EDUCATIONAL REMOTE LAB CONCEPT FOR ENERGY HARVESTING ENHANCED WIRELESS SENSOR NETWORKS

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ABSTRACT

Wireless sensor networks (WSNs) are typically used in application areas without wired infrastructure. WSNs must be energy efficient, because they are powered by batteries or energy harvesting systems. Teaching of practical aspects of energy harvesting enhanced WSNs can be improved by integration of performance-centered tasks.

This work presents an educational remote lab concept for energy harvesting enhanced WSNs. Students can learn how WSNs work and how energy harvesting influences their behavior.

It is part of the European project Remote-labs Access in Internet-based Performance-centered Learning Environment for Curriculum Support.

1. INTRODUCTION AND RELATED WORK

Wireless sensor networks (WSNs) are networks built from small devices typically used to collect information about their environment. Application areas are manifold. Environmental monitoring [1], precision agriculture [2], wildlife monitoring [3], human health-care [4], or structural health monitoring [5] are only a few examples. They show the necessity of a wireless communication and a dedicated power supply. These two characteristics are often found in WSNs. WSNs are used in case of missing wired infrastructure and if it is impossible or too expensive to wire the sensors up. Most WSNs consist of a number of sensor nodes and a base station. The sensor nodes measure physical quantities of the environment and transmit the processed data to the base station. There, the data is stored or forwarded to another network.

The kind of wireless communication depends on the application area. Especially, it depends on how the sensor nodes are distributed and the amount of data which has to be transmitted. Basically, there are two types of network topologies.

Star topology consists of one base station and a certain number of sensor nodes. Each sensor node is able to communicate directly with the base station. Only one hop is necessary to transmit the data. This network topology is one of the simplest topologies. No routing protocol is necessary to find the way of the data through the network. The only thing which should be considered is the problem of possible collisions during the communication at higher network utilization and the hidden terminal problem [6]. Therefore, some kind of synchronization and time slots for each sensor node may be introduced to reduce collisions. However, this topology can only be used if all sensor nodes are placeable in communication range of the base station.

Mesh topology consists of one or more base stations and also a certain number of sensor nodes. Most of the sensor nodes cannot communicate directly with the base station, but each sensor node is in the communication range of another sensor node. Data is forwarded towards the nearest base station in a multi-hop manner. Therefore, a routing protocol is needed to find the best path through the network. Here also, synchronization and time slots may reduce collisions. Each added sensor node can extend the range of coverage of the WSN using this topology.

As mentioned before, each sensor node needs its own power supply. Non-rechargeable batteries are often used [7], because they provide a reliable and continuous supply for the nodes. However, the lifetime of the sensor node is limited. It depends on the average power consumption and on the capacity of the battery. Lifetime cannot be extended at will by reducing the average power consumption of the sensor node, because each battery also has a leakage current which discharges the battery slowly but constantly [8]. Therefore, the batteries have to be replaced or recharged after a certain period of time. This task could be very time-consuming, because some WSNs can consist of thousands of nodes [9], or the nodes are placed at hard-to-access locations [10]. This problem is called battery replacement problem [11].

Energy harvesting systems (EHSs) can extend the lifetime of sensor nodes or even enable perpetual operation. They convert ambient energy of the environment into electrical energy using energy harvesting devices (EHDs). For example, solar cells convert the radiant energy of the sun into electrical energy. Due to the fact that the converted energy is not continuous, a certain amount of the converted energy has to be stored to enable a continuous operation of the sensor node [12]. Existing energy harvesting enhanced WSNs typically use Nickel-Metal-Hydride (NiMH) batteries, Lithium-Ion (LiIon) batteries, double layer capacitors (DLCs), or a combination of them to store the energy [13, 14].

The state of charge of the energy storage component is important information for power-aware applications, services and protocols. For example, this information can be used to find a sensor node with a high state of charge to perform a measurement task or to select a route through the network. This relieves certain sensor nodes with a low state of charge and may extend the lifetime of the overall WSN as we have shown in [15]. The type of the energy storage component is not important for such considerations. Power-aware software can be implemented for battery supplied sensor nodes as well as energy harvesting enhanced sensor nodes. Later ones suffer from the fact that the harvestable energy may depend from the location of the sensor node. For example, the harvestable energy in the South of a building is much higher than that in the North of a building during a sunny day (northern hemisphere) which can be seen later in Figure 2.

It can be seen that an energy harvesting enhanced WSN is a complex system. Practical teaching of this topic is challenging, because students have to consider a lot of influences, for example the state-of-charge or different routing protocols. It is important to provide good practical exercises to impart knowledge to the students. Furthermore, students should have the possibility to do the exercises at home. However, in traditional laboratories it is not possible or allowed to take the hardware away. Existing remote laboratories can be used to evaluate different application tasks using an existing WSN installation [16], but without energy harvesting capabilities. Therefore, this paper presents an educational remote lab concept for energy harvesting enhanced WSNs. The students can do their exercises at any place with an internet connection in a performance-centered manner. This lab is a part of the new European project *Remote-labs Access in Internet-based*

Performance-centered Learning Environment for Curriculum Support (RIPLECS) [17, 18].

The remainder of the paper is organized as follows: Section 2 shows the educational objectives. Section 3 introduces the concept and structure of the remote lab. In Section 4, the low-power energy harvesting hardware structure is explained. Section 5 shows the web access interface for interacting with the remote lab. Finally, Section 6 concludes the paper.

2. EDUCATIONAL OBJECTIVES AND PERFORMANCE-CENTERED LEARNING

Basically, the students should learn how energy harvesting enhanced WSNs work and how the sensor nodes interact with each other. Furthermore, they should be able to integrate energy harvesting enhanced sensor nodes in WSN applications. The subject matter is divided into educational objectives. These objectives are learned in a performance-centered manner.

2.1 Wireless Sensor Nodes and Networks

In this section, the students learn the generic structure of sensor nodes [19] and how they can be composed. Furthermore, they learn how the single units interact and how the nodes form a WSN. The following list shows the educational objectives:

Objective 1.1 Generic structure of sensor node: sensor unit, power supply unit, processing unit, and communication unit.

Objective 1.2 Interaction of the units of a sensor node: measurement data preprocessing and event detection.

Objective 1.3 WSN communication: node to node communication, multi-hop communication, routing protocols, and fault tolerance.

2.2 Energy Considerations for WSNs

In this section, the students have to deal with power consumption of wireless sensor nodes. Power states are introduced and the students learn how to calculate the average power consumption. Furthermore, low power techniques are introduced. Different power supply possibilities are shown and how to deal with them. The following list shows the educational objectives:

Objective 2.1 Power consumption of sensor node: power states and average power consumption.

Objective 2.2 Network considerations: power consumption of a WSN and network lifetime.

Objective 2.3 Energy harvesting: energy harvesting devices, energy storage, energy harvesting system, perpetual operation, energy management, and blackout sustainability.

Objective 2.4 Low power techniques: duty cycling, low power listening, region of interest, energy-aware routing, energy-aware task execution, and adapted transmission power.

2.3 WSN Application Scenario

This section deals with a practical application scenario for WSNs, a wireless alarm system. The students learn how to implement a WSN application and which things have to be considered. The wireless alarm system consists of several sensor nodes including a light sensor. An alarm should be triggered if the nodes are exposed to light which simulates a housebreaker's flashlight.

Objective 3.1 Wireless alarm system: base station software, sensor nodes software, logging, and fault tolerance in this application scenario (sensors, power supply, node, routing, and base station).

3. EDUCATIONAL REMOTE LAB CONCEPT

This section shows the concept of the educational remote lab for energy harvesting enhanced WSNs. Figure 1 shows the remote lab setup. In the following sections all component of the remote lab setup and the interaction of them are explained in detail.

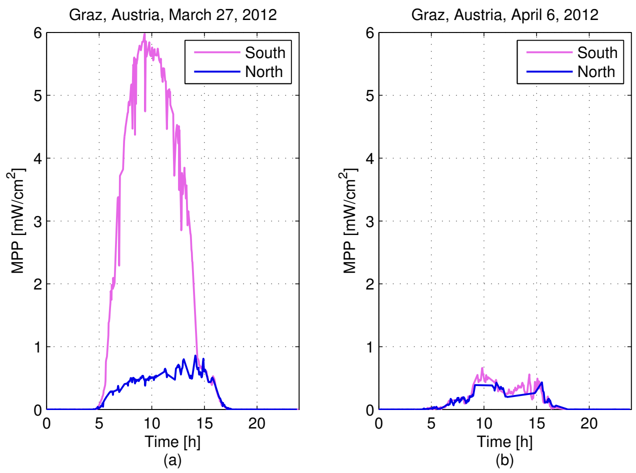

Figure 2: Maximum power point of two solar cells placed at different locations. The traces are measured during a day with good weather conditions (a) and bad weather conditions (b).

3.1 Energy Harvesting Enhanced Sensor Nodes

The energy harvesting enhanced sensor nodes are equipped with solar cells. They are not connected by wires to any other device or power supply. They can be programmed and a WSN can be set up. Together with the continuously supplied sensor nodes they can form a combined WSN. A detailed description of the hardware concept can be found in Section 4.

The solar cells are exposed to the ambient lighting of the lab setup. The ambient lighting can be controlled by the measurement and control unit. Therefore, realistic environmental conditions can be generated. It is possible to simulate lighting condition during a whole day including sunrise, day light, sunset, and night. Obviously, this has to be carried out in some kind of fast motion to be able to simulate a couple of days and nights during one exercise scenario. Furthermore, the changes of different ambient lighting condition can be simulated. For example, the difference of harvestable energy is significant between a day with good and a day with bad lighting conditions. We have measured the maximum power point (MPP) of solar cells with the on-site characterization instrument presented in [20]. Figure 2 shows the trace of the MPP of two sensor nodes placed in the South and in the North of the institute's building during a day with good and a day with bad weather conditions.

3.2 Continuously Supplied Sensor Nodes

The continuously supplied sensor nodes are used to teach the basic function of a WSN. They can be programmed and a WSN can be set up.

3.2.1 Continuous Power Supply

The continuous power supply is needed for the continuously supplied sensor nodes. It supplies the sensor nodes with a constant voltage in order to guarantee proper operating.

3.2.2 Power Supply Control

The power supply control enables a selective supply of the sensor nodes. Therefore, single nodes can be switched off remotely. This is needed to test the fault tolerance of the WSN and the running software on it (especially routing protocols).

3.2.3 Power Measurement Unit

The power measurement unit consists of a supply voltage and supply current measurement circuitry. It is used to determine the power consumption of the continuously supplied sensor nodes using the measurement and control unit.

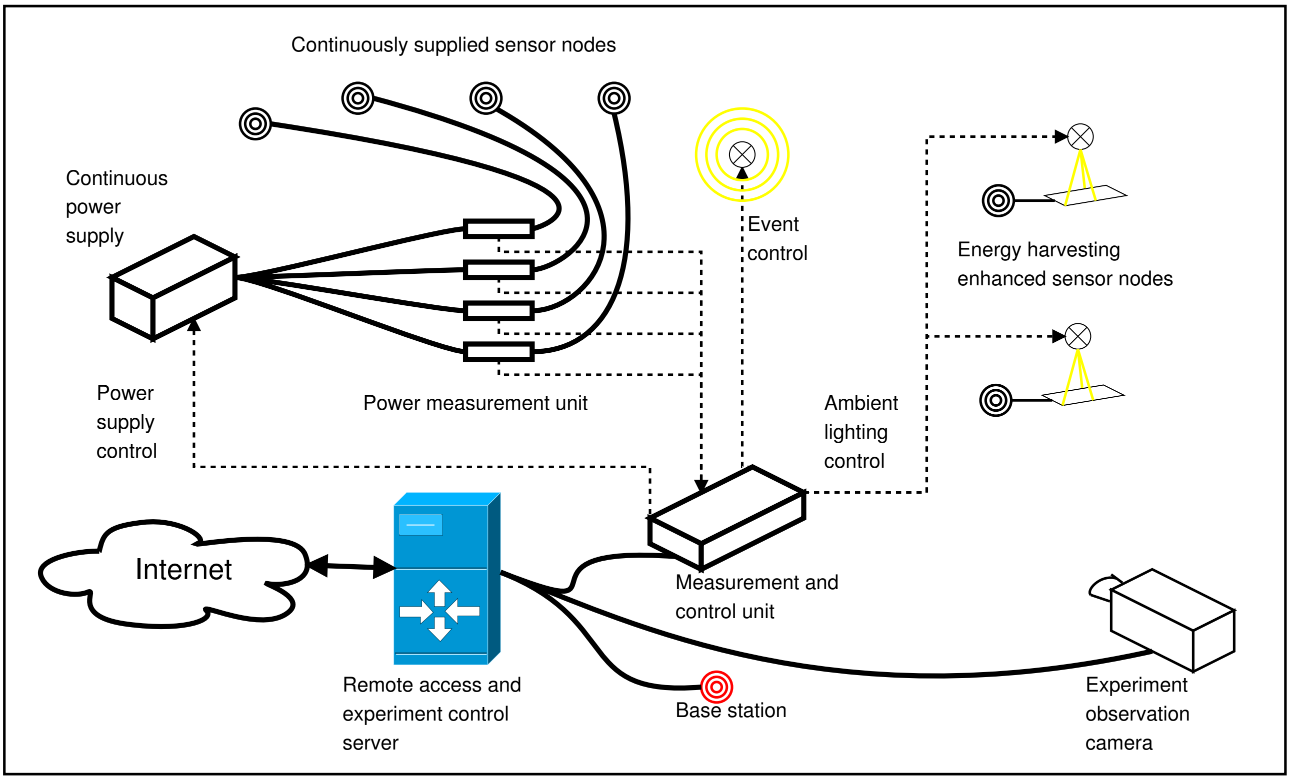

Figure 1: Educational remote lab setup for energy harvesting enhanced WSNs.

3.3 Base Station Node

The base station is needed to communicate with the WSN. It receives data and status messages from the network and transmits control and program update messages into the network. The base station is connected with the remote access and experiment control server. Thus, it enables the communication with the WSN and the students.

3.4 Remote Access and Experiment Control Server

The remote access and experiment control server is needed to perform different exercise scenarios. It enables the access from the internet to the remote lab for the students. They can log on, select an exercise scenario, reprogram the sensor nodes, reconfigure the network, control the ambient light, generate events, and perform the requested measurements. The measurement results can be also accessed through this server.

3.5 Measurement and Control Unit

First, the measurement and control unit performs the measurement of the power consumption of the continuously supplied sensor nodes. Therefore, the supply voltage and the supply current of each sensor node are measured. The power consumption can be calculated using these measurement values. Second, the measurement and control unit drives the ambient lighting. Third, the measurement and control unit is also used to drive the switchable power supply connections. Fourth, it is used to drive the event source.

3.6 Event Source

The event source is used to generate events which should be detected by the sensor nodes. In this application scenario, it simulates the flashlight of a housebreaker which must be detected by the wireless alarm system.

3.7 Experiment Observation Camera

The experiment observation camera is used to be able to view the remote lab setup in real time, thus observing sensor nodes' status LEDs, ambient lighting, and events.

4. ENERGY HARVESTING CONCEPT

As mentioned before, two nodes of the WSN are supplied by EHSs. The EHS consists of a solar cell as EHD, two selectable DLCs as energy storage components, and a connecting circuitry. The hardware structure is shown in Figure 3. The solar cell provides the electrical energy for the sensor node. A diode is used to prevent discharging of the DLCs (C1 and C2) during periods without harvestable energy. The switch S3 can be used to disable energy harvesting in order to test the runtime of the node supplied only by the DLCs. All switches of the EHS are controlled by the sensor node itself. The default positions are also indicated in Figure 3. For example S3 is closed by default to ensure energy supply of the sensor node after a reset (the solar cells must be exposed to light). Each DLC can be selected with the switches S1 and S2 in order to provide different capacities of the energy storage component. They are opened by default to provide immediate power to the sensor node after a reset. The capacities of the DLCs are dimensioned appropriately so that they match to the simulated fast motion of day and night. Switches S4 to S7 are used to select different voltage converters. The energy supply of the sensor node should be as efficient as possible. Furthermore, it is necessary to provide a constant supply voltage to the sensor node. Due to the fact that the solar voltage and the voltage of the DLCs are not constant, voltage converters are needed. The voltage may vary between $0V$ and $5.5V$ (maximum output voltage of the solar cell).

The TPS78033022 from Texas Instruments is a linear voltage regulator with a very low quiescent current of only $I_q = 0.5\,\mu A$ [21]. It is very well suited to supply the sensor node with long sleep phases (low power consumption, some microwatts) as we have shown in [22]. Furthermore, the output voltage can be changed be-

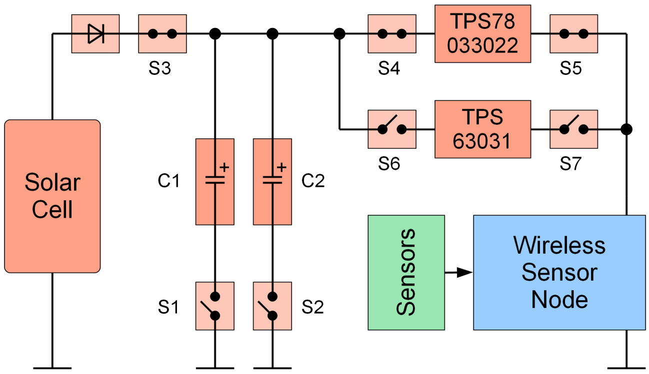

Figure 3: Concept of the energy harvesting enhanced sensor node for lab experimentation.

tween $3.3V$ and $2.2V$. The sensor node can change its own supply voltage if it is supported to save energy. However, the input voltage has to be higher than the output voltage. Therefore, this converter cannot use the full energy storage capacity of the DLCs.

The TPS63031 from Texas Instruments is a buck-boost converter, which provides a constant output voltage of $3.3V$ at an input voltage range from $1.8V$ to $5.5V$ [23]. The maximum quiescent current is $I_q = 50\,\mu A$. The advantage of this converter is the high efficiency over the full input voltage range at output currents greater than $1\,mA$. Therefore, it is better suited for sensor nodes with high activity. Furthermore, the input voltage range is greater than that of the previous voltage converter. Thus, more energy storage capacity can be used.

This structure of the EHS enables a high flexibility by the possibility of changing the hardware configuration during the experiments (S1 to S7). Hence, several different exercise scenarios can be created for the students. They range from proper dimensioning of the energy storage component over the selection of the voltage conversion circuit to the adjustment of low power techniques at the sensor nodes software. Therefore, the sensor node has to be aware of the energy state of the EHS which is enabled by a measurement of the solar voltage and the voltage of the DLCs.

5. WEB ACCESS

A first prototype implementation screenshot of the web access is shown in Figure 4. The students can observe the real-time measurement data of the continuously supplied sensor nodes in the upper left screen. So they can view the power consumption of these nodes and determine different power states. In the lower left screen, the messages of the WSN can be watched. These messages can be used to determine the routing behavior and to get status information of the energy harvesting sensor nodes and ambient light measurements of all sensor nodes. The upper right window shows a live video stream of the measurement setup. In this demonstration setup, two sensor nodes intended for energy harvesting can be watched. Both nodes are illuminated by a virtual sun, the big LED in the top center. Additionally, the right node is illuminated by the event source LED in the top right corner. In the final lab, students will be able to watch the overall lab setup. Real-time control of the WSN can be performed in the lower right screen.

The students can also select the exercise scenario and configure the sensor nodes properly. During this phase, they can switch on and off specific sensor nodes and watch the behavior of the WSN. Furthermore, they can set the ambient light level, the event level, and check the messages of the WSN. After finding the right configuration of the WSN, the students can start a short test phase (about 10 minutes). The configuration of the WSN during this test phase cannot be changed. The results of the test phase can be viewed and checked to optimize the configuration. Finally, if the results match the wanted results, the students have finished the exercise scenario.

6. CONCLUSION

This work presents the concept of an educational remote laboratory for energy harvesting enhanced WSNs. These WSNs are complex systems which are influenced by a lot of different factors, for example ambient light, available energy, and detected events. Students can use this lab to gain experiences with energy harvesting enhanced WSNs. This work lists educational objectives which are an essential part of the subject matter. These objectives can be learned by experimenting online in a performance-centered manner. One of the most important objectives is the energy harvesting enhancement. To be able to provide a wide range of application scenarios, the EHS is in different ways configurable, for example variable energy storage capacity. This ensures a high flexibility in teaching energy harvesting enhanced WSNs.

7. ACKNOWLEDGEMENTS

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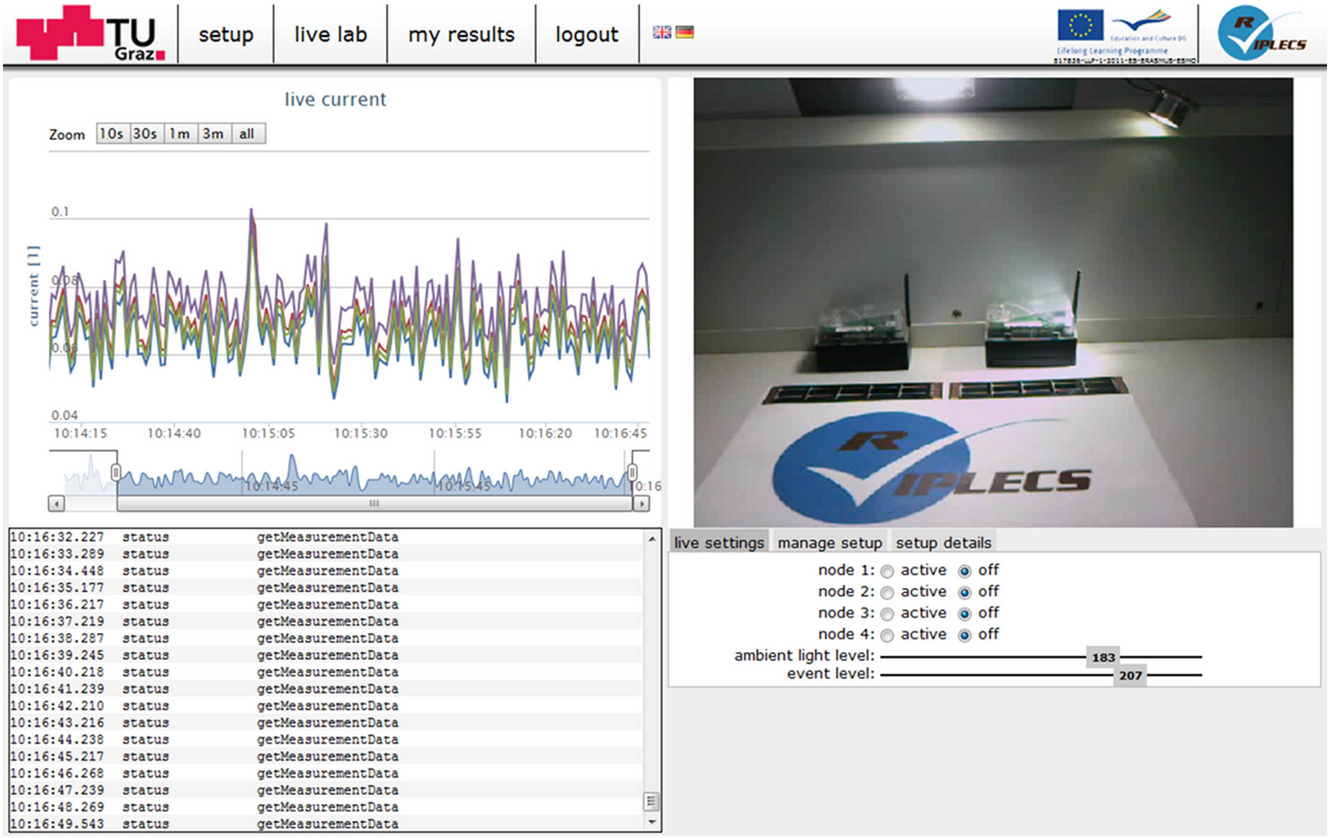

Figure 4: Web access of the remote lab. It shows the real-time measurement data (upper left screen), the WSN messages (lower left screen), the live video of the measurement setup (upper right screen), and the real-time control possibilities (lower right screen).

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