

Design and Implementation of a Hybrid Sensor Network for Milu Deer Monitoring

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Abstract—This paper presents a hybrid sensor network with both fixed nodes and mobile nodes for monitoring and protecting Milu Deer, a specific kind of rare animals in China. Our goal is to provide unprecedented fine-grained environmental and individual data for zoologists and explore potential problems in hybrid sensor networks. Total 116 nodes have been deployed up to now, which consists of 30 mobile nodes for monitoring Milu Deer's behaviour, 16 fixed nodes for monitoring environments, 69 fixed nodes for data relay and 1 sink node (or base station) for data gathering. Environmental nodes and relay nodes construct the fixed network infrastructure, which transfer environmental data and individual data to the sink node and then the server efficiently and reliably. Network protocols were designed using popular components and tailored for particular application scenarios. System performance was evaluated by both simulations and field experiments, which demonstrated the effectiveness of our monitoring system.

Keywords—Hybrid Sensor Network, Milu Deer, Mobile Node, Habitat Monitoring, System Architecture, Network Protocol

I. INTRODUCTION

Over the past few years, wireless sensor networks have triggered an exciting number of research activities. Numerous application areas have been explored and evaluated using wireless sensor networks [1]. Among these areas, environmental monitoring [2]-[5], habitat monitoring [6]-[11], and animal monitoring applications [12]-[14] get more attentions because they can benefit more from distributed, self-organized and self-healing characteristics of wireless sensor networks. These applications employed either fixed nodes or mobile nodes for long term deployments or short term experiments. In these applications, higher resolution data both in spatial and temporal can be acquired.

Milu Deer is a specific kind of rare animals in China. It's one of the most endangered species, because there are only less than 4000 Milu Deer all around the world. Chinese government has put a lot of effort into researching and protecting them. As the main institution for this, Beijing Milu Ecological Research Center plays very important role in Milu Deer's research and protection. Zoologists spend a lot of time to observe them. However, with traditional methods, it is very difficult to obtain detailed data about the Milu Deer individuals and the environment they live in.

In order to understand Milu Deer better, the following environmental and individual data are needed by zoologists:

- Environmental data and their distribution in the protection area, including air temperature, humidity, light intensity, barometric pressure, wind speed, wind direction, precipitation, and noise level;
- Behavioural data of Milu Deer, including rumination, walk, running, and so on;
- Physiological data of Milu Deer, including body temperature, blood pressure, heart rate;
- Ecological data of Milu Deer, including bellowing during the rut, locations in the protection area.

Wireless sensor networks provide opportunities to satisfy these requirements. However, there are some challenges for designing wireless sensor network based Milu Deer monitoring system, which include: 1) The large protection area have to be covered as environmental data distribution and near realtime individual data are needed; 2) Both fixed nodes and mobile nodes exist in the same system; 3) Long lifetime of more than two years should be obtained without human interposition. Unfortunately, existing sensor network systems in environmental monitoring, habitat monitoring, and animal monitoring applications cannot cope with these challenges.

To solve above challenges, a hybrid wireless sensor network is designed and implemented for Milu Deer monitoring. Total 116 nodes are deployed in the protection area of Beijing Milu Ecological Research Center, which consists of 30 mobile nodes and 86 fixed nodes. The 86 fixed nodes consist of 16 environmental nodes, 69 relay nodes and 1 sink node. These nodes construct the fixed network infrastructure, which transfer environmental data and behavioural data to the server efficiently and reliably. Network protocols were designed using popular components and tailored for particular application scenarios. System performance was evaluated by both simulations and field experiments. The results show that this hybrid wireless sensor network based Milu Deer monitoring system can provide environmental and individual data imperatively needed by zoologists.

The rest of this paper is organized as follows. In Section II, related works in environmental monitoring, habitat monitoring, and animal monitoring applications are discussed. In Section III, the system architecture is described, including the hardware platform, network protocol and server side software. Section IV describes the implementation and deployment of the monitoring system in the protection area. Preliminary results of performance evaluation are discussed in Section V.

We conclude this paper and give future research directions in Section VI.

II. RELATED WORKS

Over the past few years, numerous wireless sensor network based environmental monitoring, habitat monitoring, and animal monitoring applications were designed, implemented, deployed and evaluated in the literature. These applications give inspirations for us to design and implement the Milu Deer monitoring system.

A. Environmental Monitoring Applications

In environmental monitoring applications, sensor nodes are always utilized as miniature weather stations [3]-[5]. These nodes can measure air temperature, humidity, light intensity, barometric pressure and so on, just as traditional weather stations. However, higher spatial resolution can be realized than traditional weather stations. In these applications, no mobile nodes are needed.

B. Habitat Monitoring Applications

Habitat monitoring applications appeared when wireless sensor network technology moves from laboratory to practical applications. There are several very famous habitat monitoring applications, such Great Duck Island Project of Berkeley [6], [9], [10]. In these applications, environmental data are the main monitored parameters just as in the environmental monitoring applications. As a result, nearly no mobile nodes are needed in these systems.

C. Animal Monitoring Applications

Wild animals monitoring is a difficult and laborious work for zoologists as they have to tail after the monitored animals for relative long time. Wireless sensor network technology relaxes this work by installing appropriate sensors on target animals. ZebraNet Project of Princeton is one example of these applications [12], [14]. Recently, this technology began to apply on domesticated animals monitoring [13]. In these applications, either fixed nodes or mobile nodes are used. None of them employed both fixed nodes and mobile nodes.

D. Inspiration from these Applications

To the best of our knowledge, none of existing applications in environmental monitoring, habitat monitoring, and animal monitoring areas include both fixed nodes and mobile nodes in a hybrid wireless sensor network. However, these applications give inspirations for us: 1) Environmental monitoring applications give references to design environmental nodes; 2) Animal monitoring applications provide guidelines for designing collars wore by Milu Deer; 3) The hybrid sensor network is designed by studying the fixed network or mobile network in these applications in-depth.

III. SYSTEM DESIGN

Requirements of the zoologists can only be satisfied by a hybrid wireless sensor network. Firstly, the protection area in which Milu Deer live should be covered by enough nodes to construct network infrastructure for data transfer. Secondly,

Milu Deer wearing collars act as mobile nodes in the network. Thirdly, environmental nodes should distribute in the protection area evenly with appropriate density that the zoologists need. Fourthly, boundary of the protection area should be located, that is to say, a virtual fencing is needed. Finally, monitored data should be stored permanently for future analysis.

A. System Architecture

With these requirements in mind, a system architecture as shown in Figure 1 was designed. In this architecture, fixed sensor nodes are installed evenly along the boundary of the monitoring area. Then, inside the monitoring area, fixed sensor nodes are located to realize maximum coverage. To assist this procedure, a tool is designed to display the coverage effect, which will be shown in section IV. The fixed nodes construct the network infrastructure. Locations of environmental nodes can be selected evenly from the locations of all the fixed nodes as they can also forward data as relay nodes. The rest fixed nodes can be used as relay nodes. As a result, when mobile nodes wander in the monitoring area, at least one fixed nodes can see them and forward data for them.

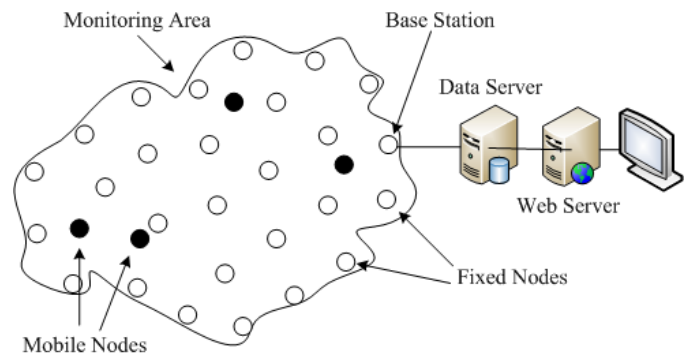


Figure 1. System architecture of the Monitoring System

According to the environmental data and appropriate density needed by zoologists, two kinds of environmental nodes are designed. One has wind speed, wind direction and precipitation sensor and the other not. The number of different kinds of node and their monitoring parameters are listed in Table 1.

B. Sensor Node Design

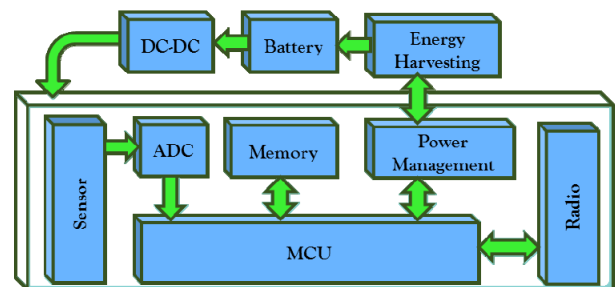


Figure 2. Sensor node architecture

The I-type environmental node, II-type environmental node and mobile node for Milu Deer are designed following the architecture shown in Figure 2. As the nodes are all deployed outdoor, solar energy harvesting is used to satisfy the lifetime

requirement. Considering that continuous raining is possible in summer, a two-stage battery system is used as energy storage. In the first stage, Ni-MH rechargeable batteries are connected to the solar panel and used as the main power source. In the second stage, high volume Li-SOC12 un rechargeable batteries are used as the reserved power source. All nodes use processing and communication components similar with MicaZ [15]. That is to say, Atmega128L from Atmel is used as MCU and CC2420 from TI is used as Radio. Other components, such as sensors and their signal conditioning circuit, are selected according to particular requirements of corresponding nodes.

TABLE I. NODE TYPES AND MONITORING PARAMETERS

Node Types	Number	Monitoring Parameters
Sink Node	1	None
Environmental Node I	4	Air Temperature, Humidity, Light Intensity, Barometric Pressure, Wind Speed, Wind Direction, Precipitation, Noise Level, Battery Voltage
Environmental Node II	12	Air Temperature, Humidity, Light Intensity, Barometric Pressure, Noise Level, Battery Voltage
Mobile Node for Milu Deer	30	3-axis Accelerations, 2-axis Obliquities, Bogy Temperature, Blood Pressure, Heart Rate, Bellowing, Location, Battery Voltage
Relay Node	69	Battery Voltage

The relay nodes possess the same components with environmental nodes and mobile nodes except sensors. The sink node is powered by the server with which it connects through serial port. As a result, sensors and power harvesting and storages are not needed.

C. Network Protocol Design

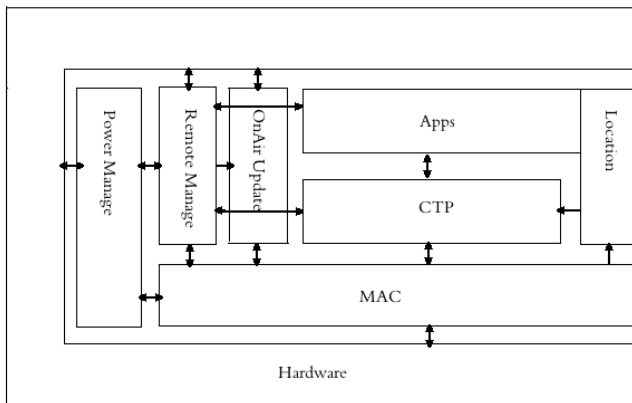


Figure 3. Overall software architecture of the fixed node

Software running on all the nodes is based on TinyOS operating system [16]. The overall software architecture of the fixed node is shown in Figure 3. Popular components are used to design the network protocol. In the MAC layer, Low Power Listening (LPL) is used to reduce energy consumption [17]. In

the network layer, Collection Tree Protocol (CTP) is used which provides link quality estimation and uplink route discovery [18]. These components are used also because their source codes are available in TinyOS. However, the source code of CTP in the most recent version of TinyOS has bugs which will lead to network breakdown. These bugs have been found and corrected, as described in the next section.

For mobile nodes, as they don't need to forward data for other nodes, no network layer is needed. Mobile nodes can sent their data to the nearest fixed node and then go to low power mode. The fixed nodes are responsible for delivering the data to sink node.

For convenient maintenance, remote management interface and over the air programing functions are provided for all nodes. As a result, they can be reset and programed from the server remotely.

D. Server Software Design

Figure 4 describes the architecture of the server side software. Two servers are used to store data and provide services separately. The "Monitor" module monitors the status of the low-level wireless sensor network, and will automatically reset the network if any error occurs. The "Collector" module reads data from the serial port, which connects to the sink node. The data are stored into the MySQL database system and decoded and analysed by the "Analyzer" module. The results from the "Analyzer" are also stored into the database. The "Web Framework" can accept the user requests, present the data, and handle other functions such as permission control.

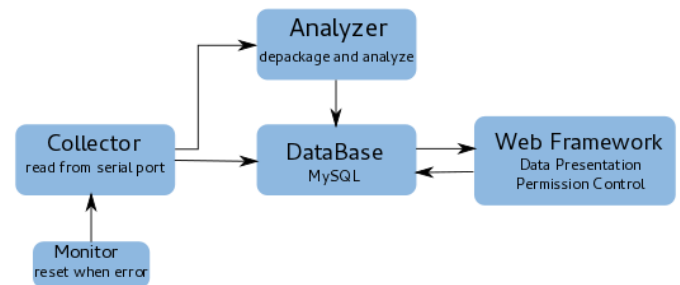


Figure 4. Architecture of the server side software

IV. IMPLEMENTATION AND DEPLOYMENT



Figure 5. Locations of the fixed nodes in the protection area

From June 2011, we began to deploy the monitoring system in Beijing Milu Ecological Research Center. With the procedure mentioned in section III, 86 fixed nodes are used to cover the monitoring area, as shown in Figure 5. Figure 6 and Figure 7 show the relay node and I-type environmental node separately.



Figure 6. A relay node for data forward



Figure 7. A I-type environmental node

The number of mobile nodes is determined by zoologists to satisfy the sample size in their research. 30 nodes are needed for this purpose. These nodes are packaged in collars and then wore by Milu Deer, as shown in Figure 8.

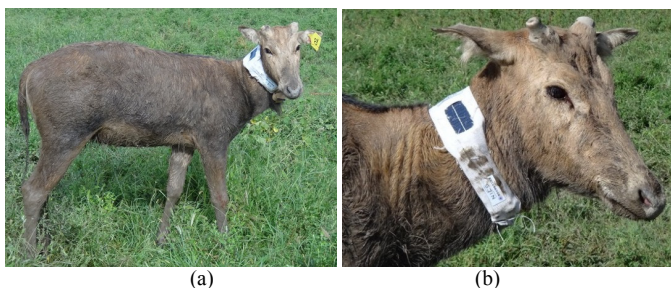


Figure 8. (a) A Milu Deer wearing collar containing sensor node, batteries and antennas; (b) Close view of the collar

The locations shown in Figure 5 are optimized and adjusted gradually using our customized tool. The coverage effect using this tool is shown in Figure 9. It is shown that the protection area is almost covered using the 86 fixed nodes except small areas covered by water and trees. However, as Milu Deer may appear in these areas, further adjustment is needed or several more nodes can be used to cover these areas.

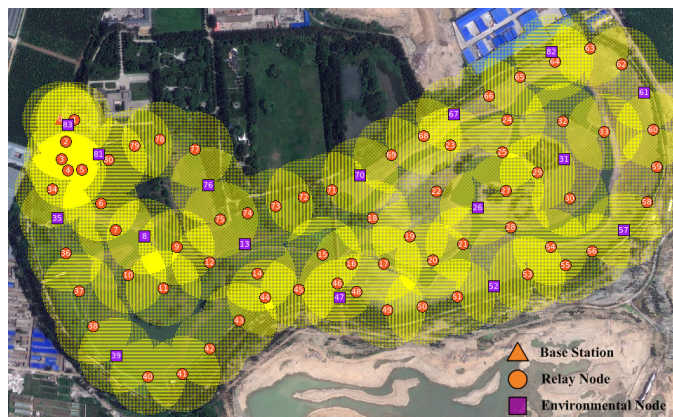


Figure 9. Coverage effect of the fixed nodes

V. PERFORMANCE EVALUATION



Figure 10. Network breakdown because of CTP bugs

Since deployed, system functions and network performance were tested. In the short period after the system started, the network functions were right and monitored data could be collected. However, we found that the network would break down gradually if the environment got worse. Figure 10 showed an example we encountered. It is obvious that the whole network was broke to four parts. Only the data from the part nearest to the sink node could be collected. The other three parts were isolated from the sink node. This condition would not recover until the server detected and reset the whole system.

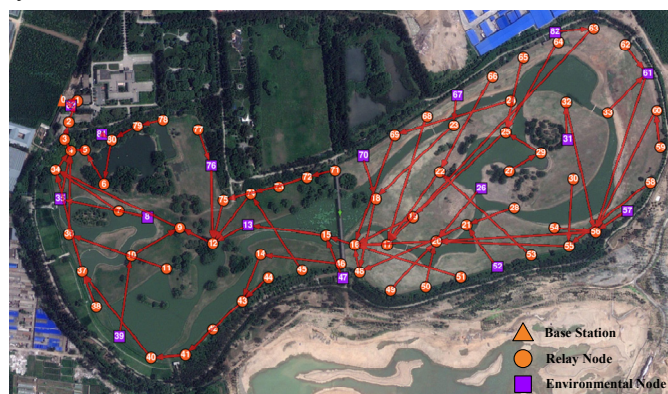


Figure 11. Network topology with corrected CTP

Tracking the source code, we found that the origin of this problem is that the source code of CTP in the most recent

version of TinyOS has bugs. The link quality estimation function and the parent node selection mechanism are sensitive to channel conditions, which are prone to be affected by weather conditions, such as humidity and wind.

We have corrected these bugs and tested network performance again. The network topology after long time running is shown in Figure 11. It is obvious that with these bugs corrected, the whole network is always connected even when channel conditions vary significantly in such a long time.

VI. CONCLUSIONS AND FUTURE WORKS

In order to obtain detailed data about the Milu Deer individuals and the environment they live in, a hybrid wireless sensor network based monitoring system has been designed, implemented and deployed. Total 116 nodes have been deployed up to now, which consists of 30 mobile nodes for monitoring Milu Deer's behaviour, 16 fixed nodes for monitoring environments, 69 fixed nodes for data relay and 1 sink node (or base station) for data gathering. Network protocols were designed using popular components and tailored for particular application scenarios. System functions and network performance were evaluated by both simulations and field experiments, which demonstrated the effectiveness of our monitoring system.

In the future, a few fixed nodes will be added to improve the coverage effect of the monitoring area. Then, more tests will be executed to analyse data latency, delivery rate, power consumption, and other important system parameters. On the other hand, the mobile nodes will be redesigned according to our experiences from initial deployments to reduce volume and weight, which will make the Milu Deer feel more comfortable.

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