Self-Powered Wireless Sensor Network for Environmental Monitoring

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***Abstract*—Environmental monitoring serves a vital scientific role by revealing long-term trends that can lead to new knowledge and better understanding of the environment. Wireless Sensor Networks (WSNs) are ideal systems for environmental monitoring. Inch scale sensors, with low cost can be deployed over large areas to collect data. However, the energy efficiency of these sensor nodes is limited. Energy harvesting techniques can extend the network lifetime. In this paper, we introduce a self-powered prototype for real-time temperature, humidity and soil moisture monitoring. The prototype uses solar panels to harvest energy from the environment.**

I. INTRODUCTION

Environmental monitoring describes the processes and activities that need to take place to characterize and monitor the quality of the environment. Traditionally, environmental monitoring is achieved using a small number of expensive and high precision sensing units. Collected data are retrieved directly from the equipment at the end of the experiment after the units have been recovered. The design and implementation of a Wireless Sensor Network (WSN) provides an appealing alternative solution. Although the sensor nodes might be equipped with sensors with less precision, the network can provide spatial resolution of the area. The users can also have remote access to the monitoring area.

Today, the use of WSNs for monitoring applications covers a wide area of the environmental monitoring [1], from air and water quality monitoring to rainforest and biodiversity monitoring. Sensor nodes are the elementary components of any WSN and they can provide many functionalities including: signal conditioning and data acquisition, temporary storage for the data, data processing, analysis of the processed data, self-monitoring (e.g. supply voltage), scheduling, receipting and transmission of data packets, and coordination and management of communications and networking.

However, they also pose a number of challenges, with survivability being one of the most crucial. The lifetime of any individual node and as a consequence, of the whole network, is solely decided by how the limited amount of energy is utilized. Energy harvesting can alleviate this problem. Self-powered WSNs provide the possibility of very long sensor node lifetimes while their deployment would have the least impact on the existing infrastructure. Moreover, with a carefully designed routing mechanism, the total network lifetime can be extended compared with traditional battery-powered WSNs.

In this paper, we present a self-powered WSN for real-time temperature, humidity and soil moisture monitoring. Since the monitoring network deployment should have a minimal impact on the existing infrastructure and be designed to operate autonomously for an extended period of time, cognitive networking techniques were applied [2] and the routing protocol is carefully designed to minimize power consumption. We used the Spectrum and Energy Aware Opportunistic Routing (SEA-OR) for self powered WSNs [3]. SEA-OR was specifically designed following self-powered WSN restrictions. It is aware of the energy consumption of the network and can significantly extend the network lifetime compared with traditional battery-powered WSNs.

The remainder of the paper is structured as follows: Section II reviews the related work, the SEA-OR protocol is briefly presented in Section III and the system architecture is provided in Section IV. Simulation results are shown in Section V. We conclude the paper in Section VII.

II. RELATED WORK

WSNs are a promising solution for a number of monitoring applications [4], such as building monitoring [5] and highway bridges [6]. Environmental condition monitoring in homes have been examined in [7]. The authors proposed a framework to monitor temperature, humidity and light intensity, which is based on a combination of pervasive distributed sensing units, information system for data aggregation, and reasoning and context awareness. The reliability of the sensing information is encouraging.

Recently a number of systems have been proposed for carbon dioxide monitoring [8]. In [9], a remote carbon dioxide concentration monitoring system is developed. The system reports geological CO_2, temperature, humidity and light intensity of the outdoor monitoring area. Similarly, in [10] an urban CO_2 monitoring system is presented. The system operates outdoor at an urban area around 100 square kilometres.

Indoor environment can pose different challenges to a monitoring system. Indoor and outdoor air quality monitoring through a WSN is presented in [11]. Each node has an array of sensors and it is connected to the central monitoring unit either hardwired or wirelessly. In [12], a real-time indoor air quality monitoring system is proposed. The system has seven sensors monitoring seven different gases. In [13], a system with aggressive energy management at the sensor level, node level, and network level is presented. The system detects Volatile Organic Compound (VOC) and CO and saves energy through context-aware adaptive sampling. A low-power ZigBee sensor network to monitor VOC pollution levels in indoor environments is proposed in [14]. The network consists of end device sensors with photoionization detectors and routers.

In this work, we proposed a system for real-time temperature, humidity and soil moisture monitoring, using the SEA-OR protocol through a self-powered WSN. The wireless units follow a cognitive networking technique to minimize the coexistence problem. The prototypes follow a dynamic routing approach hence, they can join or leave the network at any time. Two sensor units, one temperature/ humidity sensor and one moisture sensor are used. Finally, the system is compared with a system without cognitive principles.

III. USING THE SEA-OR PROTOCOL

In this section, we briefly review the Spectrum and Energy Aware Opportunistic Routing (SEA-OR) for completeness. More details can be found in [3].

A. Description of SEA-OR

SEA-OR tends to discover multiple paths, close to the shortest path, towards the destination. In SEA-OR, a node that has a packet to transmit seeks forwarding candidate node to serve as relay node for the next hop. The relay node is selected based on the spectrum availability as well as the relay node location and availability and the remaining energy (residual energy) in the relay node. In this way, SEA-OR discovers paths that are centred around the shortest path. Then, it expands or shrink these paths based on the network conditions, in terms of spectrum availability, and node conditions, in terms of availability and residual energy, during packet transmission.

B. Next node selection criterion

SEA-OR follows opportunistic routing principles. A packet transmission begins with a RTS/ CTS handshake. During the handshake, the transmitter senses for an available channel to broadcast the RTS to every neighbor node. The transmitter uses the link with the highest spectrum availability. On the reception of the RTS, the neighbor nodes reply with a CTS if they are available after time T_{SEA-OR}. Time T_{SEA-OR} is used to prioritize the nodes based on their residual energy and distance from the transmitter. T_{SEA-OR} equals to:

$$T_{SEA-OR} = C_1 \times (E_{th} - E_{res}) \times \log(\frac{RSSI(d)}{A})) + SIFS \tag{1}$$

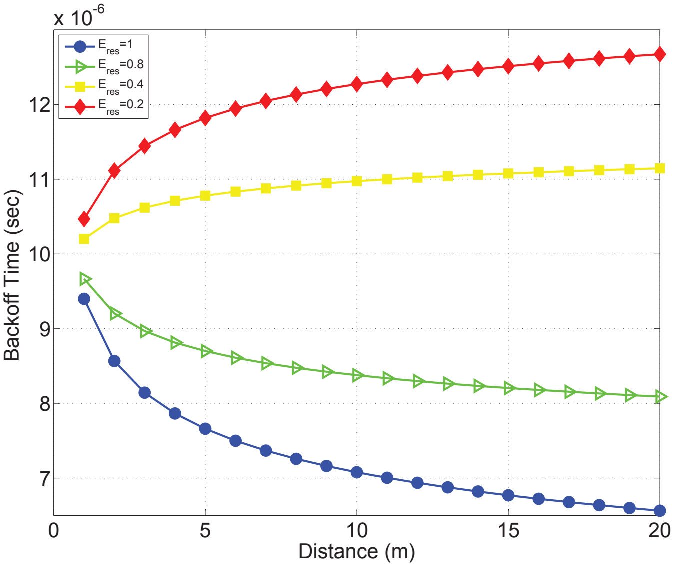


Fig. 1: The T_{SEA-OR} for nodes in different distances from the transmitter and for different E_{res}, following Eq.1 for $E_{th} = 0.70$, $C_1 = 10^5$ and A = -30.

where C_1 is a constant related with the capacity of the battery, E_{th} is the threshold below which a node minimize transmissions, E_{res} is the percentage of the residual energy in the node, d is the distance from the sender, A is the RSSI at one meter of distance and $SIFS$ is the Short Interframe Space. RSSI can also be calculated as:

$$RSSI(d) = -10 \times n \times log(d) + A \tag{2}$$

where n is the propagation path loss exponent.

The use of the energy threshold E_{th} is important for the proposed self-powered WSN. If the node runs out of energy and the battery is completely drained, this can shorten the life and the efficiency of the battery. Moreover, the node has to wait for the battery to be fully charged before participate again in packet transmissions. The use of the E_{th} minimize the risk of weaken/ ruin the battery. When the energy level is below the threshold, the node has low probability to participate in packet transmission. The node will participate in a transmission only if all the neighbor nodes are in similar energy level or if it is the only available node. When the battery level increases, the node participates normal again. In this way, the node never leaves the network and the battery is protected.

It is clear from Eq.(1) that the node prioritization is based on the residual energy E_{res}, and the $RSSI(d)$. An estimation of the E_{res} can be acquired through a simple circuit while the $RSSI(d)$ can be extracted from every packet between the communicating nodes.

Figure 1 shows the T_{SEA-OR} for nodes in different distances from the transmitter and for different E_{res}.When the nodes have similar E_{res}, SEA-OR tends to use nodes which are in greater distance and hence, closer to the destination. As the E_{res} decreases, the protocol uses nodes that are closer to the transmitter. In this way, the nodes have sufficient time

Fig. 2: GRIT Lab Roof (photo: GRIT Lab)

to perform power harvesting [15] and avoid running out of energy.

IV. SYSTEM ARCHITECTURE

In this section, we describe the proposed monitoring application scenario. We highlight the system hardware infrastructure and then provide some additional details on each of the hardware components which make up the self-powered WSN.

A. Application scenario

A self-powered, outdoor WSN monitoring application is considered in this work. A number of wireless sensor nodes, in conjunction with a number of simple relay nodes, are deployed in the monitoring area. Each sensor node contains two sensors and a wireless transmission module. The relay nodes simply contain a wireless transmission module. The data from the sensors are passed to the transmission module which forwards all the necessary data to the control room, through the relay nodes. Both the sensor and the relay nodes are powered by a customized solar battery system consisting of a solar panel, Lithium-Ion battery pack, and charging circuit.

The sensor network will be deployed in two specific outdoor environment to perform experimental measurements. They are the GRIT Lab at the University of Toronto [16], shown in Fig. 2 and the green roof at the Evergreen Brick Works in Toronto [17] shown in Fig. 3. The Green Roof Innovation Testing Laboratory (GRIT Lab) is a research facility that investigates the environmental performance associated with "green" and "clean" technologies such as green roofs, green walls and photovoltaic arrays [16]. It provides us with a closed, controlled environment inside a densely populated area to deploy the sensors and also already has a wired sensor network installed recording data, providing us the opportunity to validate our recorded data.

The Evergreen Brick Works provides a much larger space to deploy a larger network in a more urban setting. It also has a much more challenging wireless environment which will test the limits of our communication protocols and is a more environmentally exposed area providing more for system survivability.

Fig. 3: Evergreen Brick Works Green Roof (photo: Google)

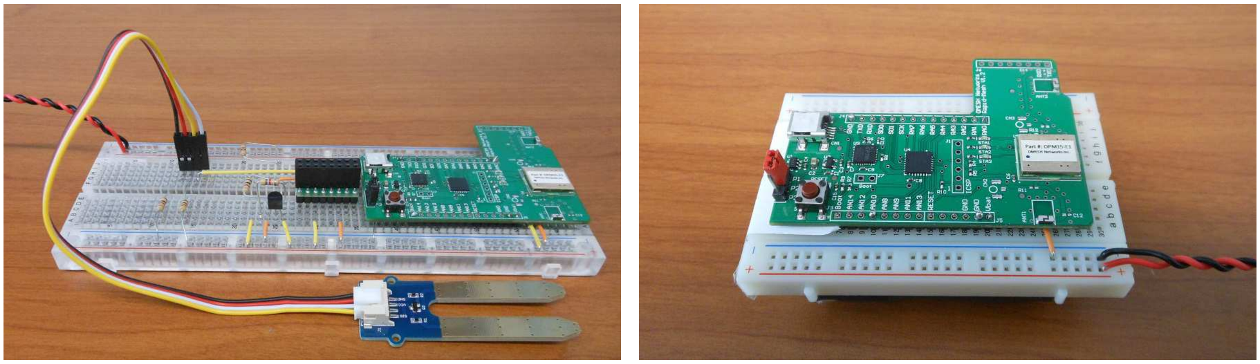
B. Hardware Infrastructure

The WSN deployed in this work consists of four major hardware components as shown in Fig. 4. They are:

- **Sensor nodes.** The sensor nodes are the primary data collecting elements in the network. The prototype follows similar approach as in [18]. They consist of two sensors (temperature/ humidity sensor and soil moisture sensor) which feed data to the radio module for transmission. The radio module passes the data to the control node either directly or via one of the relay nodes. The sensor nodes are powered by a solar module.
- **Relay nodes.** The relay nodes are similar to the sensor nodes. They use the same radio modules but do not have any sensors and therefore do not generate any data of their own. They are designed to assist the sensor nodes in transmitting their data to the control node. The relay nodes are also powered by a solar module.
- **Control node.** The control node is the final destination for all the data generated in the network. It consists of a radio module connected to a computer system. The radio module is connected to the computer via a USB interface (which also powers the radio module) and passes all of it's data to the computer. Then, the data can either be stored, plotted in real time via a GUI, or remotely accessed.
- **Solar module.** The solar modules are the power sources for the sensor and relay nodes. They consist of a solar panel, a Lithium-Ion battery pack and a charging circuit designed to efficiently charge the battery pack and protect it from both under and over voltage conditions.

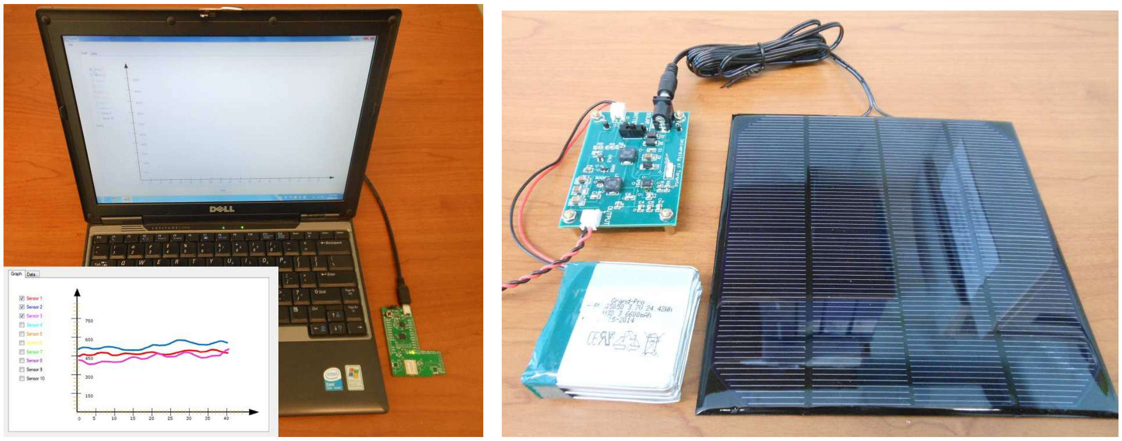
The details of these hardware components are described in the following sections.

1) Sensor nodes: As discussed earlier, the sensor nodes consist of two sensor devices and a radio module, see Fig. 4(a). The sensors used are a DHT11 basic temperature/ humidity sensor and a Grove soil moisture sensor (092355). The temperature/ humidity sensor is connected to the radio module by a 1-Wire interface which provided digital temperature/ humidity



(a) Sensor Node

(b) Relay Node



(c) Control Node

(d) Solar Module

Fig. 4: The various nodes and modules which make up the WSN

readings. The moisture sensor provides an analog output which is proportional to the moisture level in the soil. This is read by an ADC input on the radio module and stored in a digital format. The data from these two sensors is read on regular intervals, formatted into a packet and handed off to the radio module for scheduling and transmission.

The radio module is an OMesh Networks RapidMesh OPM15 Development Board [19] which has a radio chip, two antennas and a micro-controller on board. The module performs spectrum sensing and uses up to three channels to transmit the sensed data. Also, it can implement the routing protocols developed to improve the energy efficiency of the sensor node. This is a critical issue as the nodes are designed to be deployed and operate unattended long periods of time so they must make the most efficient use of the limited energy resources available to them.

2) Relay nodes: The relay nodes are similar to the sensor nodes except they do not have any sensors and therefore do not generate any sensed data of their own. They consist solely of a RapidMesh OPM15 Development Board programmed forward the data, see Fig. 4(b). They are needed to extend the range of the sensor nodes and to help collect data from multiple sensor nodes as they try to send their data to the control node. They also perform the same energy efficient routing protocols as they must also make the most efficient use of the limited energy resources available to them. Failure of a relay node could result in the lost of data from numerous sensor nodes.

3) Control node: The control node is the sink for the network and collects all the data from the sensor and relay nodes. It is connected directly to a computer system via a USB port which allows bidirectional communication and supplies the radio board with power, see Fig. 4(c). As with all the other nodes, it consist of a RapidMesh OPM15 Development Board. The board receives the sensed data packets, removes the packet wrapper and passes the sensed data onto the computer. This data can be displayed by the GUI running on the computer terminal or it can be saved for later retrieval. Also, if the computer is connected to the internet, the data from the sensor network can be accessed remotely or transmitted to a remote location.

4) Solar Module: The solar module is the power source for the sensor and relay nodes, see Fig. 4(d). It consists of: a $165\ mm \times 165\ mm$ photovoltaic solar panel with operating voltage of $5\ V$, a $3.7\ V$ lithium-ion battery rated at $6600\ mAh$, and a custom designed charging board. The panel is connected to a rechargeable battery through the charging board. The main criteria that governed the selection of the components for the solar module were that:

1) it must to be as small as possible to make them easy to deploy and cause minimal interference to the environment they are being deployed in,
2) it must be able to supply continues power to the nodes even during prolonged periods of darkness, and
3) it should be as efficient as possible at converting sunlight into stored energy.

To help meet these criteria, a custom charging circuit board was developed. It uses Maximum Power Point Tracking (MPPT) to maximize the power output of the solar panel and provide as rapid charging of the battery as possible.

It is also designed to prevent overcharging of the battery and has a cutoff voltage, similar to E_{res} from Eq.(1), to prevent the battery from being completely drained, as both conditions can shorten the life of the battery. The capacity of the battery pack was chosen to allow the sensor nodes to operate continuously for at least 48 hrs without any sun to recharge the battery.

V. SIMULATION EVALUATION

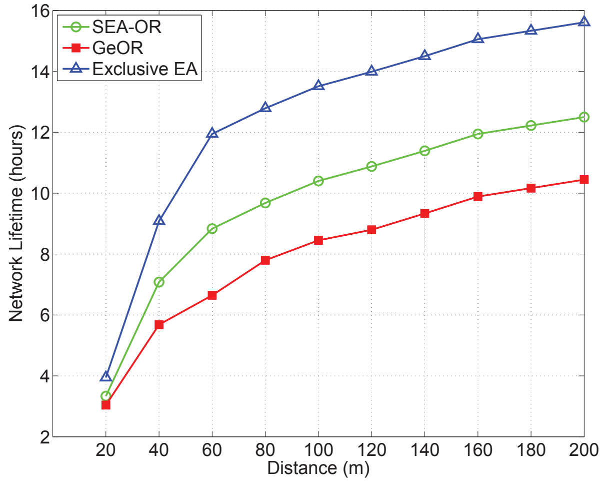
To evaluate the performance of the protocol we conducted simulations in a large scale network. The simulated nodes follows the same characteristics with the hardware requirements as described in the previous section. We compared SEA-OR with Geographic Opportunistic Routing (GeOR) and Exclusive Energy Aware (Exclusive EA) routing. GeOR follows similar approach with [20] and it forwards all the packets to the neighbor node that is closer to the destination. On the other hand, Exclusive EA forwards all the packets to the node that has more residual energy.

Ten topologies were evaluated with a number of nodes between 900 to 1100. The nodes were deployed randomly, following a Poisson distribution. Each node had a transmission range of 12 m. The distance between the source and the destination was varied between 20 to 200 meters. For each topology the source generated 1000 packets towards the destination. In every topology, 10 different source-destination pairs were selected.

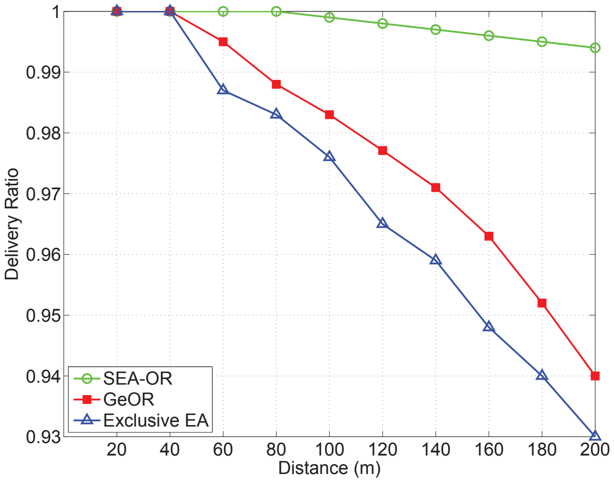
Network lifetime. There are a number of definitions for network lifetime [21], depending on the application. In this work, network lifetime is considered as the time until “connectivity” [22] or “coverage” is lost, i.e. there are no paths between the source and the destination or one of the nodes runs out of energy. The network lifetime of the three protocols is shown in Fig. 5(a).

SEA-OR significantly improves network lifetime over GeOR. As the distance between the source and the destination increases, there are more nodes in the routing path. The spectrum awareness of SEA-OR forwards the packets in shorter time than GeOR. As a consequence, the nodes have to remain active for a shorter time and the energy consumption per node is smaller.

Delivery ratio. SEA-OR improves the delivery ratio of GeOR, as shown in Fig.5(b). The use of RSSI in the prioritization metric, helps SEA-OR decrease collisions and forward the packets over reliable links. Consequently, the number of retransmissions decreases.



(a) Network lifetime



(b) Delivery ratio

Fig. 5: Performance comparison between SEA-OR and GeOR in different source-destination distances.

VI. EVALUATION

The next steps are to deploy the network in the two test environments and evaluate how the system performs under realistic conditions. So far the system has shown promising results in a laboratory environment but has yet to be fully tested on a large scale in an outdoor environment.

The main criteria that need to be evaluated are:

- **Data accuracy.** Can the sensors accurately measure the environmental conditions. Is there any sensor drift or other abnormalities caused by the changing environmental conditions.
- **Data reliability.** Can the sensor and relay nodes reliably stay in communication and ensure that the sensed data is delivered to the control node in a timely and accurate manor.
- **Network survivability.** This is essential the network lifetime. Can the solar module provide a constant power

source for the sensor node indefinitely. Factors such as location, time or year, and weather will have an impact this.

The first criteria can only be evaluated reliably at the GRIT Lab location. Since the facility has a series of highly accurate, wires sensors already installed throughout the facility that are data logged, there is a means by which to compare the results obtained by the sensor network.

Both of the environments provide an opportunity to examine the remaining two criteria. In terms of data reliability, the two environments provide very different wireless environments with the GRIT Lab being very much line-of-sight while the Brick Works has a lot of brick and metallic elements which will cause interference and reflections. In terms of survivability, the Brick Works provides a more open environment with less chance of the sun being blocked by buildings which the GRIT Lab is in a more urban core with large buildings around it. So the chances for getting enough sun to recharge and maintain the batteries at a reasonable level are greater at the Brick Works site.

VII. CONCLUSIONS AND FUTURE WORK

In this work, a self-powered wireless sensor network designed for outdoor environmental monitoring was proposed. The main components of the system were described along with the criteria that were used when making component selection. Criteria for testing and evaluating the WSN in two outdoor environments were also outlined. The next steps are to deploy the network in these environments and evaluate the performance of the system against the evaluation criteria and determine what changes or improvements (if any) are needed to meet those criteria.

VIII. ACKNOWLEDGEMENTS

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