EPIC-RoofNet: An Experimental Testbed for Solar-powered Wireless Sensor Networks

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Abstract- **We describe an experimental wireless sensor network (WSN) that was developed for conducting experimental studies of adaptive network protocols and algorithms for rechargeable sensor networks. The network is deployed on the roof of an academic building at the University of North Carolina at Charlotte, and comprises of wireless sensor nodes that periodically sample environmental parameters such as solar irradiance and temperature and transmit them to a centralized base station. Additional node-specific and network performance parameters are also determined in real time and recorded. All sensor information collected at the base station are available online through a shared folder.**

Keywords: **Wireless sensor networks, solar harvesting, adaptive protocols, distributed algorithms.**

I. Introduction

We present an experimental WSN that was developed for conducting experiments on solar-powered sensor nodes. Due to constraints in cost and size, the solar panels and the energy harvesting and storage hardware are expected to be insufficient to meet the energy consumption requirements of wireless sensor nodes under all environmental conditions. The problem is exacerbated by the fact that solar irradiance is highly dependent on the location, orientation, and other node-specific parameters as well as the environmental conditions such as cloud cover and seasons. Hence, the amount of solar energy available at such solar-powered sensor nodes can be highly unpredictable and at times insufficient for meeting the power requirements of the node. The goal of the current research is to design network protocols and processing schemes that enable the nodes to dynamically adapt their energy consumption based on estimated energy resources. The *EPIC-RoofNet* was deployed in the roof of the Energy Production and Infrastructure Center (EPIC) building at UNC Charlotte to provide an experimental platform for this research. *EPIC-RoofNet* has been designed primarily with two objectives. Firstly, it comprises of a set of pyranometer sensor nodes that are essential to obtain solar irradiance data from wireless sensor nodes placed in outdoor settings. This data is used for developing statistical models characterizing the spatial and temporal variations of solar energy available at the nodes. Secondly, it is used for a platform for experimental validation and performance evaluation of adaptive network protocols and energy-conservation schemes that is the focus of this research.

EPIC-RoofNet has been developed in two stages. In the first stage, it was primarily used for collecting solar irradiance data as described above. In the second phase, the code was modified for implementation and performance evaluations of cooperative power control, adaptive routing, and multi-channel operations, which are being researched by the team. The network is built using *MICAz* sensor nodes using *TinyOS*. All implementations consider data collecting traffic where nodes periodically transmit data to a centralized base station. The base station is implemented in a laptop computer connected to local area network of the University of North Carolina at Charlotte (UNC Charlotte) for saving data in a shared drive. The details of the implementation are provided below.

The rest of the report is organized as follows. The first phase of our deployment is summarized in section II. Section III describes the modifications in the second phase of our deployment. Conclusions are presented in section IV.

II. Phase-I

In the first phase, initiated in August 2012, a total of 13 MICAz motes were deployed for collecting solar irradiance data as shown in Figure 1(a). Each of these nodes were developed using a MICAz mote that were interfaced with a pyranometer sensor and an external temperature sensor using the MDA300 data acquisition board. The nodes were programmed using Crossbow's *Mote Works* platform of Tinyos1.x that uses *XMesh* [1] routing to deliver periodic data packets from each node to the base station. XMesh is a link quality based dynamic routing protocol that uses periodic route update messages (RU) from each node for link quality estimation. Each node promiscuously listens to the radio traffic in the neighborhood and selects the parent that would be the least costly in terms of energy to reach the base. A parent must already be a part of the mesh and must have been a descendant node for the last three Route Update Intervals (RUI). Link quality estimation is performed by monitoring the multi-hop headers of received packets and running an exponentially weighted moving average (EWMA) algorithm to smooth out

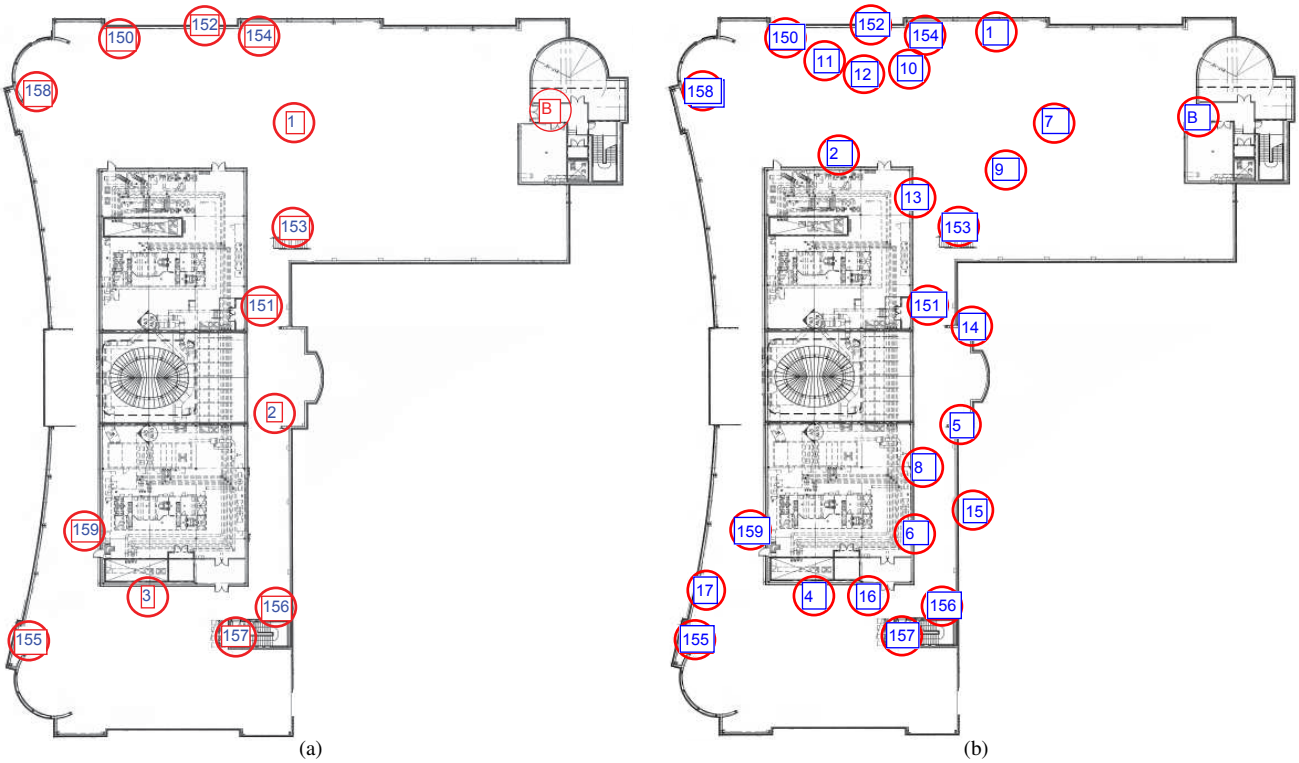

Fig. 1. Node locations in (a) Phase-I (a) Phase-II of *EPIC-RoofNet*

the estimate. Consequently, XMesh enables a set of interconnected wireless sensor nodes to form a mesh network rooted at the base, which is dynamically adapted based on link quality measurements.

Also to avoid idle listening, nodes use low-power listening (LPL) [2] with IEEE 802.15.4 MAC where they sleep most of the time and wakes up in a periodic interval. If they sense the channel to be busy, they remain on. Otherwise, they go back to sleep to conserve energy. The periodic wake-up interval is assumed to be 128 milliseconds. The beacon interval and the data interval are assumed to be 15 minutes and 5 minutes respectively. All the nodes sense every 5 minutes and forward these sensing values to the sink. The laptop computer running the base server/sink is connected to the Internet via UNC Charlotte WiFi network and automatically transfers the data gathered from the testbed to a Dropbox database for offline monitoring.

The physical construction of a solar irradiance sensing node is depicted in Figure 2. The figure shows the connection of a pyranometer [3] with a MDA300 data acquisition board attached to a MICAz mote. The MDA300 is designed as a general measurement platform for the MICAz nodes. These devices can interface with various analog sensors or with digital devices. The mote can sample from the MDA300, and it can actuate other devices via a set of output terminals. Other than sensing solar irradiance values, the mote senses ambient temperature from using the MDA along with the current battery voltage. 13 such nodes are deployed on top

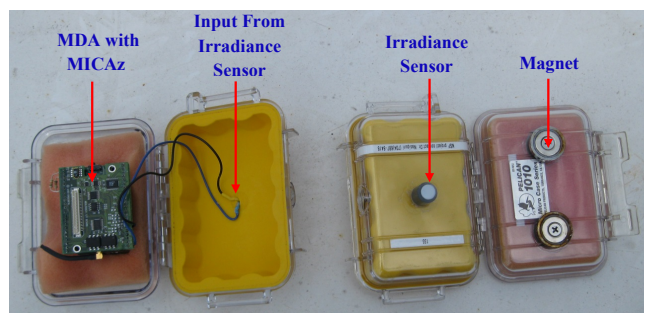

Fig. 2. Construction of an irradiance sensor node in *EPIC-RoofNet*.

of the EPIC roof to from a network where nodes sense the necessary parameters and forward it in a tree structure to the sink. Figure 1(a) depicts the locations of the sensor nodes in Phase-I. Nodes are placed in different places of the roof with different orientations, so that a wide variety of spatial variance of solar irradiance can be captured.

Images of some of the nodes deployed, depicting the sun and shading conditions that are being characterized from irradiance measurements, are shown in Figure 3. In Figure 3 we show the positions of three motes along with their irradiance measurements in three different days, illustrating high variations in the amount of irradiance over both time and space. This motivates the necessity of developing adaptive schemes that take care of the spato-temporal variations of solar energy availability.

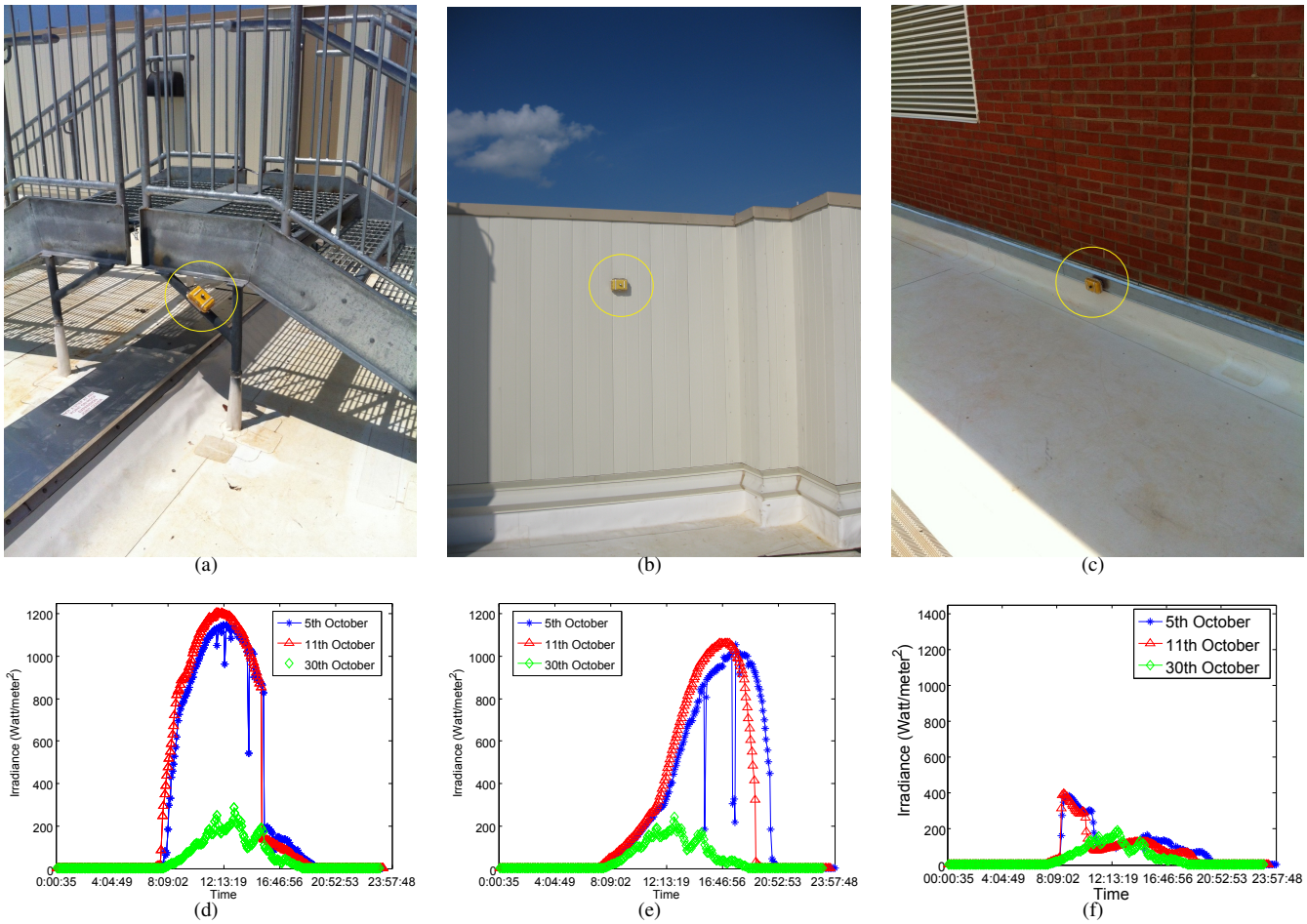

Fig. 3. Samples of nodes deployed in *EPIC-RoofNet* (a) Node 153 (b) Node 155 (c) Node 159. Irradiance measurement of (d) node 153 (e) node 155 and (f) node 159 for two sunny days (5th and 11th October, 2012) and a cloudy day (30th October, 2012). Node 159 is kept in the shaded region, whereas 153 and 155 gets sunlight most of the time.

III. Phase-II

In the second phase, we added 12 more MICAz motes on the existing network. The new deployment scenario is shown in Figure 1(b). Also we shifted from Tinyos-1.x to Tinyos-2.x. All the motes are programmed with new driver for MDA300.

We used *Collection Tree Protocol (CTP)* [4] with LPL and some other modifications as our routing protocol. CTP works pretty similar to XMesh. CTP uses a quality metric named *expected number of transmissions (ETX)*. An ETX is the expected number of transmission attempts required to deliver a packet successfully to the receiver. Hence, a low ETX value indicates a good end to end quality of a route, and vice versa. The sink always broadcasts an ETX = 0. Each node calculates its ETX as the ETX of its parent plus the ETX of its link to the parent. This measure assumes that nodes use link-level acknowledgements and retransmissions. A node i chooses node j as its parent among all its neighbors if ETX$_{ij}$+ETX of $j <$ ETX$_{ik}$+ETX of $k \; \forall k \neq j$, where ETX$_{ij}$ and ETX$_{ik}$ are the ETX of link $i \rightarrow j$ and $i \rightarrow k$ respectively. In this process a node chooses the route with the lowest ETX value to the sink.

All the necessary network parameters including beacon, data and sensing intervals are kept similar to that of the first phase. All nodes periodically forwards their parent, battery voltage, irradiance and temperature readings along with other necessary parameters for lifetime calculation such as number of beacon and data transmissions-receptions and overhearing in last 5 minutes. They also calculate the remaining lifetime in hours based on its remaining capacity and from its usage in the last 5 minutes. The remaining lifetime is calculated as $\frac{B}{\mathcal{I}}$, where B is the remaining capacity of the battery and $\mathcal{I}$ represents the estimated current drawn at the node. Based on the experimentally validated model [5], the current drawn in each node is calculated as follows:

$$\begin{aligned} \mathcal{I} &= \frac{I_{Bt}T_{Bt}}{T_B} + M.I_{Dt}T_{Dt} + N.\frac{I_{Br}T_{Br}}{T_B} + O.I_{Dr}T_{Dr} \\ &+ F.I_{Dt}T_{Dt} + \frac{I_sT_s}{T_D} + N_P.I_PT_P \end{aligned} \quad (1)$$

where I_x and T_x represent the current drawn and the duration, respectively, of the event x; and T_B represents the beacon interval. Transmission/reception of beacons is denoted by B_t/B_r, data transmit/receive is denoted by D_t/D_r and processing and sensing are denoted as P and S, respectively. O

#Time, Node-ID, parent, battery voltage, irradiance, temperature, Beacon-trans, Beacon-recv, Data-fwd, Data-recv, Data-overheard, Lifetime

07-18-2013 20:59:59, 151, 1, 2.783004, 2.916504, 83.925680, 0, 1, 5, 0, 0, 71

07-18-2013 21:25:00, 151, 1, 2.783004, 2.916504, 82.937840, 0, 0, 5, 0, 1, 72

07-18-2013 22:30:04, 151, 153, 2.776834, 2.916504, 81.173840, 0, 1, 5, 0, 2, 69

07-19-2013 07:45:31, 151, 153, 2.758485, 37.914551, 76.199360, 0, 1, 5, 0, 1, 61

07-19-2013 11:50:44, 151, 153, 2.758485, 370.395996, 94.403840, 0, 0, 5, 0, 1, 61

Fig. 4. (a) A snapshot of the data file sent by node 151.

and F are the overhearing and forwarding rates, respectively, and N is the number of neighbors. M is the rate at which a node transmits its own packets. If there are no retransmissions, then $M = \frac{1}{T_D}$, where T_D is the data interval. N_P represents the number of times that a node wakes per second to check whether the channel is busy, and is set to 8 in our application. We assume that each node is able to estimate all the dynamic parameters that are used in equation (1), by periodic assessment of its overheard and forwarded traffic. All the necessary parameters are measured offline and are listed in Table I.

TABLE I

PARAMETERS USED

Var	Values	Var	Values	Var	Values	Var	Values
I_{Bt}	20 mA	T_{Bt}	140 ms	I_{Br}	20 mA	T_{Br}	140 ms
I_{Dt}	20 mA	T_{Dt}	140 ms	I_{Dr}	20 mA	T_{Dr}	140 ms
I_P	20 mA	T_P	3 ms	I_S	7.5 mA	T_S	112 ms

We assume that the battery capacity B (energy resource) is estimated from the battery voltage.[1] We consider MICAz nodes, which operate in a voltage range of 2.7V to 3.3V [6]. The actual battery voltage is related to the ADC reading as follows: $V_{bat} = \frac{1.223 \times 1024}{\text{ADC reading}}$. Thus, assuming that the capacity is 100% when the battery voltage is greater than or equal to 3V (ADC reading = 417 from MICAz voltage sensor), and 0% when it drops below 2.6V (ADC reading = 482), the battery capacity can be estimated as $B = \min\left(100, \frac{482 - \text{ADC reading}}{0.65}\right)$. This method is used to provide a computationally simple assessment of the battery health.

This finishes our first step towards inplementing adaptive power control [7] and multi-channel routing [8], [9] schemes on top of CTP for rechargeable WSNs.

[1]A model for estimating the battery state of charge is currently being developed by the researchers, and will be described in future publications.

IV. CONCLUSIONS

The report summarizes different steps of the deployment and observations of EPIC-RoofNet testbed for solar irradiance measurements. The key observations of this deployment is the wise variations of solar irradiance in both time and space. Thus a number of adaptive features (routing, power control, channel selection, duty-cycle and sampling rate adaptation etc) based on individual nodes energy budgets need to be included, which is the current considerations of the researchers. The report also summerizes the transition from the older version of Tinyos to its newer version.

ACKNOWLEDGEMENT

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