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Abstract—The Pods ad-hoc wireless sensor network has been designed to study the environment of endangered species of plants. This paper presents the overall design of this network, focusing on the design of the network nodes and of the algorithms we use.

In designing and building the Pods network, several issues have become apparent that are more widely applicable to sensor networks in general. Of these issues, the two most fundamental are scaling and energy efficiency. In the foreseeable future large sensor networks can and will be built, and any algorithms used must scale to many thousands of nodes and to networks with diameters of hundreds or thousands of hops. As such networks are built, energy efficiency becomes an essential element of both the overall cost and the ease of deployment. These two elements can therefore significantly affect the viability of a wireless sensor network design. Algorithms developed as part of the Pods project, particularly the MOR routing protocol, provide good performance on both of these measures.

I. INTRODUCTION

Many species have evolved on the islands of Hawaii and are found nowhere else in the world. Unfortunately many factors, including at least human encroachment, the introduction of alien species, and habitat destruction, have caused many of these species to become extinct. Many more such species are currently endangered. Although major efforts such as the creation and maintenance of national parks and other reserves can help, in many cases lack of specific information about what threatens a given species is still an obstacle to helping these species recover. This lack of information is particularly significant in Hawaii, where the rugged topology and large elevation differences combine with predictable tradewinds to create a large number of very distinct microclimates – for example, rainforests and dry environments – within a few kilometers of each other. Some species of plants are reduced to a few known individuals in remote areas, and it is not accurately known what environmental conditions they experience. Having biologists personally visit the location to study these plants is not only expensive, but also likely to be counterproductive, since the habitat may be damaged and alien species may be introduced when the area is visited.

To address this problem the Pods project have designed a wireless sensor network to study these plants remotely. Each individual sensor unit (each pod) must be small so it can be easily disguised, must be low power, and must be reliable. Sensors should have a long lifetime so there is little need to visit the area to recharge the units. Sensors should include traditional environmental sensors – such as light, temperature, and rainfall – to help determine the environmental factors that affect a plant’s health and well being, and less traditional sensors – for example high-resolution digital cameras – to detect phenomena such as herbivore visits and the state of growth of plants.

Major issues:
- scaling: how big of a network can I build?
- energy: how long can it function?

Other issues:
- cooperation and event detection: how do I know if a tree has fallen in the forest?
- position: how does the node know where it is?
- mobility: if a node moves, can it still communicate? if a researcher moves, is it still possible to communicate with the nodes?

Fig. 1. Practical Issues in Sensor Network Deployment.

Our experience with the Pods network has led the author to some insight about major architectural issues in the design of a wireless sensor network – this paper presents these issues, summarized in Figure 1.

Section II describes related work within the Pods project. The main contributions of the paper are in Section III, focusing on a number of issues that were encountered in the Pods project and are likely to be significant for other wireless ad-hoc sensor networks. This section also describes the solutions that have been considered within the Pods project. Section IV looks at other related work, and Section V provides a summary and conclusions.

II. THE PODS ENVIRONMENTAL SENSOR NETWORK

The pods network [1] is designed to provide environmental data in near real time, within a few minutes of the measurement. The near real time makes it easier for scientists to correlate observed events with events occurring elsewhere, and to decide when to visit the site in person. In an ad-hoc wireless network such as the Pods network, each node is a source and
may be a destination of communication, and is also willing to forward data for other nodes. In its most fundamental mode of operation, each pod in the network measures environmental data at a regular rate, and uses the ad-hoc network to transmit this data to an internet-connected base station. Pods are placed to maximize the amount of information reported as well as connectivity and reliability of the network [2]. In particular, it is essential that whenever possible each pod have multiple routes connecting it to the base station, since the goal of minimizing visits requires that the network remain connected even though any individual pod may fail.

Pods that are monitoring the weather must send at most a few bytes to the base station for each item of data collected. In our deployments so far, each pod sends three items every 10 minutes. The subset of pods that takes pictures must send such a picture, typically about 700KB for a 2-megapixel image, to the base station. Our deployments so far take a picture every hour [3]. Overall data rates are therefore very low – assuming one pod in 10 is a camera pod, about 20 bytes per second (about 160 b/s) for each pod is sufficient to bring all the data to the base station. Even in a network with thousands of nodes, such overall data rates are low, meaning the radios and processors can be turned on for sampling and communication, and then placed into a low-power sleep mode for the remainder of the time\(^1\), conserving energy and potentially extending the lifetime of the pods' batteries.

\(^1\)The pods can easily be reprogrammed, even remotely, to stay up continuously, or to change the frequency of monitoring, as desired.
protocol is much less, since routing is entirely within either the backbone network, or one of the side networks.

B. Energy Consumption and Energy Efficiency

Energy is an issue for any device not connected to an external source of power. Energy can be in batteries, and the lifetime of the network therefore depends on the size of the batteries and the power consumption of the unit. Energy can also be generated, perhaps through solar panels or other means (wind, water, solar heat), and then the power consumption of the unit dictates the size and cost of the energy generating unit.

Our current PODS design uses IPAQ handhelds running Linux. These consume approximately 1.5W (300mA at 5V) when running and using the wireless 802.11 card. We have not used the sleep mode in any actual deployment to date since the units do not always reliably reawaken from sleep mode, which would be a problem in a network deployed in a study area. Nonetheless, when compared with DSR and AODV the MOR protocol does minimize the number of packets sent and received (by minimizing the number of unnecessary retransmissions) as well as complete a given transmission in a smaller amount of time, both of which help reduce the total energy consumption for a given transmission of data.

A pod with a power consumption of 1.5W will discharge a fairly large lead-acid battery in about a month, assuming perfect energy efficiency, and is therefore practical if the deployment of a large number of large lead-acid batteries is practical. Non-rechargeable batteries offer a small advantage in weight-to-energy and bulk-to-energy ratios and can therefore be preferable, but either way having to recharge or replace large amounts of batteries on a monthly basis is impractical in a sensitive ecological area.

An alternative to using batteries is to use renewable energy sources, particularly solar energy. Assuming that about 3 hours of sunlight per day can be relied on (a conservative assumption in the tropics), and that the units use about 36Wh/day, a 12W solar panel is sufficient to power the pod indefinitely. Unfortunately, it is hard to make such a panel inconspicuous. This is important not only because the panel may be stolen, but also because it might draw undue attention to the area where the endangered plants grow, which may be dangerous for the plants. In addition, conspicuous equipment is inappropriate for public recreation areas such as national parks.

One way to substantially reduce energy consumption is to use a low-power, low-capability processor, for example general-purpose microcontrollers such as the ones from PIC [10] or special-purpose sensor units such as the “Smart Dust” from Berkeley [11] – the former use as little as 0.01W in active mode and a fraction of that in sleep mode. Reduced power consumption usually implies reduced radio range [12], though since the energy required to cover an area of size \( r^2 \) grows as \( r^4 \) (for nodes near the surface of the earth), increasing node density can give lower overall power drain for a given area.

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2The diameter of a network is the maximum number of hops between any two nodes or, if all communication is to a base station, the maximum number of hops from any node to the base station.
While energy consumption can be a major concern in current sensor network designs, hardware development trends (cheaper, smaller, faster, and less power hungry) as well as the design of more specialized and efficient hardware can be expected to lessen the impact of this issue as time goes on. Nodes that need to do substantial processing or need high bandwidth for communication, however, will continue to need relatively high power levels.

C. Event Detection and Inter-node Cooperation

Sensor networks are deployed to measure and detect. The measurements must be performed on a regular basis, but events happen less predictably. For the Pods project, an event is anything that affects the viability of individuals in the endangered species. For other sensor networks, events may be better defined and somewhat more predictable, for example the approach of an enemy vehicle or a lack of fuel in the tank of a vehicle.

Particularly challenging are events that can only be detected by cooperation among multiple nodes. In some environments, for example, an atmospheric inversion (with lower airmasses colder than higher airmasses) is an event of interest. This can be measured using a network of sensors deployed along the side of a tall mountain. If all the nodes report all their data to a central processor, this central processor can determine the presence of the event. To reduce data rates, however, it might be better to have the nodes collaborate to determine whether the average air temperature at the higher nodes exceeds the average air temperature for the lower nodes. Such distributed computation requires inter-node communication and cooperation. The specification of such a task need not be difficult – many programming languages have been developed for parallel and even massively parallel computation, and can probably be used to specify these tasks. Implementing such a task may require specialized communication protocols, for example to provide geocasting [13] to specify an entire area as the destination for a message.

Two particular forms of event detection may be of general interest. The first is non-event detection: the recognition that nothing interesting is happening, and no data actually needs to be sent. In an environmental sensor network, for example, this can be the case if the data is identical to the last sample sent. In most environments, temperature, and to a lesser extent light levels, wind, and rain do not change drastically from minute to minute. A simple protocol is to only send data when the measurements show a change in the environment. A more complex protocol might compare measurements from adjacent sensors and only send one measurement from an entire area that has a common value. These strategies become less effective as the sensors become more accurate, but in large sensor networks may substantially decrease the amount of data that needs to be sent.

The second special form of event detection consists of a posteriori event detection. If a particular event is observed, perhaps by watching images of an area some time after the event has taken place, the relevant data can be retrieved and analyzed to determine whether the event could have been detected based on the data itself. For example, if plants are wilting, it is likely that there is a drought or a disease. The latter would be hard to detect with environmental sensors, but the former can presumably be correlated with a shortage of rain. If the data supports the hypothesis of a drought, the sensor network can be reprogrammed to detect future occurrences of this event, perhaps alerting researchers when a drought is detected.

The techniques described in this section essentially perform data compression. There can be a tradeoff between this data compression and the promptness of data delivery. For example, an algorithm to reliably detect droughts might only report the drought after it is in the advanced stages, whereas had the data been reported continuously and promptly, an alert scientist might have detected the drought in its early stages. Sensor network designers must keep such tradeoffs in mind.

D. Position Detection and Processing

The geocasting and location-dependent processing just described require that nodes know their own locations. The simplest way to locate a node is to equip it with a GPS (Global Positioning System) satellite receiver, and to allow the computer to query the GPS system. Unfortunately this is also relatively expensive and, arguably, inefficient for nodes that are not intended to move. For nodes which are mobile, the GPS value must be read frequently, which has the added disadvantage of requiring considerable power.

Another way of determining node position is to use an external GPS to record the position when the node is deployed, and to somehow configure the node with its own position. This is practical when the nodes are deployed once at a time, but not when they are airdropped or otherwise deployed in large numbers.

Determining approximate position based on radio range or radio signal strength is an area of active research, for example, by Savarese and others [14], by Robinson and Marshall [15], or by Bulusu and others [16]. These location algorithms generally rely on a subset of nodes which know their exact position, and on other nodes computing their approximate position based on reachability information and assumptions about radio range and signal uniformity. Approximate positions determined in this manner may be sufficient to support some of the location-dependent computations described above.

E. Mobility

1) Fixed-Mobile Network: Although all the nodes for networks described so far are fixed after deployment, the Pods project (and other projects) have encountered the issue of nodes which are not fixed. The simplest case is where fixed nodes in a sensor network need to communicate with one or a few mobile nodes. Some of the Smart Dust proposals, for example, involve the use of an Unmanned Aerial Vehicle (UAV) flying over the network to collect data from fixed sensors. In our own project, we wish that researchers in the field could use the fixed network to both directly receive
data, and also function as an infrastructure network to provide connections back to the Internet. In both cases, this is known as the fixed-mobile problem.

From the point of view of routing, the fixed-mobile problem simply requires running the routing protocol sufficiently frequently that the mobile unit can be reached through the nearest unit. This is similar to the problem of providing continuous service to a customer traveling through multiple cells in a cellular telephone system, though unlike the cellular telephone system, the infrastructure nodes may use the same protocol and channels to communicate with each other as they do with the mobile unit.

MANET routing protocols are designed for mobile nodes, and therefore can directly route in the fixed-mobile case. The only concern is whether they are sufficiently efficient to justify their use in this case, or whether a more specialized protocol (such as MOR) that takes advantage of the inherently stable nature of most of the network might be more efficient. Since in the fixed-mobile problem most of the network nodes are fixed, this seems likely, but has not been verified to date.

2) Mobile Sensor Nodes: The second major scenario involving mobility is that of self-propelled sensors, such as sensors on unmanned land, water, and aerial vehicles. Such units most commonly have two conflicting goals, sensing the target area and maintaining connectivity with other nodes and perhaps the base station.

The author is not aware of specific work in this area. As a first step, a MANET routing protocol can be used to provide connectivity when possible. However, in most such networks units will probably be able to function for a period of time while disconnected from the network, and later attempt to reconnect again. One can even imagine different units giving each other all of their data, so the one that reconnects to the network first can report both units’ data back to the base station.

IV. OTHER RELATED WORK

Nitin Nagar and the author considered some of these issues, particularly scalability and energy efficiency, in a paper [17] focused on routing in wireless sensor networks.

Sacks and others [18] are studying the design of ad-hoc wireless sensor networks with much greater focus on the design of individual nodes rather than of the network as a whole, viewing node software design as a special case of operating system design, though issues such as cooperation are considered. Along similar lines, Hill and others [19] focus on the system architecture more than on issues of the network as a whole.

At the other extreme, Gupta and Kumar [9] have studied the capacity of entire wireless networks. This work is fundamental in its area, but does not attempt to address the same range of issues that are presented in the current paper. Likewise, work by Heinzelman [20] is focused specifically on protocol architecture, neglecting other aspects of wireless sensor network design that are addressed here.

V. SUMMARY

Having a pressing real-world problem to drive a research project has given us powerful insights into the problems of designing and building real-world wireless ad-hoc sensor networks. Building the networking protocols and the communication hardware is an essential step, but much more needs to be accomplished to make the network practical. Energy efficiency becomes not only a theoretical measure of a system’s performance, but an issue of how often batteries must be changed or how large a solar panel is needed to power a unit – issues that become more acute when faced with the problem of frequently carrying heavy batteries across rugged terrain or of trying to camouflage a large solar panel. Likewise, trying to design a network to reach a given area and collect detailed information about the environment of specific plants drives home the requirement for scalability.

The design of the Pods is one among many possible, though it does, to the extent possible, satisfy the requirements for scalability and energy efficiency. Scalability is addressed through the use of scalable routing protocols and, where appropriate, by the use of a two-level hierarchy, and energy efficiency is provided by the use of the smallest processors that will perform the desired functions, together with efficient routing protocols that allow processors to minimize the number of transmissions and enter sleep mode sooner.

The Pods network also provides a useful testbed for experiments in event detection, position detection, and for addressing the fixed-mobile problem.

In conclusion, we have found it very profitable to focus on using our research to attempt to address a real-world problem, and find that in the process have confronted issues that are likely to apply to many different kinds of practical ad-hoc wireless sensor networks.

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