Autonomous Monitoring of Vulnerable Habitats using a Wireless Sensor Network

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ABSTRACT

In the natural sciences, researchers use a variety of techniques that rely on extensive man-hours and can therefore be difficult to scale. This obviously limits questions that concern large spatial scales or that involve large numbers of animals. Here, we describe the design and deployment of a wireless sensor network that delivers high resolution sensor data while monitoring seabirds on a UK National Nature Reserve. We describe some of the problems encountered and the solutions we have used. In general, the network has successfully demonstrated its utility in a real world scenario and will be extended and enhanced for the coming field season.

Categories and Subject Descriptors

H.3.4 [**Information Storage and Retrieval**]: Systems and Software – distributed Systems, information networks; J.2 [**Computer Applications**]: Physical Science and Engineering: – Earth and atmospheric science.,

General Terms

Management, Measurement, Design, Reliability, Experimentation.

Keywords

Wireless Sensor Networks, ScatterWeb Platform, Ecology, Seabirds, Animal Behavior

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1. INTRODUCTION

Research in wireless sensor networks (WSN) has primarily focused on hardware design, self-organization, various routing algorithms, or energy saving patterns. This trend is changing and an interest in real-world scenarios leveraging WSNs is now evident. Several research groups have started to deploy testbeds [1, 2, 3] and there have already been some examples of the use of WSN in ecological research [4]. We can now begin to address the challenges arising from real world deployment rather that those in simulations or lab based experiments. One very important challenge is the design of flexible interfaces to the WSNs and the integration of deployment, management, and data-collection functions into tools researchers from other fields than computer science will find usable.

In this paper we describe the deployment of a WSN on Skomer Island in March 2007. We discuss our experiences, conclusions and resulting modifications for the upcoming deployment in April 2008.

Skomer Island is a UK National Nature Reserve located off the west coast of Pembrokeshire, Wales. The University of Oxford, UK has an existing research programme on the island investigating the behavior and spatial ecology of the Manx Shearwater (*Puffinus puffinus*), a burrow-nesting, highly pelagic seabird that spends most of its life at sea. These birds rely on the ocean ecosystems to which they attend, and are sometimes referred to as integrators of oceanic resources. As such, their behavior informs us both about the health of the ecosystems that they inhabit and also acts as a model for the behavior of a variety of similar seabirds.

Recently, researchers have been actively investigating the spatial behavior of Manx Shearwaters using miniature GPS loggers [5]. This technique has indicated both the range and duration of their foraging trips, but has relied on very intensive manual techniques. Researchers performed manual burrow inspections every 20-30 minutes to recapture tracked birds. This technique is obviously hard to scale and limits the number of animals that can be feasibly tracked or monitored.

By detecting birds' activity around entrances to the burrows as well as the identity of tagged individuals, the deployed system was able to inform researchers about the birds' arrivals and departures almost instantly. In addition, our WSN based solution was able to provide valuable high-resolution environmental data about the temperature and humidity inside and outside of the burrows over the period of the study. This combination of immediate notification and the ability to record a variety of high resolution variables at each burrow allows researchers to not only monitor a larger number of birds, but to address questions that would previously have been infeasible.

We also address the general lack of tool integration in the deployment of such networks. In this paper we describe our integrated system which allows researchers near-instant feedback from the network in the field, redundantly records sensed data, and transmits the data back to mainland servers for later analysis and processing. From working closely with field researchers, we believe such a system has real long-term utility and is simple enough to deploy and use in the field.

2. SYSTEM ARCHITECTURE

2.1 System Components and Overview

We designed and deployed a pilot system with ten battery-powered sensor nodes placed next to the monitored burrows, a solar-powered base station, and a mainland server used by researchers to access live and historical data. We used a General Packet Radio Service (GPRS) connection between the base station and the mainland server. A second data collection unit was deployed as a backup strategy for the case when the main base station would fail. Figure 1 contains an overview of the components of the system.

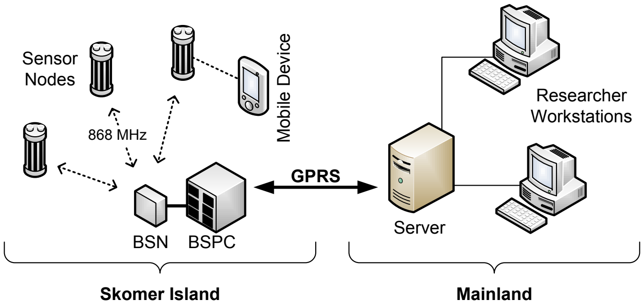


Figure 1. System Components.

The WSN formed a star topology and communicated with the base station using Time Division Multiple Access (TDMA) access control. The base station transmitted the collected data to the mainland server once a day. The second low power data collection unit intercepted all WSN data packets and logged them to an SD memory card. We used the same approach to deliver instant notifications to researchers in the field. Research workstations received data from the island, delivered by the server, as it was transmitted live from the island. During fieldwork on the island, researchers were equipped with handheld devices that could receive instant notifications of birds' activity at monitored burrows. These devices could also monitor the vital status information of nodes in the network (battery status, alive/dead, most recent transmissions).

2.2 System Components

2.2.1 Sensor Nodes

To build the network we used the Modular Sensor Board (MSB) platform [6] from the Freie Universität Berlin, Germany. The MSB platform was designed with a focus on modularity: components of the platform can be stacked together and thus allow rapid adaptation to new requirements. The MSB430 board represents the core of this platform. It contains, among other components, a low power TI MSP430F1612 microcontroller, a Sensirion SHT11 temperature and humidity sensor and the Chipcon CC1020 868 MHz radio transceiver, usually configured for the data rate of 19.2 kbit/s. The board is equipped with an SD/MM memory card slot for external storage of up to 4 GB. Various digital and analog sensors may be attached to 32 external available add-on connectors. The power consumption of the MSB430 ranges between 250 µA and 115 mA depending on the application.

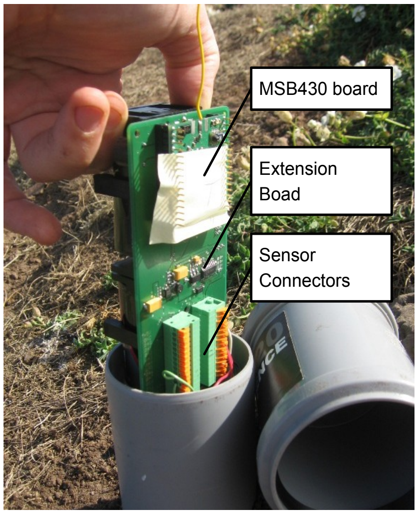


Figure 2. Node Assembly.

We designed a custom extension board compatible with the MSB platform. The goal was to find a generic solution that could be used in new scenarios in the future. The board was equipped with two D-Cell batteries which usually provide a capacity of up to 10 Ah. They powered the MSB430 and six switchable outputs with stabilized 3V and 5V. The board exposes a JTAG interface for MSB430 programming and a series of spring-loaded connectors so additional sensors could easily be added in the field. Four connectors allowed us to use 5V based digital sensors as inputs, the remaining eight operated at 3V. Furthermore a charging circuit for NiMH batteries was provided. The circuit was designed for any voltage in the range from 6V to 12V.

The extension board and MSB430 were connected as shown in Figure 2 to form a sensor node. Nodes were placed in short sections of PVC pipe that were partially buried near each burrow (see Figure 3). PVC pipe was chosen as it was an economical and readily available waterproof housing. To reduce the possibility of damage to the landing Manx Shearwaters, we were limited to sensors at the height shown (around 30cm). This constraint significantly reduced the radio range in the network. We observed an expected degradation in the range of the nodes from around

1000m (line of sight measurement with antenna at 1m height) down to line of sight only within 50m.

Each installation at a burrow consisted of a sensor node with a temperature and humidity sensor. Two passive infrared (PIR) sensors and a Radio Frequency Identification (RFID) reader in the burrows were attached using 1.5m long cables. Seven nodes were equipped with additional temperature and humidity sensors on a 1.5m cable for sensing the environment inside the burrow.

Figure 3. Typical Deployment.

The environmental conditions were measured every two minutes. The two PIR sensors were used to detect birds' activity. The first sensor was installed outside and the second one inside of the burrow. By observing the order in which the PIR sensors were tripped, we aimed to determine whether a bird was entering or leaving the burrow. The RFID reader, placed in the entrance, was activated only when movement was detected and turned off after 5 seconds of inactivity. This approach allowed to reliably detect identity of the tagged individuals and promised reducing of the energy consumption of the system.

Many of the tracked Manx Shearwaters are already fitted with aluminum identification rings. To minimize the interference with the birds, RFID tags were glued to those rings with cyano-acrylic glue (see Figure 4).

Figure 4. RFID tag.

A single sensor node consumed up to 35 mA while sending data over the radio and another 100 mA during the uptime of the RFID reader. We experienced on average 250 activations of the reader and collected between two and four RFID tags during a day. At all other times node was suspended in the low power mode and the CPU was stopped (LPM1 with 250 µA power consumption). The power consumption of the PIR and SHT11 sensors are negligible.

The radio transceiver was deactivated by default, thus no spontaneous communication with sensor nodes was possible. The time in the network was synchronized during the initialization of the system. The time and date were used to timestamp the collected sensor data. Because of the small number of nodes deployed we implemented a TDMA access control with 6 seconds long time slots and 60 seconds frame length. Nodes used the available slot and activated the transceiver only when collected data was queued or a failure was detected (e.g. low battery status). The transceiver was deactivated with a 250 ms delay after all remaining data was transmitted. This allowed the base station to issue control commands (e.g. to correct the time) to the nodes in the field.

2.2.2 Base Station

The network was deployed in a star topology with the base station as the data sink. The base station contained two main computing components: an MSB430 board, referred further as the Base Station Node (BSN), and an EPIA Via single-board PC, referred further as the Base Station PC (BSPC). Both were connected using a serial interface and powered independently.

The BSN was turned on at all times and operated in the Active Mode; the radio transceiver was enabled and used to communicate with the sensor nodes in the field. The node synchronized the clocks in the network and archived the received data on the SD memory card. The card had sufficient storage capacity and was providing a redundant backup solution at no extra energy cost.

Figure 5. Base Station.

The BSPC read newly archived data over the serial connection during its scheduled up times between 2:00 a.m. and 03:30 a.m. every night. The BSPC was enclosed in a Pelican case depicted in Figure 5 along with a Freescale 68332 microcontroller managing the schedule, a hard-disk drive, a PCMCIA-based GPRS radio modem, 802.11g wireless network card, and the base station node. We provided an LCD interface for monitoring of the schedule. The schedule was field-programmable and could be updated remotely by editing a configuration file on the base station computer. The BSPC also included a GPS receiver whose output was not incorporated during this deployment. The base station was equipped with a solar system consisting of a 30 by 45 cm solar panel, charge controller, and two 17 Ah lead-acid batteries. During testing the batteries were fully charged in three days of full sunlight and a week of overcast. We didn't use the solar panel in the field since we gained access to power from an existing solar array at the research station on the island.

The BSPC ran Microsoft Windows XP. On startup, a GPRS and a virtual private network (VPN) connection to the server on the mainland were established which allowed us to open maintenance connections from our desktop systems to the base station. Connecting remotely to the BSPC, we could easily change its up time schedule; maintain the installed software and send commands to the BSN and sensor nodes. Researchers could use the BSPC's 802.11g wireless network capabilities to establish a remote desktop connection from their laptops in the field as well.

The BSPC run data replication service which provided a continuous stream of incremental data updates to the server as long as the base station computer was powered on. The replication service was written using the Microsoft Robotics Studio (MSRS) software. We chose to use a custom-built service instead of any built-in file replication facilities in the Windows operating system because of the limited bandwidth available. Once per boot-up new data and the content of system event logs were also transmitted.

We deployed a modified version of the BSN that was not connected to the BSPC. The node was not communicating with the network. It was intercepting the data sent to the main BSN and storing it on its SD memory card as a backup.

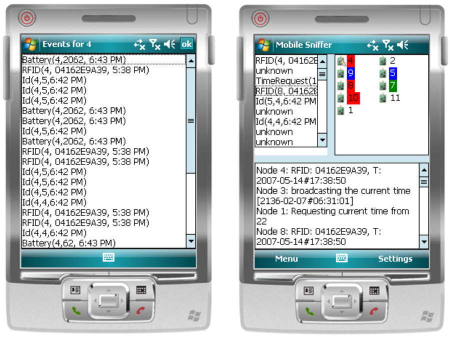
2.2.3 *Data Server*

Data from Skomer Island was replicated to a dedicated server in Cambridge, UK. The replication services stored all records received from the base station on the island on the local server for further processing. Directories were monitored and all new entries were automatically imported into the database using a custom developed web service while collected data was available via a custom web interface that generated quick overview over the measured data. Direct access to the data records in the database was also possible.

Researchers could also run the replication service on their workstations and download raw data records as if they were delivered directly from the base station on the Skomer Island.

2.2.4 *Support Tools*

After deployment, in response to requests from researchers, we developed additional tools for use in the field. We equipped researchers with Windows Mobile based phones and PDAs that were paired with dedicated MSB430 nodes via Bluetooth. The MSB430 ran a custom application that intercepted the communications between nodes in the field and the base station..



```
Battery(4,2062, 6:43 PM)
RFID(4, 04162E9A39, 5:38 PM)
Id(4,5,6:42 PM)
Id(4,5,6:42 PM)
Id(4,5,6:42 PM)
Battery(4,2062, 6:43 PM)
Battery(4,2062, 6:43 PM)
Id(4,5,6:42 PM)
Battery(4,2062, 6:43 PM)
RFID(4, 04162E9A39, 5:38 PM)
RFID(4, 04162E9A39, 5:38 PM)
Id(4,5,6:42 PM)
Id(4,5,6:42 PM)
Id(4,5,6:42 PM)
Id(4,4,6:42 PM)
RFID(4, 04162E9A39, 5:38 PM)
RFID(4, 04162E9A39, 5:38 PM)
Id(4,4,6:42 PM)
Battery(4,62, 6:43 PM)
```

```
RFID(4, 04162E
unknown
TimeRequest(1
RFID(8, 04162E
Id(5,4,6:42 PM
unknown
Id(4,4,6:42 PM
unknown
unknown
```

```
Node 4: RFID: 04162E9A39, T:
2007-05-14#17:38:50
Node 3: broadcasting the current time
[2136-02-07#06:31:01]
Node 1: Requesting current time from
22
Node 8: RFID: 04162E9A39, T:
2007-05-14#17:38:50
```

Figure 6. Windows Mobile based WSN management software.

The client application (see Figure 6) on the handheld device displayed detailed instant notifications of birds' activity at monitored burrows: their identity, and the names of activated PIR sensors. Additionally the application presented a comprehensive history of events for a given node and allowed the operator to maintain the WSN by sending commands to the nodes. A similar solution for desktop computers was provided for stationary use with researcher's laptops.

In addition to the PDA-based portable monitor, a standalone LCD-equipped MSB430 was also provided. Its LCD display provided a visual readout of recent RFID sensor activity.

3. RESULTS

One of the primary aims of the pilot deployment was to assess the impact of our sensor network on the Manx Shearwaters and the sensitive environment in which they live. There does not appear to have been any negative impact of the network on the monitored birds. Of the birds monitored throughout the study, there were no observed changes in their behavior in comparison to unmonitored birds: eggs hatched successfully at 89% of the monitored burrows, chicks received around the same amount of food and reached similar sizes as chicks from burrows without sensors. The low impact of the network is encouraging for future deployments when we will monitor a significantly larger number of burrows in the colony.

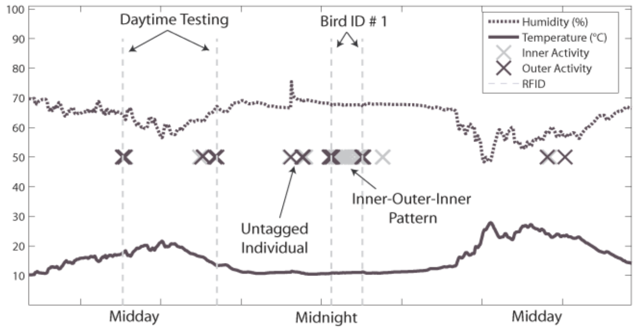


Figure 7. Aggregated data of the experiment.

Figure 7 shows an example of data gathered from a wireless senor near the beginning of the study. Visits from individual birds can be discriminated from daytime tests and the change in temperature and humidity over two days is obvious.

Figure 8 shows a 24-hour histogram of events detected at one node over a 1 month period. It is interested to note both the ambient activity over the day, and the peaks in activity around midnight (when the birds were returning), 4 a.m. (when they were leaving) and some peaks when the network was being tested during the day.

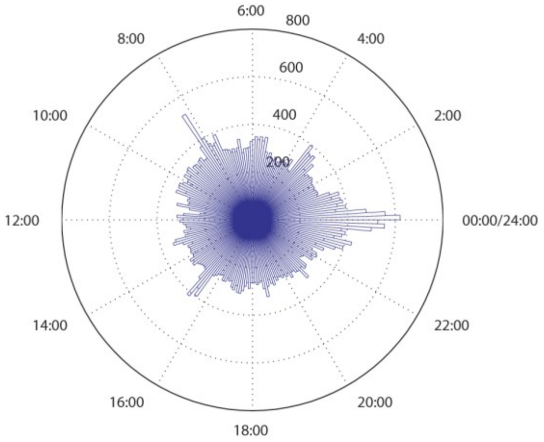


Figure 8. 24-hour histogram.

4. DISCUSSION AND FUTURE WORK

Over the duration of the study, data transmission was improved by iteratively enhancing both the transmission software and by reconfiguring the in-burrow setup of the sensors. As an example, we initially noted that outer sensors were overly affected by ambient light conditions and prospecting juvenile birds. Reconfiguring the layout of the outer sensors prevented these problems and reduced the sensor 'noise'. This kind of iterative problem solving highlights both the need to test such networks in field conditions and to enable simple reconfiguration of sensors and nodes.

Throughout the season, node firmware and hardware placement was adjusted during occasional visits to the island and PC software was improved from the mainland in an effort to obtain improved data stream quality and reliability. Beyond changes to improve data reliability, a number of changes were made in attempts to improve the depth or quality of acquired data. This included adding more RFID sensors, repositioning sensors and introducing secondary data-backup nodes to validate recorded data.

The field conditions during the study also highlighted a number of engineering problems with our initial design: standard spring-loaded connectors selected to simplify reconfiguration were hard to use in the adverse weather conditions; colored cables were hard to identify at night under torchlight

As such, there are a number of more straightforward engineering changes necessary for future deployments, including more rugged and usable connectors and a more modular design, allowing researchers to quickly and easily replace nodes in the field.

In the coming season, researchers plan to investigate the relationship between foraging behavior and food provisioning. In order to achieve this, each monitored burrow must include a weighing scale at the entrance to determine the weight of returning adults. Furthermore, we want to extend our system such that the ground based sensors are able to communicate with the GPS devices that will be used on the monitored birds. We believe that the system and associated tools we describe here will allow researchers to easily use WSNs to focus on their scientific questions without having to spend inordinate time on hardware configuration and maintenance.

In any WSN deployment, changes in requirements due to shifting research goals or changing conditions are inevitable. The ability for our user-researchers to effect changes in configuration is the main requirement for unlocking and accelerating the conduct of WSN-based research within the non-engineering research disciplines. WSN's have yet to transition from their experimental nature to a properly utilitarian role in field research. Comprehensible configurability appears to be the key missing component and will be a focus of our future work.

5. ACKNOWLEDGMENTS

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