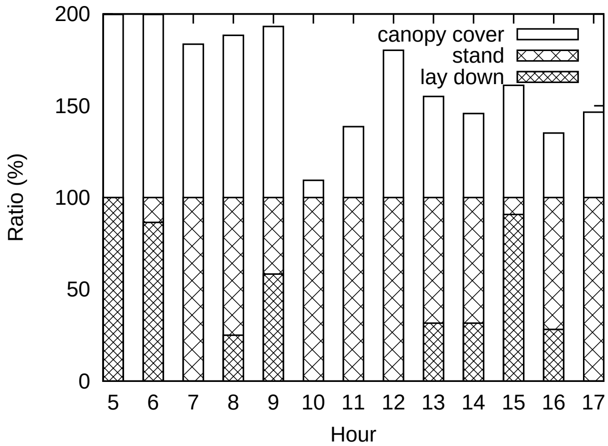
Third, the EcoNet client device must be more resilient against extreme environmental conditions than the YushanNet client device, as the mobility of wildlife is less predictable and much more diverse than that of hikers. For example, the EcoNet client device must be resistant to shaking, as animals may run and jump very fast in the wilderness. Moreover, the device must be waterproof, since some animals may live in wet areas and/or the device may be soaked in water (e.g., when the animals drink from or cross a river). However, while proper packing of EcoNet client devices is necessary to provide the anti-shaking and waterproofing functionalities, radio and GPS signals must be able to pass through the packing with acceptable receiving rates; otherwise, the system will consume more energy during data retransmission and GPS re-positioning.

Finally, in the EcoNet system, base stations must be placed at locations that have good Internet connectivity (e.g., via GPRS/3G, long distance WiFi, UHF/VHF, and satellites) and a reliable power supply (e.g., via electricity cables or solar energy). Under the YushanNet system, hikers' movements are fairly predictable and the base stations can be deployed on the trails. In contrast, when deploying the EcoNet system, we need to determine the locations that the tracked animals visit most frequently and deploy the base stations accordingly in order to ensure efficient *data harvesting*.

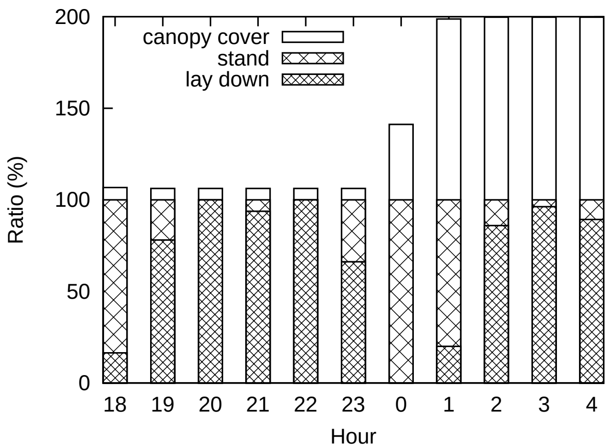
IV. The Significance of Behavior Observation and Prototyping

A. Behavior Observation

We first make the assumption that there are two factors that affect the reception of the GPS receivers on the collars, i.e. the cows' position and the canopy cover rate. The canopy cover rate is the percentage of the areas covered by tree canopy and buildings in the sky, measured by a spherical densiometer from the monitored animal's location.



(a) A cow's position and canopy cover rate during the day



(b) A cow's position and canopy cover rate during the night

Fig. 3. The position and canopy cover rate of one cow during the day and night. For Y-axis, 0 to 100% represents ratio between standing and laying down, 100% to 200% of the Y-axis represents the domain of 0% to 100% for canopy cover rate.

We did a behavior observation on the site of our experiments. The biologists recorded the cows' position every 3 minutes for a 24 hours span. The positions are identified as either standing or laying down. They also recorded the canopy cover rate from cows' locations every 15 minutes. The result is shown in Figure 3.

We distinguish day and night by sunrise and sunset time. During the day time, the cows stood 72.77% of the time and laid down in the remaining time; whereas during the night time, they laid down 72.28% of the time and stood in the remaining time.

If we take a cross comparison between the positions, the canopy cover rate, and the time, Figure 3 shows that cows stay in areas with canopy cover rate higher than 50% during the day when laying down. When standing during the day, there are no specific canopy cover rate areas they will choose, mainly just go grazing on the grass. During the night, they chose areas those have canopy cover rate lower than 7% to lay down before midnight and moved to areas with canopy cover rate higher than 99% after midnight. We will show the result we got about correlations between cows' position, the canopy cover rate and the GPS reception in section V-C.

B. Prototyping

The main reason to prototype a system is to prevent unpredicted errors and to save energy that is spent unnecessarily. Based on our measurements, a Taroko mote consumes 19.2mA while transmitting on the radio, 21.5mA while listening on the radio, and 35.8 mA when turning on the GPS receiver. Meanwhile, it consumes a merely 1.8mA when only CPU is on. The fact inspires us that we should try not to turn the GPS receiver on when it has no reception, and turn the radio on only when there is someone around.

To best suit the ecologists with the tools they need to monitor one specific species, we provide them four kinds of different sensors: *light, humidity, temperature, and accelerator*. The first three sensors are the measurements of the factors those affects wildlife's behavior and movement most, and the fourth sensor is a good indicator for the monitored animal's action. By first calculating the correlation between the environment(light, humidity, and temperature) and the wildlife behavior using the data obtained from the prototype, we can tune the system parameters to an ideal setup. A very good analogy for this is as follows. If we put a sensor node on a teenager, the temperature sensor reports constant increasing in number until noon. If the reading of the temperature sensor drops 5 degrees Celsius at noon, and the GPS receiver cannot get any fixes, we thus know that the teenager might have entered an indoor space with air conditioning; otherwise, the change in temperature won't be so violent. We then decrease the GPS sampling frequency to save power until the temperature rises again, which indicates the teenager is out in the sun again. Take turtle monitoring as another example, we find that during the day when the temperature is higher than 30 degrees Celsius, the turtles will be hiding in their caves and there is no need to turn on the GPS receivers. However we need all our 3 sensors' information to help us to judge the situation. When light value is high and temperature is higher than 28 degrees, the turtle is out in the sun and we keep the GPS receiver at higher frequency. When the light sensor value is low and he temperature is lower than 30 degrees, we know that it's about noon and the turtle might be hiding in its cave.

Figure 4 shows the data obtained from biologists monitoring turtle movements. We can see that only around 6 in the morning the turtle left its cave and showed both sensed of light and movement on the accelerator. Thus we can say that during the day when the light sensor reads 0 lumina, we don't need to turn on GPS receivers because the turtle must be in a cave and the GPS receiver won't have any reception.

C. Environment Controlled Power Duty Cycling

The current wildlife monitoring systems can only sample animals' locations at a fixed time duration, which is not a very power efficient solution. To best answer the ecologists' requirements and tune the GPS sampling frequency to best utilize the constrained power supply, EcoNet system provides them the following functions to use in the real system:

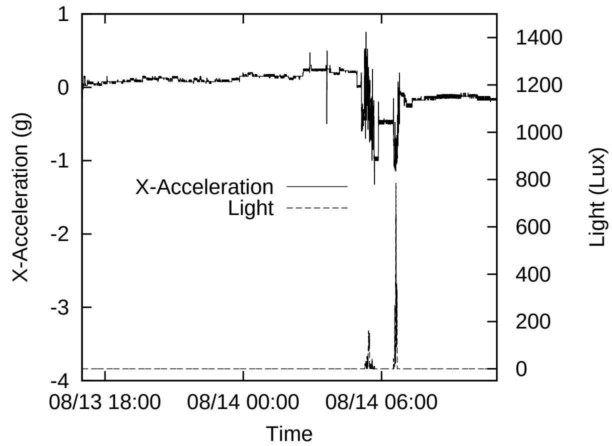


Fig. 4. The correlation of light and turtle movement

Fig. 5. An aerial photograph of the *Pasture Yen Family* property, which is about 90,000 m^2.

1) $GPS\_Sample\_Frequency\_Time$(Start Time, End Time, Sampling Period in Minutes)
2) $GPS\_Sample\_Frequency\_Temperature$(Low Temp, High Temp, Sampling Period in Minutes)
3) $GPS\_Sample\_Frequency\_Light$(Low Light, High Light, Sampling Period in Minutes)

Function 1) can set GPS to sample between start time and end time. Function 2) can set the GPS to sample when temperature is between Low and High, and Function 3) sets the GPS to sample when light is between Low and High. Ecologists can set several segments for one sensor in each collar, e.g.,

- $GPS\_Sample\_Frequency\_Time$(1200, 1600, 60)
- $GPS\_Sample\_Frequency\_Time$(1600, 0400, 10)
- $GPS\_Sample\_Frequency\_Time$(0400, 1200, 30)

will set the GPS receiver to sample once per hour between noon and 4pm in the afternoon, once per ten minutes between 4pm in the afternoon and 4am in the morning, once per thirty minutes between 4am and noon. These setting is ideal for monitoring reindeers and other animals that usually graze during the night and rest when it's hot.

We suggest that the prototype network should have the GPS receivers, radio and other sensors on as much as possible for the whole duration of the prototype's runtime. Through the trial run, we can learn lots of information about the correlation between the GPS reception quality and time, temperature, and light. We can also see when the monitored animals are used to moving to the water source to drink and prepare the collars to upload data during that period of time.i.e., to turn on the radio. Furthermore, we can see the contact data between the monitored animals (such as how often they contact each other, how long a contact is, whether they tend to contact the same set of specific individuals) to decide when to turn on and off the radios. After the trial runs, we can thus customize the codes in the collars to best suit the behavior of the monitored animals.

V. Experiments

A. Implementation Details

In this section, we describe the implementation of the EcoNet system, and present the results of two experiments conducted in *Pasture Yen Family* [6] from February 16 to 18, and June 30 to July 1, 2009. Figure 5 shows an aerial photograph of the property, which is located in Puli, Taiwan. The pasture area is about 90,000 m^2.

The EcoNet client device was prepared by packing the YushanNet client device (comprised of one Taroko mote and one GPS receiver[1]) in a LOCK&LOCK box, which is widely used for food preservation and is available in most supermarkets and accessory stores. We used LOCK&LOCK boxes for several reasons. First, the transparent box allows good penetration of the radio signals required for wireless data exchange in the EcoNet system. Second, the box is waterproof, which is important for wildlife tracking applications. Third, the box is light, cheap, and reusable. These factors render it ideal for research and experimental purposes. To ensure that the client device was tightly attached to the collar, we used plastic bands to affix the LOCK&LOCK box to the collar, and then wrapped the box and collar in black tape. The collar itself is made by a cotton weaved sling and tightened by two metal rings. Figure 6 shows an example of the packed client device, and Figure 7 shows a dog and a cow fitted with the client devices. We totally harnessed three cows and two dogs. Again we want to emphasize that all these materials can be easily purchased from the market and not expensive comparing to GPS enabled collars that cost around two thousand US dollars; whereas the EcoNet node is cheaper than four hundred US dollars.

Note that, unlike the YushanNet system, which tracks hikers' movements on trails, the EcoNet system has to adjust several system parameters to satisfy the requirements of wildlife tracking applications. For example, to prolong the lifetime of

[1]The model number of the GPS receiver used in the experiment was *Locosys GPS LS23022*.

Fig. 6. The EcoNet client device packed in a LOCK&LOCK box

(a) (b)

Fig. 7. Animals carrying the EcoNet client device

the system, the GPS duty cycle in the EcoNet system was extended to 10 minutes. Moreover, once the GPS is active, we give it one minute, at the most, to pinpoint its location before switching back to the *off* mode. We set the one-minute constraint to prevent repeated positioning attempts when the reception of GPS signals is poor, thereby saving power and prolonging the lifespan of the client device.

Moreover, the transmission power of the client device is set at 31dBm, i.e., the maximum value supported by the Taroko mote. This is because the mobility of tracked animals is much more diverse than that of hikers in the YushanNet system. It is assumed that hikers always use the trails, so the distance between any two hikers should be small; hence, in the EcoNet experiment, it is reasonable to use the maximum transmission power because it enables us to capture as many encounter events as possible.

In addition, we set the radio of the client device to the *always listening* mode, and beacons broadcast with a random interval uniformly distributed in the range of 3 to 5 seconds.

Moreover, broadcasting beacon messages at random intervals prevents the synchronized transmission problem, and thus mitigates potential collisions in the wireless network.

We deployed the base station in the living room of the farmhouse. The base station was set up using a Linux-based laptop (model number: *ASUS Eee PC 8G*) with two additional network adapters. One adaptor is the Taroko mote, and the other is the GPRS adapter.

TABLE I
LIFESPAN OF EACH ECONET CLIENT DEVICE IN THE EXPERIMENT

Node	Start Time	End Time	Lifetime (hours:minutes:seconds)
Dog1	02/16 14:53:19	02/18 08:52:43	41:59:24
Dog2	02/16 14:48:09	02/17 12:58:59	22:10:50
Cow1	02/16 14:48:09	02/18 04:40:52	37:52:43
Cow2	02/16 14:52:18	02/18 04:40:52	37:48:34
Cow3	02/16 15:39:22	02/17 17:37:40	25:58:18

B. Experiment Results

Recall that the objective of this study is threefold: 1) to evaluate the feasibility of the future large-scale ecological monitoring system; 2) to observe inter/intra-species interactions of the tracked animals; and 3) to investigate further implementation issues of wildlife tracking and ecological monitoring systems. Next, we present the results of both the three-day baseline measuring experiment and the 24 hours prototyping experiment conducted at the *Pasture Yen Family* property from February 16 to 18, 2009 and from June 30 to July 1.

1) Lifespan of the client device: Prior to the experiment in July, we ran an experiment in February to measure some baselines of the experiment. We tagged 3 cows and 2 dogs this time. Based on the battery capacity and the system parameters used in the EcoNet system, the expected lifespan of each client device is about 70 hours. However, as shown in Table I, the lifespan of the deployed EcoNet client devices in the experiment varied from 22 hours to about 42 hours, which was much shorter than the expected lifespan. There are two reasons for the poor battery performance. First, the rechargeable batteries had been used extensively in previous wireless sensor network experiments, so their capacity may have deteriorated. Second, since the mobility of animals is unpredictable, the client devices may have consumed much more energy in repositioning (when they moved to spots with poor satellite signals) or data communication (when they had more encounters than expected in the experiment). As a result, the lifespan of the client device was reduced to less than 2 days in the experiment.

2) Inter/intra-species interactions: Next, we consider inter/intra-species encounters. Figure 8 illustrates the encounters in the experiment; and Table II summaries the results, which are symmetric as each encounter involved two tracked objects. From Figure 8, we observe that most encounters took place between 5:00AM and 6:00PM, i.e., the dogs and the cows were active in the daytime and tended to be stationary at night. In addition, the dogs had many more '*self-encounters*' (i.e., direct contact with the base station) than the cows, because they were in, or close to, the living room for most of the experimental period.

In addition, from Table II, we find that the cows have more intra-species encounters than the dogs (i.e., the cows had 397 intra-species encounters, compared to only 28 for the dogs). This may be because cows are gregarious by nature, and the tracked cows belong to three generations of the same family. There were also 39 inter-species encounters in the experiment.

To the best of our knowledge, this is the first time

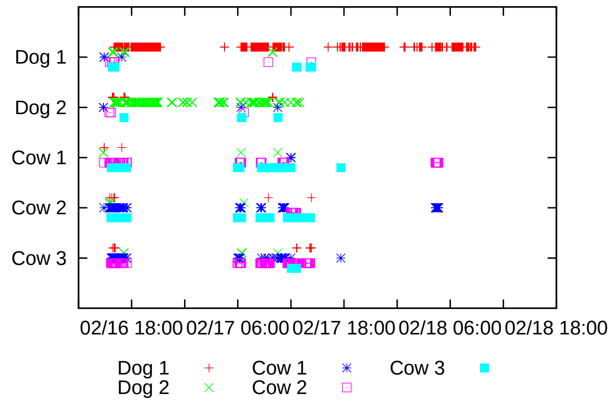


Fig. 8. Illustration of the inter/intra-species encounters in the experiment

TABLE II
SUMMARY OF THE ENCOUNTERS IN THE EXPERIMENT

	Encountered node				
	Dog 1	Dog 2	Cow 1	Cow 2	Cow 3
Dog 1		28	3	7	15
Dog 2	28		4	4	6
Cow 1	3	4		96	79
Cow 2	7	4	96		222
Cow 3	15	6	79	222	

that a wireless sensor network system has recorded inter-species interactions successfully in the real world. The results demonstrate that the proposed EcoNet system can track the inter/intra-species interactions of domesticated animals. We believe the results can be generalized to wildlife scenarios; hence, they could help scientists in a variety of applications, such as wildlife rehabilitation, disease control, and sustainable ecological development.

Next, we evaluate the distributions of the *duration of contacts* and the *inter-contact time* in the experiment. Here, *inter-contact time* means the time gap between two contiguous network contacts (i.e., an encounter between a particular node pair). Knowing the fundamental properties of the network is the key to designing data dissemination protocols and other advanced network applications [15, 22]. Figures 9 and 10 show the results of the complementary cumulative distribution function (CCDF). The results indicate that both distributions follow a power-law distribution (their parameters are -0.2551 and -0.3552 respectively), which confirms the findings reported in previous studies [15, 22]. However, as the data collected from the experiment is insufficient to represent the long-term properties of the two distributions, we defer a detailed evaluation (e.g., censorship evaluation, and self-similarity evaluation [16, 42]) to a future work.

3) GPS signal reception: Although the first pasture experiment was generally successful, one result differs from our expectations, i.e., the GPS signal reception was so poor that there were no GPS position updates in the experiment. As a result, even though we observed the inter/intra-species encounters, we do not know where the encounters occurred in the pasture area. We assume that the problem was caused by the black crepe tape used to pack the client device in the

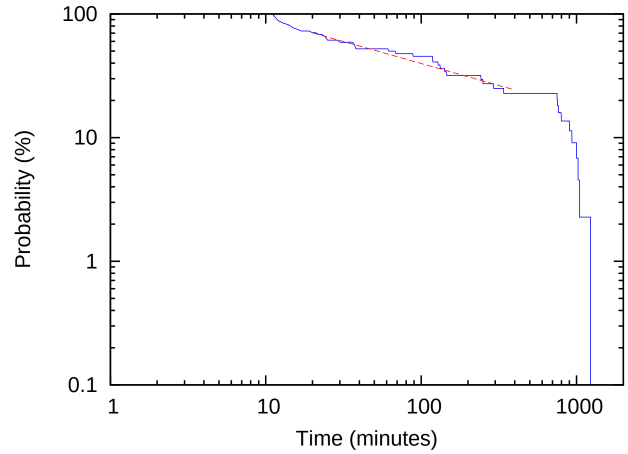


Fig. 9. The distribution of the inter-contact times in the experiment results

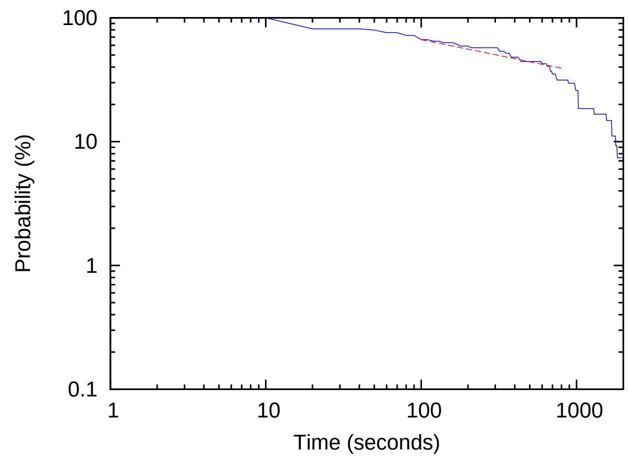


Fig. 10. The distribution of the contact times in the experiment results

experiment, the cows' position, and the canopy cover rate. Although several rehearsals at our campus were successful, we did use transparent adhesive tape to pack the client device during the rehearsals. We will discuss the effect of cows' position and canopy cover rate at sectionV-C and the tape issue here.

To verify our assumption, we conducted an experiment to compare the GPS signal reception of the EcoNet client device by packing the LOCK&LOCK box in a variety of ways using the arrangement shown in Figure 11a. For each packing method, we set the duty cycle of the GPS to 10 minutes, and measured the time to first fix after waking up from the sleep mode. We tried each tape for 100 runs, the time for non-wrapped box is 3.4 seconds, for transparent tape is 2.9 seconds, for yellow PVC tape is 7.0 seconds, and for black crepe tape is 13.5 seconds.

Specifically, we find that the transparent adhesive tape achieves a comparable reception performance to the non-wrapped case, but the yellow PVC tape and black crepe tape degrade the GPS signal reception. Moreover, the reception degrades as the number of packing layers increases.

In addition, we found that, when packing the client device, the arrangement of the components (i.e., the GPS receiver,

Fig. 11. Arrangement of components in the LOCK&LOCK box

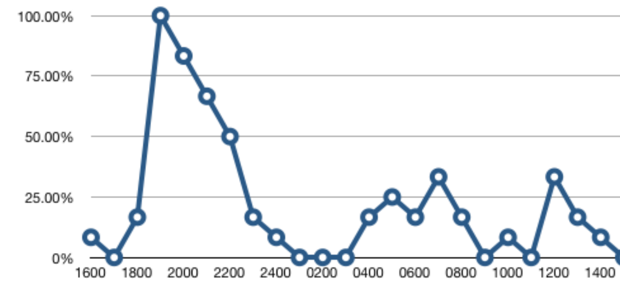


Fig. 12. Time of the Day v.s. GPS successful sampling rate

the Taroko mote, and the cable) also affected the GPS signal reception. We conducted another experiment with two device arrangements, as shown in Figure 11, and packed the LOCK&LOCK box using the black crepe tape. The results demonstrate that the average warm-up time is about 15 seconds when using the first arrangement (Figure 11a), and about 10 minutes when using the other arrangement (Figure 11b). The black square block shown in Figure 11a is the GPS antenna. Thus we can see the main difference between Figure 11-a and 11-b is if the antenna is wildly exposed or almost totally shielded, which decides the reception quality of GPS signals.

We conclude that GPS signal reception is affected by several factors, such as the number of packing layers, the type of tape used, and the arrangement of the components in the LOCK&LOCK box. We thus ran second EcoNet prototyping experiment at the same location on the same animals, except that one of the cows rebeled violently against our will to harness the collar on her neck again. Therefore, we decided to tag two cows and two dogs in the second experiment. We present the results of the second experiment in the following subsection.

C. The Revised EcoNet Experiment

On June 30th and July 1st, we ran the same experiment again at *Pasture Yen Family* using transparent tape and had the GPS antennas not being shielded this time. Due to execution difficulties, the collars are not perfectly harnessed, i.e. the whole LOCK&LOCK box is almost underneath the cows' necks, not above the necks as we wished. Luckily the GPS signals did get through, and information was gathered at base station. Despite the position of the LOCK&LOCK boxes on the cow necks, we found that the shielding effects came mainly from the tapes and the metal materials around the GPS antenna which we already discussed. However, we also discovered that there were still some periods of time when the GPS antenna cannot receive any signals. We tried to compare the time periods with cows' positions and the canopy cover rate and got the following results.

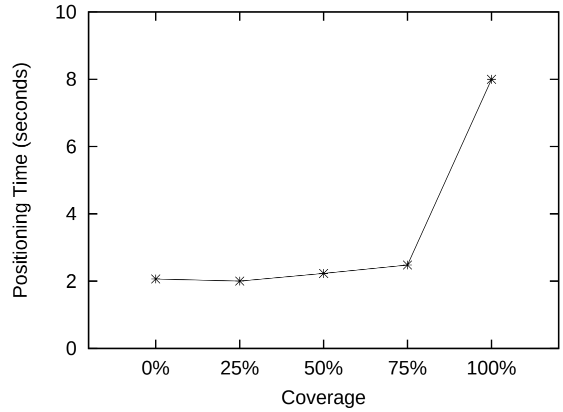
1) Position and Canopy Cover Rate versus GPS Reception: First, we represent the results from the second experiments. We expected to receive totally 164 GPS records from two cows during the day, but got only 24 records, which is 14.6% success rate. We expected to get 124 records during the night, and got 45 records, which claims 36.3% success rate during the night. However, the cows stand for 72.8% of the time during the day and only 27.7% during the night. Presumably GPS receivers get better reception when cows are standing (because they are not blocked by the cows' necks). However, we didn't find it to be this case in reality. By looking through the experiment results, we doubt that either position is not a factor that affects GPS reception or it's not the main factor.

Next, we investigate the impacts of canopy cover rate on GPS reception. During the day cows stay in areas with canopy cover rates higher than 50% when laying down. For most of the day they stay at areas that have canopy cover rates higher than 25%. Notice that the biologists can only measure the canopy cover rates when the cows moved out of the locations where they were. Furthermore, the actual canopy cover rate seen from GPS receivers' point of view will be a lot higher than the ones shown here because the GPS receivers are almost underneath the cows' necks. Biologists reported that before midnight the cows sat at areas with canopy cover rate lower than 7%, and moved to areas higher than 99% after midnight. After doing cross comparison, the numbers gotten match the GPS results. We got best result between hours from 18:00 to 24:00 and didn't get any GPS fixes from 24:00 to 04:00 as shown in Figure 12. However, this is the result from only one experiment and shouldn't be taken as a proved fact that GPS reception and canopy cover have high negative correlation. Thus we decided to run some more experiments to verify the correlations between canopy cover and GPS reception, and the result is shown in Figure 13.

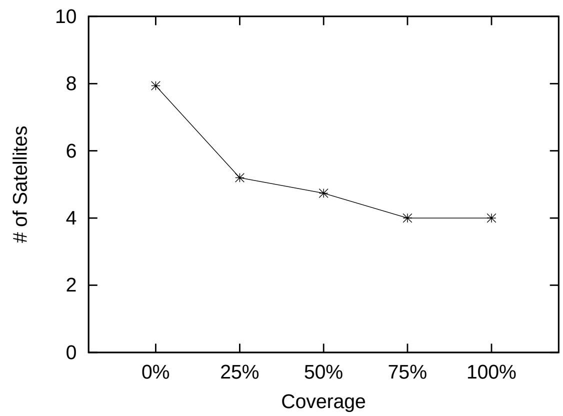
As we can see from the figure, canopy cover is an important factor that will affect the quality of GPS reception. However, there is no spherical densitometry plug-in sensors yet, so it's hard to obtain this information as a judgement to decide when to switch on/off GPSs.

2) System Tuning: The significance of prototyping, and the ability to be able to change the GPS and radio duty cycle have been shown in previous sections. Consuming the current at 35.8mA rate, the GPS receiver is the most dominating component concerning power. The radio runs at 19.2mA/21.5mA while transmitting/listening. While there is low power radio listening proposals out there[34], it does increase the probability of missing encounters. When only CPU is on, a Taroko mote consumes only 1.8mA. So in this subsection, we'll take a detailed look into how we can use the information obtained from the prototype and the on-board sensors to find the best power duty cycle of the system.

First, from the results shown in Figure 10, we observe that each contact is longer than 10 seconds. If we have the time



(a) Canopy Cover v.s. Positioning Time



(b) Canopy Cover v.s. Number of Satellites Seen

Fig. 13. Canopy Cover v.s. Time to Get GPS Fix and Canopy Cover v.s. Number of Satellites Seen

synchronized between all the nodes using time obtained from GPS receivers, we can simply put all the nodes to sleep for 4 seconds and wake up for 1 second to listen on the radio and send hello messages. If no one is around, the node goes back into sleep. If some nodes are around, we'll have at least 4 seconds to exchange data before this connection breaks because each contact is longer than 10 seconds. By doing this we reach 20% power duty cycle and save 80% of energy spent on the radio. But the information that *every contact is longer than 10 seconds* can only be obtained from prototyping the system and is species dependent, which says yet again why prototyping is important.

From Figure 12, we will say that we probably won't need to turn on GPS receivers as often as once per ten minutes between 24:00 to 04:00 because it mostly won't receive any data and won't have too much movements. During the day the GPS successfully sampling rate is also lower than during the night, intuitively we should recommend to sample less frequency during the day. However, it is this period of time that cows have the most actions. Therefore, in a dilemma like this, we should explain to the biologists and ask for their input to get the balance between power consumption and GPS resolution. Through using the power duty cycle adjusting functions described in section IV-C, we can achieve our goal to best utilize our energy.

VI. Conclusion and Future Work

We have presented a wireless sensor network-based system, called EcoNet, for both prototyping and long term wildlife tracking and ecological monitoring. EcoNet was inspired by the YushanNet system, which tracks hikers' movements by exploiting network mobility. Compared with existing approaches, which are either expensive and/or labor-intensive, the proposed solution is more scalable and could better facilitate wildlife tracking and ecological monitoring. We conducted a proof-of-concept experiment using two dogs and three cows at the Pasture Yen Family property. To the best of our knowledge, this is the first WSN system that has successfully observed inter/intra-species interactions in the real world. We show the biologists that a system should first be prototyped to prove its correctness and demonstrate how to do it in real experiments. We also discuss several deployment issues and provide potential solutions that could improve the performance of the EcoNet system in real-world experiments.

In the future we will keep working with biologists and devote our effort developing adjustable collars that can be remotely controlled and released. We plan to improve the installation of the GPS receivers so that they are placed neath the monitored animals' necks while keeping the antenna on the top. Moreover, we plan to package the Taroko mode and the GPS receiver into a smaller case, and perform a large scale field experiment in next season.

VII. Acknowledgements

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Jyh-How Huang received the B.Ed. degree in information and computer education from National Taiwan Normal University in 1998, and the Ph.D. degrees in computer science from University of Colorado at Boulder in 2008. He joined Network System Lab in National Taiwan University as a Post-Doc researcher in 2009. His research interests are DTNs, Body Sensor Networks, and Network Security. He is also a amateur mountaineer who summitted Everest in 2009.

Ying-Yu Chen received the BS (with highest honors) and MS degrees from the Department of Computer Science, National Tsing Hua University, Hsinchu, Taiwan, in 2006 and 2007, respectively. He is now a research assistant in the Institute of Information Science, Academia Sinica, Taipei, Taiwan. His research interests are wireless and mobile networks, network protocols, and opportunistic networks.

Yu-Te Huang received his B.S. degree in electronic engineering from National Taiwan University of Science and Technology in 2004, and the M.S. degree in computer science from National Chiao Tung University in 2006. He is now a full time research assistant in the Institute of Information Science, Academia Sinica.

Po-Yen Lin is currently a Ph.D student in the Electrical Engineering Department of National Taiwan University. He received his M.S. in biomedical engineering from National Yang-Ming University. His research includes wireless sensor network and delay tolerant network.

Yi-Chao Chen received the B.S and M.S. degrees in computer science and information engineering from National Taiwan University in 2004 and 2006. He entered The University of Texas at Austin to study computer science for Ph.D. degree in 2009. His research interests are wireless and mobile networks, network measurement, and sensor networks.

Yi-Fu Lin received the B.Sc.degree in nursing from the Fu Jen Catholic University, Taiwan, in 2002 and the M.Sc. degree in life science from the Nation Chung Hsing University, Taiwan, in 2006. He is currently pursuing the Ph.D. degree at the Nation Chung Hsing University, Taiwan. He is working on the conservation ecology of the chelonians in Taiwan, especially focusing on the endangered box turtles (Cuora flavomarginata)

Shih-Ching Yen received the B.Sc. degree in life science from the National Tsing Hua University, Taiwan, in 2005 and the M.Sc. degree in life science from the National Taiwan Normal University, Taiwan, in 2008. He is currently pursuing the Ph.D. degree at the National Taiwan Normal University, Taiwan. His research interests include animal behavior, wildlife management, and conservation biology.

Polly Huang is an associate professor at the Department of Electrical Engineering, the Graduate Institute of Communication Engineering (joint appointment), and the Graduate Institute of Networking and Multimedia (courtesy) of National Taiwan University. Dr. Huang received her Ph.D. in Computer Science from University of Southern California, and her B.S. in Mathematics from National Taiwan University. Prior to joining National Taiwan University, she spent time in the early stage of her career in AT&T Labs-Research, Swiss Federal Institute of Technology (ETH) Zurich, and UCLA. Dr. Huangs research interest spans wireless sensor networking and multimedia networking. She is a member of IEEE and ACM.

Ling-Jyh Chen received the B.Ed. degree in information and computer education from National Taiwan Normal University in 1998, and the M.S. and Ph.D. degrees in computer science from University of California at Los Angeles in 2002 and 2005 respectively. He joined the Institute of Information Science as assistant research fellow in 2005. His research interests are opportunistic networks, wireless and mobile networks, network protocols, network measurements, and social computing. He is a member of IEEE and ACM.