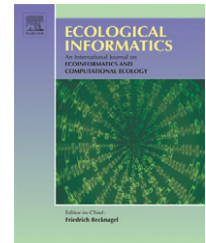


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# Ecoinformatics using wireless sensor networks: An overview

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## ARTICLE INFO

### Article history:

Received 22 April 2005

Received in revised form

9 February 2006

Accepted 15 February 2006

### Keywords:

Ecological survey

Sensor networks

Nodes

## ABSTRACT

Wireless sensor networks have the potential to become significant subsystems of ecological experiment. Sensor networks consist of large number of tiny sensor nodes, all of which have sensing capabilities. These networks allow coordinated signal detection, monitoring, and tracking to enable sensor nodes to simultaneously capture geographically distinct measurements. Sensor nodes do not require predetermined positioning making such networks especially useful for applications in remote, inhospitable environments. In this paper we have tried to see the various ecological experimental scenarios, and how wireless sensor networks can be used in that field. One of the most challenging bottlenecks in the usage of wireless sensor networks in large scale experiments is the energy constraint. Various routing protocols which have tried to optimize the energy usage are also studied in the paper.

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## 1. Introduction

Ecological research is the investigation of processes and patterns that explain the relationships between living organisms and their environment. To understand this relationship, the effect of various changes in environment on organisms is observed. Most of these observations are made over a period of months. Wireless Sensor Networks (WSN) (Akyildiz et al., 2002) comprises of numerous tiny sensors that are deployed in spatially distributed terrain. These sensors are endowed with small amount of computing and communication capability and can be deployed in ways that wired sensor systems could not be deployed. WSN capability to provide coordinated and multi-scale observations greatly extend the ability to monitor the various environmental conditions and the effect this has on the organisms under observation. Such networks make it possible to collect data over a period of time. The accuracy of data collected is also greatly improved. The ability of wireless sensor networks to collect temporally intensive and spatially

distributed data facilitates ecologists to collect data which was previously thought impossible to collect. The intimate connection which the sensor nodes have with its immediate physical environment allows each these nodes to provide localized measurements and detailed information that is hard to obtain through traditional instrumentation. But before the practical application of WSN there are many obstacles that need to be overcome. One of the most important factors that greatly hamper the usability of WSN is the energy constraint. As it is desirable to keep the size of wireless sensor nodes as small (e.g. MICA 2 motes are the size of a pack of cigarettes and have two AA size batteries), they are highly restrained in energy. According to Powers (1995), battery capacity only doubles in 35 years. So the energy constraint problem is unlikely to be solved in near future, thus the current research focus in WSN is on devising ways to optimize the battery consumption, and thus extend the lifetime of the network. The other problems are due to the limited computation power and thus their incapability to do sophistic tasks. The

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bandwidth of the wireless links is often limited, and thus it restricts the range in which a sensor node can communicate.

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## 2. General introduction to ecological modeling

Our environment due to its dynamic and spatial processes is known as a complex, highly interacting and spatially distributed system. These properties make analyzing, describing, modeling and even simulating our environment a challenging task. An experiment to study, for example, the consequences of human influences on ecological systems which do not disturb the environment is a valuable and important tool for environmental management. Such experiments are therefore identified as important and necessary tools for studying and understanding ecological processes. In situ localized observation of environmental and ecosystems processes at higher densities and over larger areas is likely to greatly improve the modeling of these processes and lead to the discovery of new classes of emergent phenomena. Wireless communication and networking can provide the technological infrastructure that will enable the needed improvement, while minimizing invasiveness and cost. Wireless environmental sensing has tremendous benefits and environmental scientists are increasingly using these potentials. Research efforts to understand communication and network-theoretic properties of generic ad-hoc energy-aware wireless sensor networks are being done. Many small-scale practical experiments that target the environmental sensing application are being conducted. While these projects give a positive feedback, the promise of wireless sensor networks for environmental monitoring (consisting of hundreds or may be thousands of small, inexpensive sensors that gather information and cooperate to relay that information to the ultimate destination) remains to be realized.

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## 3. How does wireless sensor network help in ecological monitoring

Ecological theories and hypotheses are usually complex because of natural variability in space and time, which often makes the data collection for experiments difficult. The experiments require data to be collected carefully and with proper regard to the needs. The fundamental processes in ecological systems occur over relatively long periods of time, e.g. the generation of some insects over a matter of days. Similarly, soil erosion may occur rapidly with one, possibly unpredictable, storm, while soil-building processes may require centuries. Thus, ecological processes, consisting of both organisms and their environment, are driven by dynamics with periodicities and durations spanning many time and space scales.

Thus various studies require different frequencies at which observations need to be made. Some experiments require that data be gathered every few seconds, while others may need data to be gathered every few days. The data gathering may be triggered by some environmental stimulus. As period over which data need to be collected and the region from which the data need to be collected is often very large and remotely

located, it becomes almost impossible to do this accurately. For example consider the enormous variation in the genotypes and phenotypes of organisms, and the broad array of their responses to weather and climate conditions. These combinations lead to exceedingly dynamic ecological systems that make experiments difficult to conduct. Applying WSN technology to habitat and environmental monitoring represent a class of sensor network applications with enormous potential benefits for scientific communities and society as a whole. Scattering the area of interest with numerous wireless sensors can enable long-term data collection at scales and resolutions that are difficult, if not impossible, to obtain otherwise. Since the sensors are in physical connection with the environment they are capable of providing localized measurement. It is the closest one can get to being actually present there. The need to study ecosystems at multiple temporal and spatial scales has mandated the development of high density, heterogeneous sensor networks. These networks include both fixed and mobile sensor nodes, a large variety of sensors, and infrastructure to support long-term operation. They provide unprecedented ability to study complete systems in three dimensions and over a long period of time. Advances in wireless sensor network have made significant improvement over traditional sensor networks in scale, complexity, and communication. With these advances, survivability of sensor nodes and their connectivity has become an issue of significant importance in a wireless sensor network. Survivability is the ability to provide a minimum level of service in the presence of failures or attacks such as equipment failure, destructive natural phenomena, and premeditated attacks. While there is no guarantee against such system failures, systems should be designed to survive such risks. Hence, network reliability is a major factor that needs to be considered in network planning and design. Once the network has been planned and laid out, the next step is to provide efficient routes for traffic originating at the sensor nodes, also known as traffic engineering. It is also important to manage the traffic flow and routes efficiently given that sensor nodes may fail over time. To implement a cost-effective survivable sensor network, sensor network applications are being explored, factors that influence the design are being studied, and various algorithms and protocols are being developed. For example, in the Cosumnes River project, the placement of data loggers and beacons was optimized to achieve a cost-vs.-efficiency tradeoff.

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## 4. Description of a sensor node

UCB Mica mote (Hill and Culler) or Crossbow Berkeley Motes were developed by collaboration between University of California at Berkeley (UCB) and Intel Corporation. Each mote is battery-powered, featuring its own processor, analog-to-digital converter (ADC), and a radio frequency (RF) transceiver for communications with other motes. The motes are designed to withstand tough weather conditions. Operating system named "TinyOS" (Hill et al., 2000) runs on each of the motes, TinyOS manages communication with the neighbors. TinyOS is a tiny micro-threading distributed operating system developed by UC Berkeley, with a NES-C (Nested C)

source code language (similar to C). These nodes come with five sensors installed — temperature, light, acoustic (microphone), acceleration/seismic, and magnetic. More sensors, maximum of up to eight, can be added to the motes if desired. Their low-power requirement and small size make it possible to place them anywhere. The operating frequency is ISM band, either 916 MHz or 433 MHz, with a data rate of 40 kbits/s and a range of 30 ft to 100 ft. Each node has a low-power microcontroller processor with a speed of 4 MHz, a flash memory with 128 kbytes, and SRAM and EEPROM of 4 kbytes each. There are three types of sensor nodes — S-link (strain gauge), G-link (accelerometer), and V-link (supports any sensors generating voltage differences). Up to 2 MB of data can be stored on these nodes. A 3.6-volt lithium ion internal battery (9 V rechargeable external battery is supported) is used for these nodes. A single receiver (Base Station) addresses multiple nodes.

## 5. Examples of practical implementations

### 5.1. Great Duck Island (<http://www.greatduckisland.net>)

College of the Atlantic (COA) conducts field research programs on several remote islands. One of them, Great Duck Island (GDI) is located near Mount Desert Island, Maine. At GDI, the major interests in monitoring were, studying the usage pattern of the nesting burrows when one or both of the parents alternate between incubation and feeding at sea over a 24–72 h cycle, burrows and surface environments parameters to be observed over a period of a 7-month breeding season (April–October) and observation of the difference in the micro-environment with and without large number of nesting petrels. For all these studies unique data and suitable data acquisition rates were required. Most of the data acquired are through occupancy detection and temperature difference between burrows with adult birds and burrows that contain eggs, chicks, or are empty. Petrels most likely would leave the burrows late evening and early morning, so measurements need to be taken every 5–10 min to calculate the time entry and exit (by watching for temperature spikes

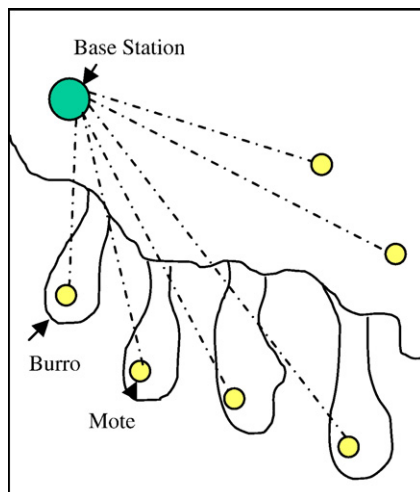


Fig. 1 – Burrows with sensor nodes.

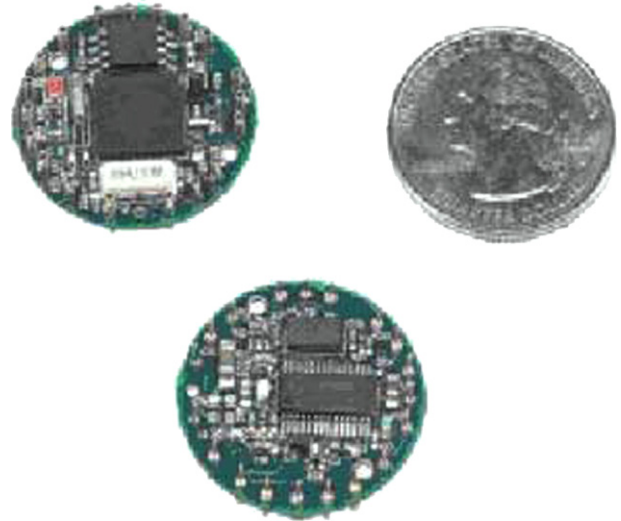


Fig. 2 – Mica2Dot ([http://path.berkeley.edu/~singyiu/vehicledetection/research/smartdust/basic\\_components.htm](http://path.berkeley.edu/~singyiu/vehicledetection/research/smartdust/basic_components.htm)).

inside a burrow, researchers can determine when a petrel is present). Also petrels are unlikely to enter or leave during the light phase of a 24 h cycle, so other general environmental differentials between burrow and surface conditions during the extended breeding season can be captured by records every 2–4 h. The differences between “popular” and “unpopular” site can be captured from hourly sampling, especially at the beginning of the breeding season. The choice of breeding site in most probability depends on more than one environmental condition. Thus many factors need to be observed over a period of time to understand petrels’ choice of a specific nest site (Fig. 1).

A smart sensor network was set up there as an example in 2002. The network consisting of 150 motes was set up at the GDI. This experiment was to help biologists monitor the population of 18,000 petrels. These petrels roost in burrows at the GDI during summer, and motes had to monitor the “micro-environmental” conditions such as temperature, humidity, and atmospheric pressure, and also track the presence of birds and chicks using passive infrared sensors. To suit the requirements the motes had to be small. The mote designed by UCB–Intel team called “Mica” was of size smaller than a pack of cigarettes. Still this was considered to be too big for the application, thus “Mica2Dot” was developed. “Mica2Dot” was of size of a large coin (Fig. 2).

These motes had to be placed inside burrows, thus solar cells could not be used, so lithium battery was used. A mote having micropower processors and other low-power components would drain the battery within a few days. Thus the motes were designed to spend 99% of their time in sleeping mode, with all systems shut down except for a timer that provided a wake-up call at a specified interval. The network radio communication was checked several times a second and sensor readings were taken once every few minutes. The data were then aggregated and sent out only when needed. Thus reducing the communication overhead. In one field season some 32 motes deployed on the island recorded well over

1 million readings. For habitat monitoring, sensors for temperature, humidity, barometric pressure, and mid-range infrared were added. Readings from the motes are periodically sampled and relayed to the base station on the island. These in turn feed into a satellite link that allows researchers to access real-time environmental data over the Internet. In June 2003, there was a second generation network with 56 nodes. The network was augmented in July 2003 with 49 additional nodes and again in August 2003 with over 60 more burrow nodes and 25 new weather station nodes. These nodes formed a multihop network transferring their data back “bucket brigade” style through dense forest. Some nodes are more than 1000 ft deep in the forest providing data through a low-power wireless transceiver. The Duck Island smart sensor network was an operational prototype, used to validate technologies and processes.

A similar experiment was set up recently in redwood forest near Sonoma, in northern California. The 120 motes used in the experiment had to be set up with care as the range of these motes was 30 m. All the motes dumped their data to a central mote, which radio-relayed the information to UCB, 70 km (43 miles) away.

### 5.2. PODS—a remote ecological micro-sensor network (Edoardo and Bridges)

PODS is a University of Hawaii, SensIT project, trying to provide technology to monitor rare and endangered species. Near-real time observing of important events is required, such as visitation by pollinators, consumption by herbivores and even human visits, along weather conditions and events. To make good observations of the rare plants high-resolution digital cameras were used. The cameras are triggered at regular intervals and sometimes in response to specific events. A network of digital weather instruments was also set up to measure the environment. The instruments measured rainfall, wind, temperature, humidity and solar radiation. Data for these rare plants need to be gathered from a variety of locations like low shrubs to dense tropical forests, around mountains and down valleys. Environmental conditions can be severe, too varying from freezing cold to highly acidic rainfall. The sensor network should be capable of automatically configure themselves. Since the nodes have limited resources, they should conserve their resources, such as power. Security of data is also ensured to minimize the possibility of it being harmed or stolen. To meet all these requirements a communication network was built using a series of “pods”. These pods collect and pass on information. A pod is built around a power source, embedded computer, GPS receiver and wireless communications gear. A plug permits the connection of a network of weather instruments. The data collected from all the pods are passed on to the base station, which is connected to Internet. The pods are arranged taking into account communication ranges and communication chain fails. The pods are of three types. The most general type is the communication pod, this pod handles all network communication. The specialized pod is communication pod with the added sensing instrument. The base station pod provides temporary local storage and processing of data and connects to the Internet.

### 5.3. UC Botanical Garden’s Mather Redwood Grove

Redwood’s are being monitored using sensor nodes to study the moisture the trees absorb from fog. University of Berkeley are using wireless sensors capable of capturing the light, temperature and humidity to capture environmental data from the trees. A prototype using 50 sensor nodes and 5 redwood trees has been set up. The small size of the nodes makes them very optimal in terms of visibility and impact. Each node is about 3 in.<sup>3</sup> which are capable of transmitting radio signals at 50 kbytes per second.

Wireless sensors are significantly cheaper and easier to install thus can be easily deployed in redwood forest and would provide a higher fidelity picture of the ecosystem. The nodes have C battery, and would last for months, sending out variety of environmental data for data processing. The sensor nodes have been designed to withstand harsh environment of the forest (Fig. 3).

The later phases of the project would expand the number of trees included (in Big Basin Redwoods State Park in Santa Cruz County and at a site in Sonoma County), and thus use a far larger number of sensor nodes. Additionally the sensors will also collect data from the tree to measure the amount of water flowing, so as to measure the amount of data absorbed from soil and fog.

### 5.4. The wireless vineyard

Sensor motes monitor temperature throughout the vineyard. Each mote in the vineyard currently takes one temperature



**Fig. 3—Preparation to mount a miniature wireless sensors.** Adapted from [http://www.berkeley.edu/news/media/releases/2003/07/28\\_redwood.shtml](http://www.berkeley.edu/news/media/releases/2003/07/28_redwood.shtml).



**Fig. 4**– A sensor node deployed in vineyard. <http://www.intel.com/technology/techresearch/research/rs01031.htm>.

reading per minute and stores the results. The mote records the highest and lowest temperature readings for each hour of the day. Intel Research Berkeley Lab is using thousands of embedded sensing devices to wirelessly connect forming a communication network.

The sensor nodes are deployed in a vineyard and collect temperature reading every minute and store the data. They also compute an hourly highest and lowest temperature, guiding the irrigation for the vineyard, and helping in making a better harvesting decision (Fig. 4).

## 6. Factors influencing sensor network design

Sensor networks comprise of three main components, sensor node, sink and monitored events. Most of the applications assume that the sensor nodes are stationary. The bandwidth requirements and energy consumption increase in case of moving nodes. The sensed event depending on the application can be dynamic or static. There is a significant increase in the traffic when tracking a dynamic event, as periodic reporting is required. Nodes can be deployed in either deterministic or self-organizing fashion. In deterministic the nodes are placed manually and the routes are predetermined. In self-organizing systems sensor nodes are randomly scattered, and the routes are randomly decided, and as the nodes have limited energy, the route setting is greatly influenced by energy considerations. Multihop routing is more desirable as the transmission power of a radio is proportional to distance squared or even higher order in the presence of obstacles, and multihop routing will consume less energy than direct communication.

But multihop routing requires topology management and medium access control. Direct transmission would give good performance if all the nodes are near enough to the sink (Heinzelman et al., 2000). But most of the time sensors are

scattered randomly over an area of interest. Thus an energy optimized routing becomes unavoidable. Depending on the application, the data delivery model to the sink can be continuous, event-driven, query-driven and hybrid. Each sensor node periodically sends data in continuous delivery model. In event-driven and query-driven models, the transmission of data is triggered when an event occurs or a query is generated by the sink. Some networks are a combination of both these, these are called hybrid models.

### 6.1. Routing protocols

There are various types of routing protocols, like data-centric protocols, hierarchical protocols and location-based protocols. We discuss a few of them here.

#### 6.1.1. Data-centric protocols

Due to the huge number of sensor nodes it is not feasible to assign global identifiers to each node in the sensor network. This along with the random deployment of the sensor nodes makes it hard to select a specific set of sensor nodes to be queried. Thus data are sent from all the sensor nodes in the region, with significant redundancy. This is very inefficient in terms of energy consumption, thus routing protocols that will be able to select the sensor nodes in the region of interest and also apply data aggregation during relaying of data are considered. This consideration has led to data-centric routing, which is different from traditional address-based routing where routes are created between addressable nodes managed in the network layer of the communication stack.

In data-centric routing, the sink sends out queries which are region aware and waits for data from the sensors located in the selected regions. The queries are attribute-based to specify the properties of the data. SPIN (Heinzelman et al., 1999) is the first data-centric protocol, which considers data negotiation between nodes in order to eliminate redundant data and save energy. Later, directed diffusion (Intanagonwatt et al., 2003) has been developed and has become a breakthrough in data-centric routing.

**6.1.1.1. Directed diffusion.** Directed diffusion is a data-centric information dissemination paradigm for wireless sensor networks. The elements of directed diffusion are sending interests, setting up gradients, and reinforcing the paths. An interest message is a query that has the information about the data that is required from the sensor nodes. Data can be either collection of information or an event triggered by some physical phenomena. Gradients are directional state created in each node, set towards the neighbor from which interest is received. One or more of these paths are reinforced. Each task is named in an attribute list. The task description specifies an interest for data matching. Interest is a named task. Interest is sent into the network from a sink. Interest may also have information about duration of the task and the interval at which response is required. Initial interest messages are also called exploratory, and it tries to form a connection with the nodes that have the required data. At each node a cache of distinct interests is maintained (this allows interest aggregation). They contain

information about the previous hop. The interests propagate through the network. The nodes in the region or nodes that have data for a particular interest send data marked as exploratory through the gradient established. As a result exploratory data may follow multiple gradient paths to the query source node. Once the exploratory data is received, the query source node reinforces one of the paths based on the routing protocol being used. To reinforce the node sends a positive reinforcement message to the neighbor initiating the sending of data. The data sending interval is less than the exploratory sending interval. The reinforced neighbor reinforces its neighbor in turn, and this is done all the way until the data source. Data messages are marked as exploratory at a regular interval. Many other protocols have been proposed which are either improvement on directed diffusion or following similar concept.

**Flooding and gossiping:** Flooding and gossiping (Hedetniemi and Liestman, 1988) are two classical mechanisms for data propagation in sensor networks without the need for any routing algorithms and topology maintenance. In flooding, each sensor receiving a data packet broadcasts it to all of its neighbors. This chain continues until the packet arrives at the destination or the packet has already traveled the maximum number of hops. Gossiping is a slightly enhanced version of flooding where the receiving node sends the packet to a randomly selected neighbor, which picks another random neighbor to forward the packet to and so on.

**Sensor Protocols for Information via Negotiation: SPIN** (Heinzelman et al., 1999) is a data-centric routing mechanism. The idea behind SPIN is to name the data using high level descriptors or meta-data. Before transmission, advertisement mechanism exchanges meta-data among sensors, which is the key feature of SPIN. Each node upon receiving new data advertises it to its neighbors and interested neighbors, i.e. those who do not have the data, retrieve the data by sending a request message. SPIN's meta-data negotiation solves the classic problems of flooding such as redundant information passing, overlapping of sensing areas and resource blindness, thus achieving a lot of energy efficiency.

### 6.1.2. Location-based protocols

Most of the routing protocols for sensor networks require location information for sensor nodes. Location information is needed in order to calculate the distance between two particular nodes so that energy consumption can be estimated. Location information is utilized in routing data in an energy efficient way. For example, if the region from which data are to be collected is known, using the location of sensors, the query can be diffused only to that particular region which will eliminate the number of transmission significantly.

**6.1.2.1. GEAR.** Geographical Energy Aware routing (Yu et al., 2001) uses a geographical and energy aware neighbor selection heuristic to route the packet towards the target region. The process of forwarding a packet towards the region involves choosing a neighbor that is closest to the destination among all the neighbors. When all neighbors are away, choose

a neighbor that minimizes the cost value to the neighbor which is computed as

$$c(N_i, R) = \alpha d(N_i, R) + (1-\alpha)e(N_i)$$

where  $d(N_i, R)$  is the distance from  $N_i$  to the centroid  $D$  of the region  $R$  normalized by the largest distance among all the neighbors  $N_i$  and  $e(N_i)$  is the consumed energy at node  $N_i$  normalized by the largest consumed energy among the neighbors of  $N$ .

On reaching the region of interest recursive forwarding technique is followed to flood the packet in the region to minimize the cost consumption.

## 7. Summary

Application of sensor networks in ecological experiments is useful to ecologists. The use of sensor networks in ecological experiments would make data gathering a very accurate, extensive and easy job. The intimate connection with their immediate physical environments allows sensor networks to provide localized measurements and detailed information that complement the macroscopic measurements and analysis. The low-level energy constraints of the sensor nodes have mandated a routing protocol which optimizes the lifetime of the sensor network.

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