EPIC-RoofNet: A Sensor Network Testbed for Solar Irradiance Measurement and Analysis

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***Abstract*—This paper describes the development of an experimental wireless sensor network (WSN) testbed for studying the nature of irradiance measurements at the sensor nodes that are deployed at different points in the WSN, and oriented differently depending on the deployment geometry. The network was developed on the roof of an academic building at the University of North Carolina at Charlotte (UNC Charlotte), where the sensor nodes are equipped with pyranometer sensors to periodically collect the irradiance measurements at different points and send then to a centralized base station using multi-hop communication. The collected data is analyzed to demonstrate the spatial and temporal variation of energy availability at each individual node, resulting from the localized variations in the light levels.**

***Index Terms*—Wireless sensor networks, solar harvesting, irradiance sensing, data collection, analysis.**

I. Introduction

The fundamental challenge for the adoption of large-scale rechargeable wireless mesh sensor networks is the difficulty of predicting ambient energy patterns and network traffic during at individual node levels in the design phase. For instance, when using solar power harvesting, all nodes will experience typical diurnal and seasonal variations in light levels, but the effect of shading from nearby obstructions will vary significantly from one node to the next. At the same time the deployed nodes have different orientations, affecting the irradiance collected by the solar panels. Changes of weather and sun orientation also change solar power intake over time. Similar problems exist with other sources of renewable energy such as vibration, thermal gradients, and electromagnetic waves, which find numerous applications such as structural, environmental or climate monitoring.

To illustrate such spatio-temporal variations from a real network setting, a WSN testbed named EPIC-RoofNet is developed for real-time irradiance data collection. The testbed comprises of a set of sensor nodes equipped with pyranometer sensors [1] and are placed in an outdoor setting to obtain solar irradiance measurements. The EPIC-RoofNet was deployed at the roof of the Energy Production and Infrastructure Center (EPIC), which is an academic building at UNC Charlotte[1]. EPIC-RoofNet is built using *MICAz* sensor nodes that are programmed using *TinyOS* [2]; the nodes periodically record their irradiance measurements and transmit them to a centralized base station. The base station is connected to a laptop that uploads the measurements over several months in a shared drive, via the local area network of the UNC Charlotte. This recorded data is then used for developing analysis characterizing the spatial and temporal variations of solar energy availability at the sensor nodes. The measured data is also available for public use at https://github.com/Amitangshu/Irradiance_sensing.

[1]The experiments were conducted when the author was at UNC Charlotte

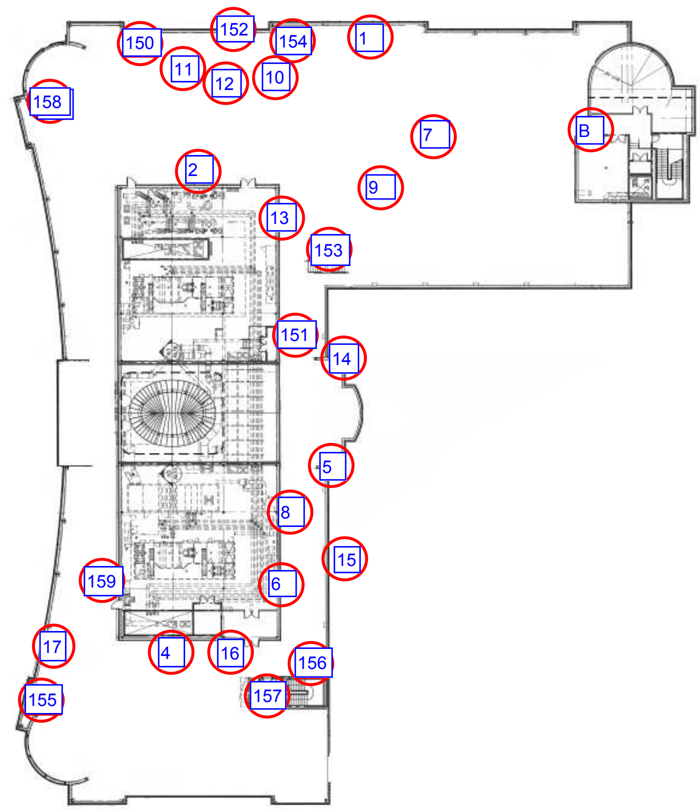


Fig. 1: The placement of the sensor nodes in EPIC-RoofNet. Nodes 150–159 are equipped with pyranometer sensors, whereas others are deployed as relay nodes. B denotes the basestation.

The paper is organized as follows. Section II describes the network topology and implementation details of the EPIC-RoofNet. Section III describes the data collection and analysis of irradiance measurements obtained from the network. The paper is concluded in section IV.

II. EPIC-RoofNet: Implementation Details

A. Network topology setup

EPIC-RoofNet consists of a total of 25 MICAz sensor nodes; out of which 10 nodes are equipped with irradiance sensors whereas others are deployed as relay nodes, as shown in Fig. 1. Nodes 150–159 are interfaced with a pyranometer

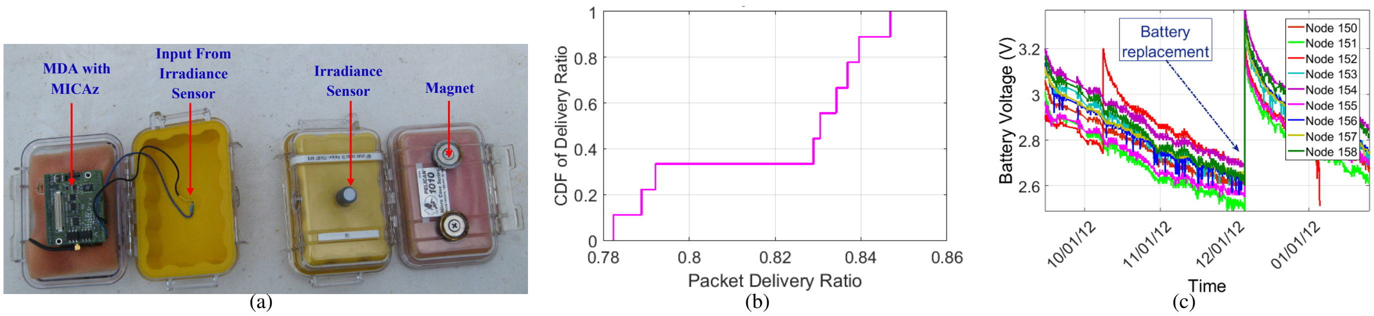


Fig. 2: (a) Construction of an irradiance sensing node in EPIC-RoofNet, which consists of a pyranometer sensor attached to the MDA data acquisition board. (b) The distribution of the packet delivery ratio to the basestation. (c) The drop in battery voltages over time.

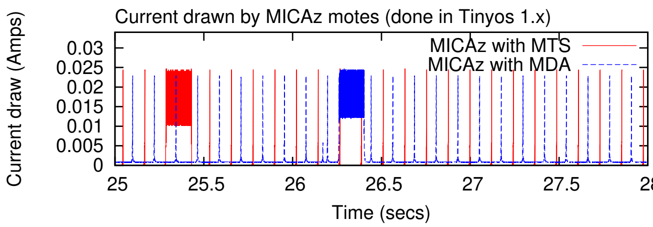


Fig. 3: Low-power operation of a MICAz sensor node with MTS and MDA data acquisition boards. The node wakes up with an interval of 128 milliseconds, which ensures that the preamble length is also ∼128 milliseconds.

sensor for irradiance measurement using the MDA300 data acquisition board [3], and nodes 1–17 are relay nodes. The nodes were programmed using Crossbow's *Mote Works* platform of Tinyos2.x that uses the *Collection Tree Protocol (CTP)* [4] to build a dynamic, multi-hop, link-quality aware routing tree rooted at the basestation.

To conserve energy the nodes use low-power listening (LPL) [5] with IEEE 802.15.4 MAC, where they put their radios in sleep mode most of the time, and wake-up in periodic interval to sense the channel. If the channel is sensed to be busy, they keep their radios on, otherwise they put them in sleep mode. The nodes are programmed to wake-up periodically with an interval of 128 milliseconds. Fig. 3 shows the low power operation of a typical sensor node, with a wake-up interval of approximately 128 milliseconds; while transmitting the node also transmits a preamble which spans the duration of a wake-up interval, i.e. ∼128 milliseconds. The nodes record the irradiance measurements every 5 minutes and send them to the basestation using the multi-hop routing protocol. They also exchange beacon messages among their neighbors with an interval of 15 minutes.

Fig. 2(a) shows the physical hardware of a solar irradiance sensing node. A pyranometer [1] is attached to a MICAz mote through a MDA300 data acquisition board. These MDA boards are generally used as a measurement platform to interface external analog/digital sensors with the MICAz nodes. The nodes also sense the ambient temperature using the inbuilt temperature sensor on the MDA along with their current battery voltages. Two magnets are embedded into the node boxes to attach them with the roof surfaces. The boxes are made completely water-proof to prevent any damage due to seasonal effects. The boxes are then deployed on the rooftop at different orientations, so that their pyranometers experience a wide variety of solar irradiance levels.

B. Testbed results

Fig. 2(b) shows the distribution of packet delivery ratio of the network nodes to the basestation. From this figure we can observe that the delivery ratio is above 78% for all the sensor nodes; In fact more than 60% nodes have a delivery ratio above 83%. The sensor nodes are equipped with two AA alkaline batteries with a capacity of 2,500 mAh. The Micaz sensor nodes typically consumes 17.4 mA in transmit mode (at 0 dBm) and 19.7 mA in transmit mode [6]. Fig. 2(c) shows the drop in battery voltages of these sensor nodes over time. Micaz sensor nodes typically operates in between 2.5–3.2 volts, thus we can observe that the nodes can typically operate for 3 months with these alkaline batteries. However with lower sampling rates, this lifetime can be easily extended over an year.

III. Irradiance Data Analysis

A. Spatial and temporal variation of irradiance

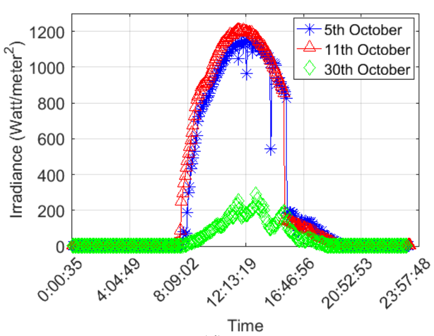
Fig. 4 shows the location of three sensor nodes at different points at the roof, along with their irradiance measurements in three different days. The figure clearly illustrates the high temporal and spatial variation of irradiance measurement at these three points. For example node 159 is placed in a shaded region as shown in Fig. 4(c) which results in lower irradiance even at peak hours, whereas nodes 153 and 155 are placed under sunny regions and thus these nodes typically receives enough sunlight. Also the irradiance characteristics vary based on the node's orientations, for example node 155 receives maximum amount of sunlight during the afternoon hours, whereas node 153 receives the light staring after 8 AM. Fig. 4 also shows the temporal variations of the irradiance measurement; for example 30th October, 2012 was a cloudy day which results in 5–6 times less irradiance at nodes 153 and 155 even at the peak hours. We can also observe the the peak irradiance measurements are in between 1000-1200 Watt/meter^2, which approximately matches with the *Global Horizontal Irradiance (GHI)* at the earth surface [7].

Fig. 5 shows the distribution of daily average solar irradiance of all the sensor nodes at EPIC-RoofNet. From this figure we can observe that almost 90% of the nodes have an average irradiance measurement of less than 200 Watts/meter^2, whereas 40% nodes have an irradiance level below 100 Watts/meter^2.

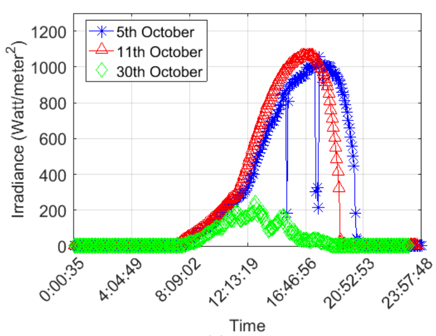
(a)

(b)

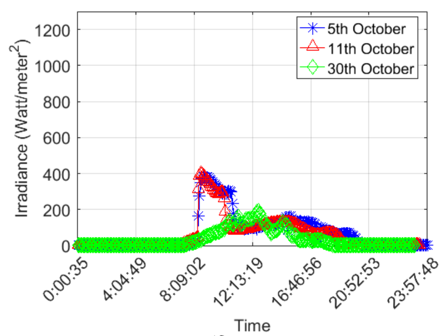
(c)



(d)



(e)



(f)

Fig. 4: The locations of (a) Node 153 (b) Node 155 and (c) Node 159 in EPIC-RoofNet along with their irradiance measurements (d)-(f) during two sunny days (5th and 11th October, 2012) and a cloudy day (30th October, 2012). Nodes 153 and 155 are placed in a sunny region, whereas the node 159 experience low irradiance due to shading.

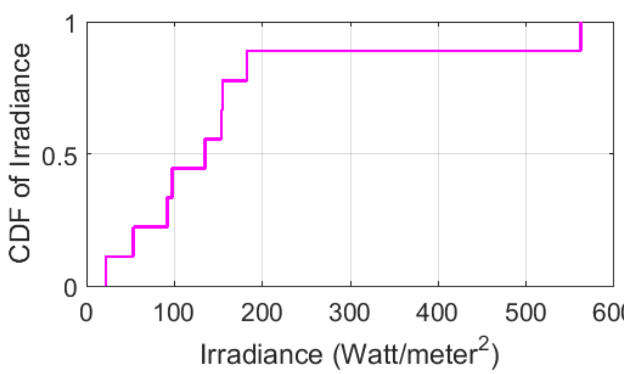


Fig. 5: Distribution of daily average irradiance levels at the sensor nodes.

B. Forecasting irradiance measurements

We use an *Autoregressive moving average (ARMA)* based model for forecasting the irradiance measurements, to illustrate how accurately we can predict the irradiance characteristics. The ARMA model consists of two polynomials; (a) one for autoregression which involves regressing the lagged values of a time series, while (b) the other one for moving average which involves error term as the linear combination of the previous error terms. Mathematically the ARMA model of order (p, q) for time series X is written as follows:

$$X_t = c + \epsilon_t + \underbrace{\sum_{i=1}^{p} \phi_i X_{t-i}}_{\text{Autoregressive model}} + \underbrace{\sum_{i=1}^{q} \theta_i X_{t-i}}_{\text{Moving-average model}} \quad (1)$$

where ϕ_i and θ_i are the parameters of the AR and MA model respectively, and c is a constant. The error terms, ϵ_t, are generally assumed to be Gaussian i.i.d. random variables with zero mean and constant variance.

Fig. 6(a)-(c)-(e) show the comparison of the actual irradiance readings, along with the 6-step predicted response (i.e. 30 minutes forecasting) for the nodes 153, 155 and 159 respectively. From these figures we can observe that the ARMA model can predict the irradiance measurements pretty accurately for all three nodes. Fig. 6(b)-(d)-(f) show the average energy availability per hour per sq. m. along with the 1-step predicted response, which also confirms the accuracy of this model. We can also observe that the peak hourly energy density is ∼4000 KJ/meter^2.

C. Seasonal trend of irradiance

Fig. 7(a) shows the yearly trend of irradiance measurements of node 156 over the span of almost one year. The trend

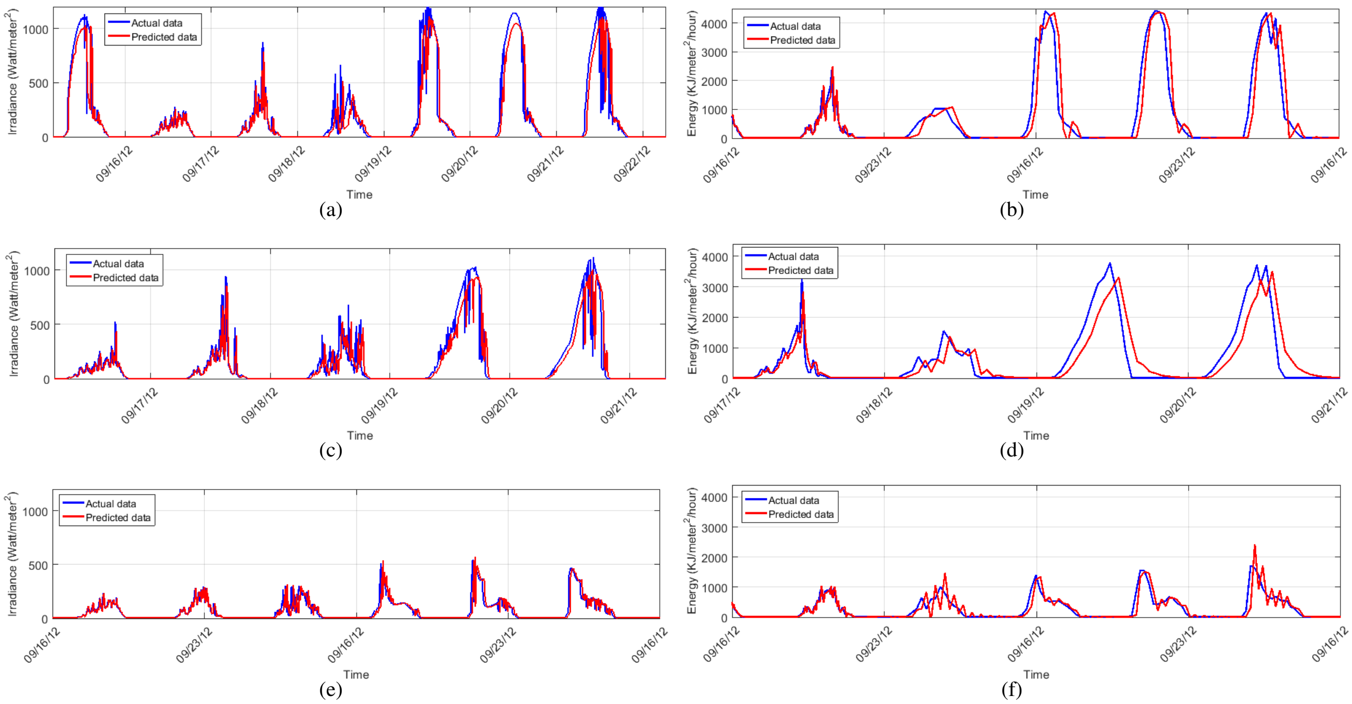


Fig. 6: Actual and predicted irradiance measurements and energy densities over time for (a)-(b) Node 153 (c)-(d) Node 155 and (e)-(f) Node 159. The goodness of fit between the actual and the predicted measurements are 68.85%, 68.48%, 54.92%, 51.93%, 65.71% and 558.11% respectively.

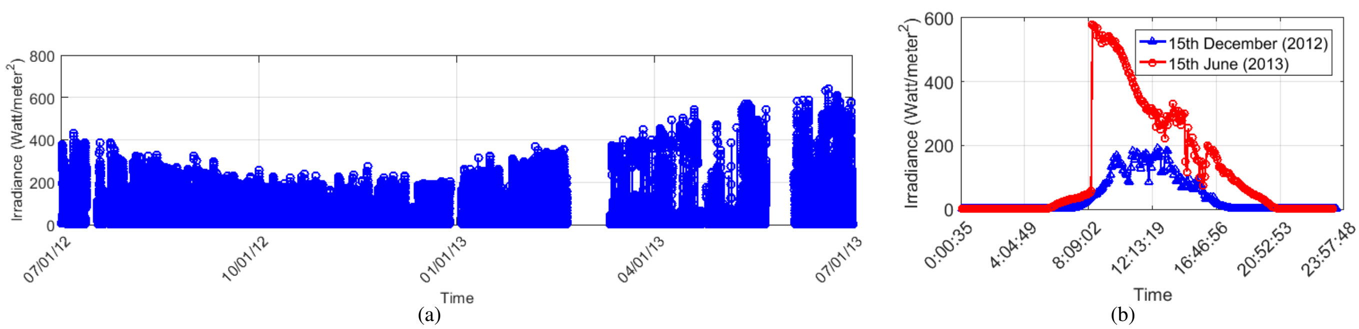


Fig. 7: (a) Seasonal variation of irradiance level at Node 156. (b) The variation of irradiance at Node 156 during a winter and a summer day.

clearly follows a seasonal pattern, i.e. the irradiance is more in between April–July, starts reducing after August, and becomes minimum during November–January. Fig. 7(b) illustrates the irradiance measurement during a summer day (15th June) and a winter day (15th December). The peak irradinace measurement at winter time is almost 3 times lower than the summer days. From Fig. 7(b) also illustrates the variation of daytime during summer and winter; during December the irradiance measurement goes to almost zero around 5 PM, whereas during June around 9 PM the irradiance level drops to zero.

IV. Conclusions

The paper describes the deployment of a multi-hop wireless sensor network testbed for solar irradiance measurements. The measurement results illustrate wide variations of solar irradiance in time and space. The paper also used a forcasting model for irradiance prediction ahead of time, which can be exploited for developing different adaptive protocols [8], [9] and taking proactive actions so that the individual sensor nodes do not run out of energy due to battery drainage. The effect of seasonal changes on irradiance characteristics is also studied from the testbed results.

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