Experiencing Wireless Sensor Network Concepts in an Undergraduate Computer Science Curriculum

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Abstract

Incorporating Embedded Systems courses in a general and broad Computer Science undergraduate curriculum can be a challenging task. The lack of experience with relevant tools and programming languages tends to limit the amount material that can be included in courses on this area. This, combined with limited familiarity and theoretical background within the field, makes motivating the students a serious issue.

In this paper we describe our effort to change one of the embedded systems courses at the University of Twente in a way that enables students, without additional prior knowledge, to obtain a broad experience on the field of Wireless Sensor Networks and possibly motivate them to follow a further specialization in Embedded Systems. To achieve this goal we moved away from the traditional course where students first had to practice with all the tools and languages needed to program embedded systems, after which they could work on the real challenges, to a course where students could work on the final challenges from the start.

Reversing this order eliminated the amount of time and effort students had to spent on learning tools and languages of which they did not yet understand the final purpose. This reversal led to a course that was received with great enthusiasm. Furthermore, given the progress the students showed during the course, this new approach proved to be highly effective. Hopefully the effects of this course can be seen in the following years in the form of a higher number of students choosing a specialization in Embedded Systems.

Categories and Subject Descriptors C.2.1 [*Network Architecture and Design*]: Wireless communication; C.2.4 [*Distributed Systems*]: Distributed applications; K.3.2 [*Computer and Information Science Education*]: Computer science education

General Terms Experimentation, Theory

Keywords Wireless Sensor Networks, Embedded Systems, Education

1. Introduction

With the ongoing integration of Embedded Systems in the everyday environment the demand for engineers schooled in the domain of these systems is ever present. This makes it essential for universities to lay down the foundations for understanding of the field of embedded systems (8). This task is one of the important challenges for Embedded Systems research groups. Personal conversations with new and upcoming Computer Science students indicate that a large fraction of the students enrolling in an university level course only have a vague notion of what the entire field entails and consequently which direction they want to specialize in. Reasons for choosing Computer Science frequently come down to an interest in game development or a general appreciation of computers. For undergraduate students like this Embedded Systems remains an often overlooked direction of specialization.

At the University of Twente, students start their academic education in Computer Science with a three year Bachelor's track. During this track the participating students are prepared for the choice of a subsequent Master's course. To achieve this goal, students follow a combination of fundamental courses on the field of Computer Science and courses on a variety of subjects relevant to the differ-

WESE '09 October 15, 2009, Grenoble, France

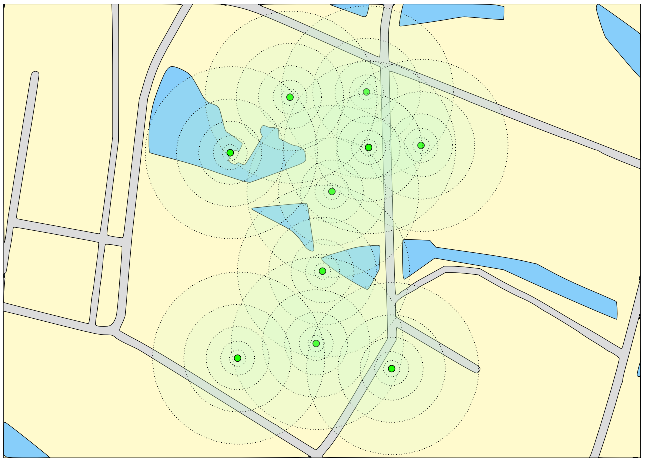

Figure 1. Possible deployment of wireless sensor nodes on campus

ent research groups within the faculty. This second group, contains several courses in the field of Embedded Systems. The knowledge provided by these more specific courses gives students the opportunity to make a well informed decision about their field of interest.

Although the described broad Bachelor's course knows many benefits, it requires additional consideration for Embedded Systems education. Since a broad curriculum usually leans towards general purpose computing (13), the more specialized knowledge generally needed to work with areas like Embedded Systems is absent. In previous years this fact surfaced for a significant part of the students participating in a course on Wireless Sensor Networks (WSNs).

1.1 Wireless Sensor Networks

Wireless Sensor Networks are a fairly recent technology where a large number of small embedded devices is deployed in a common application. These devices, or so called Sensor Nodes, are tiny embedded computers with wireless communication capabilities and a variety of sensors.

The envisioned number of distributed applications for these networks is limitless. Well known examples include environmental monitoring, for example on the great barrier reef where water quality and temperature are checked using a Wireless Sensor Network (9). Applications in logistics, like the monitoring of storage conditions for spoilable goods (11). Structural monitoring, like detecting vibrations and damage to buildings caused by earthquakes (16) and health care applications like computer assisted revalidation of patients (15). The effects of the research in this field hold the promise to have a major impact on society in the upcoming years.

Important considerations and challenges in WSN research are, among others:

- Resource constraints due to energy efficiency.
- Aspects of wireless communication and networking.
- Collaboration between different nodes in order to run a distributed application.

Due to these points, education in Wireless Sensor Networks is closely related to education in Embedded Systems in general. Aspects of Wireless Sensor Networks include distribution, hardware/software co-design, signal processing, real-time issues and decision making with incomplete information. As such this course can be an invaluable base for further education and specialization in the field of Embedded Systems.

1.2 Goals of the course

The aforementioned course has been part of the Bachelor's curriculum for several years. It is an eight week course that rewards the students with five European Credits upon successful completion. In the previous years the course aimed to educate students on:

- C programming.
- Simulation.
- Topology finding in WSNs.

Since active learning is one of the ways to achieve better results from a course (10), this course contained assignments where students could apply their knowledge in practical experiments. During these experiments well known software like OmNet++ (4), TinyOS (6) and AmbientRT (12) was introduced to the students.

Although this software provides a very realistic experience within the field of WSNs and Embedded Systems, minimal experience with C programming, Embedded Systems and wireless communication proved to be an insurmountable obstacle for students with no prior interest in Embedded Systems. The learning curve is too steep for an eight week course.

This led to a situation where a significant portion of the time available for this course was spent educating these students to actually be able to use the programming environment and simulation software needed for the assignments. The time spent in this initial phase was so disproportionate that these students lacked the time to apply their new skills to finish the real assignments. This resulted in a general experience of low efficiency and consequently led to an assessment of the course that was below our standards.

Although we do feel that understanding languages and tools like these is valuable for many students, it is hard to motivate students to learn this material before they know what they can use these tools for. Based on this acquired experience, it was decided to formulate new goals for this course.

In previous years, the focus of the course was divided among a single topic of WSNs, the programming environment and simulation tools. This year, we aimed to teach the students about topics covering a wide spectrum of WSN related aspects. By giving the students a taste of topics ranging from very low hardware access on wireless sensor nodes up to the higher level of distributed applications on a WSN we hope to provide a complete overview of what working with these networks means.

To the point we aimed to provide students with information on the following topics:

- Low level hardware access.
- Resource constraints.
- Wireless communication and networking.
- Collaboration between nodes in a distributed application.

Furthermore we wanted to give students experience in conducting research in groups and the writing of scientific reports.

Providing students with this knowledge however, is of limited use if they will never make use of it in their further education or career. Therefore, another goal is to give the students a meaningful and inspiring experience with Embedded Systems on which they can decide if a further specialization in this direction might be a serious option.

The new approach to achieve these goals, and experiences we had in the first year using this approach, are described in the remainder of this paper. Section 2 describes the new approach, followed by Sections 3, 4 and 5 describing the resulting organization of the course. Finally this paper is concluded by Sections 6 and 7 explaining our experiences of the first year with the new organization and our conclusion.

2. Approach

As stated in Section 1.2 we aimed to create a course on WSNs that provides meaningful insight in the subject. The limited experience of the students on related topics made including lectures in the course a logical option: Without at least a small introduction into the terms used in a field it is hard to talk and reason about it.

Learning efficiency however, benefits from practical experience (10). By performing real life experiments the students encounter real challenges and a more fundamental understanding than by just obtaining knowledge from hearsay. Furthermore, programming real devices gives students a possibly exciting and new experience demonstrating the possibilities of embedded systems.

With this in mind we decided that the course should contain a theoretical element in the form of lectures on various subjects covering aspects from the low hardware layers up to the high application layers. We decided to schedule lab hours immediately after the lectures so the students could quickly apply their new knowledge in practical experiments.

In previous years, enabling students to perform practical experiments on WSNs proved to be a complex task, even when only one aspect of WSNs was covered. Therefore, an implication of the goal to cover a wide range of WSN topics is that we need to significantly reduce the amount of time spent on the struggle to use the tools. It is our firm believe that learning to work with the real tools for embedded systems in a later stage becomes an easier task if the students have had the opportunity to see the challenges and work with them beforehand. With this in mind we decided to look for hardware with a more accessible working environment.

Furthermore, we tried to make all the practical experiments motivating and entertaining without compromising the educational value. To achieve this goal we paid special attention to the visibility of the results. This will be described in further detail in Section 5. We also tried to motive the students by including an element of competition in the form of a final challenge. The students had to demonstrate the effectiveness of their solution to a given problem during an organized event. To prevent this competition from limiting the cooperation between the students, which is undesirable (10), we opted for a challenge to achieve a difficult objective. A competition where the objective is to win from other students would prevent cooperation and as a result limit the shared learning experience.

The results of the cooperation were not included in the final grade, the day of the competition was solely meant as an informal conclusion to the course that improved the familiarity of the students with our Embedded Systems research group.

A final noteworthy aspect of our approach is the gradual increase of creative freedom we have incorporated in the exercises. The first couple of exercises are written in a rather strict way. They contained clear tasks for the students, with strict guidelines on what to do and how to do it. In this phase the necessary skills with the programming environment were obtained so that in the later exercises the students could work on creative solutions without being hindered by an unfamiliar programming environment. These later assignments allowed for more creativity and independent thinking. In the final assignment the students were left completely free in their approach of a complete research task.

3. Lectures

During the course five lectures were given on the following topics: Introduction to Wireless Sensor Networks, the MAC and PHY layer, Routing and Network Topology, Time Synchronization and finally Localization. These lectures on average were rather short, about 1 hour each and were mainly used as a small introduction in the concepts. In order to motivate the students to keep visiting the lectures we included material that could be applied in the immediately following lab hours.

The first lecture introduced the field of Wireless Sensor Networks with demonstrations of real life applications and a Master's project on a relevant subject (7) finished at our university. This method of introduction is in line with our vision that to motivate students it is essential to first show them how their future knowledge can be applied.

The subsequent lectures provided the students with more theoretical knowledge that could be used as a foundation for the practical assignments. Examples include algorithms like Ecolocation for localization (17) and Dynamic Source Routing (14) as a routing protocol.

It is our believe that the used topics provide a good overview of WSN technology and therefore help to achieve our stated educational goals.

4. Environment

To enable the students to do practical experiments we needed to decide on which lab equipment and software we should provide. As stated in Section 2 it was essential to have an accessible environment allowing the students to do meaningful experiments with a significantly reduced start-up time. Given the limited experience in C programming and the fact that the students had already followed several courses on Java programming, we opted to let the students work with Sun™ SPOT Development kits (5). These kits contain Java programmable wireless sensor nodes. Although these nodes include a CPU that is uncharacteristically fast for WSN applications, they provide easy access to low level hardware, for example the SPI bus and the CC2420 radio chip (1). The radio is similar to radio's used in regular Sensor Nodes so realistic research on communication challenges can be conducted with this hardware. Furthermore, these nodes contain an interesting variety of sensors that can be used in experiments. By default a Sun™ SPOT has a temperature sensor, a light sensor and a 3D accelerometer.

In our lab the students, working in groups of two, had access to computers running Linux. Linux was chosen for several reasons, the main two being better driver support and easier access to the virtual serial ports used by the Sun™ SPOTs both in comparison to the other OS running on the lab systems. On these computers the students had access to

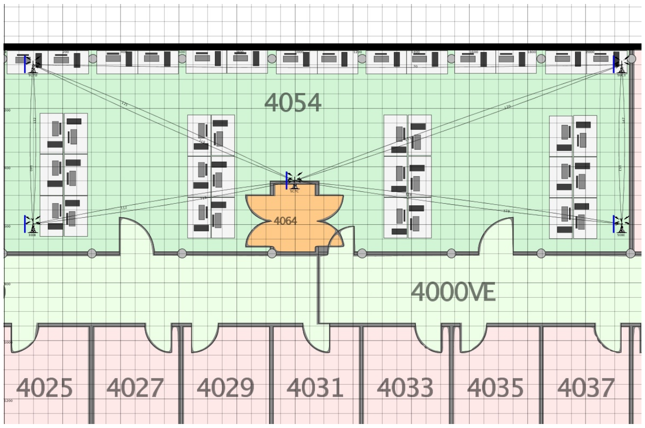

Figure 2. Map of the infrastructure in the laboratory

the NetBeans IDE (3) and a library we developed in order to assist the students in their experiments. We will explain more on the way this library was used in Section 5.

Sun™ has developed plugins for NetBeans to assist in developing software for Sun™ SPOTs. In total the combination of Sun™ SPOTs, Linux and NetBeans is a very accessible package that can be used by second year Bachelor's students.

Apart from the programming environment several topics covered in the assignments required the availability of an infrastructure network. For assignments on topology finding for example it is valuable to have infrastructure nodes present that are always available. To create this infrastructure network we attached several Sun™ SPOTs to the main power using USB chargers. These nodes were programmed to perform the tasks needed for the individual assignments. Five infrastructure nodes proved to be sufficient for 58 students working in groups of two. Figure 2 shows a map of the provided infrastructure.

5. Assignments

As described in Section 2 we opted to ease the learning curve for students by starting out with a number of smaller, more defined, assignments, followed by a larger research task. This Section describes these assignments including the incorporated methods to make the results visible and the assignments motivating.

5.1 Introduction

The first assignment was mainly an introduction in the environment. We let the students complete an online course (2) and let them do three small experiments with the sensors. The online course is written in an accessible way and contains a large amount of valuable information on what exactly the Sun™ SPOTs are and how to program them.

The experiments with the sensors required the students to plot graphs of the light and temperature sensors included in the Sun™ SPOTs and to write a simple game with the accelerometer. Especially this last experiment was met with great enthusiasm and provided the necessary motivation to quickly complete the preceding tasks.

During this first assignment students gathered experience with the programming environment and the used libraries. Essential basics like uploading custom software to the Sun™ SPOTs and serial communication with the devices were introduced in an isolated and clear manner, thus forming a foundation for the upcoming assignments.

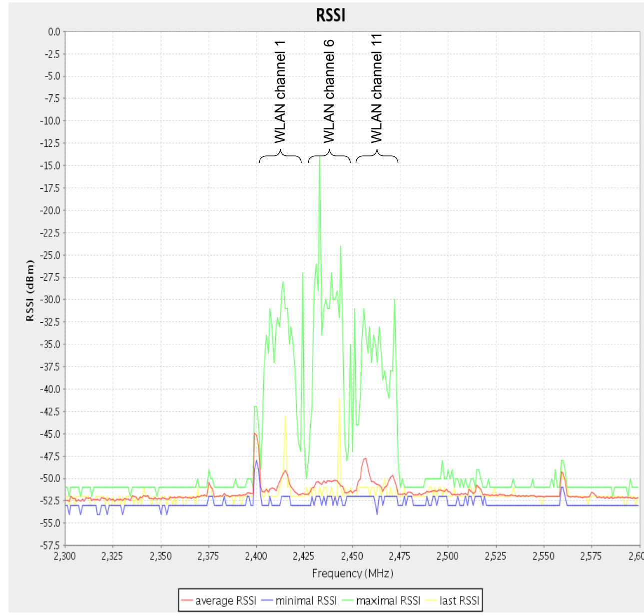

Figure 3. RSSI scan with visible WLAN channels

5.2 MAC and PHY layer

Since wireless networking and collaboration between nodes is essential for the concept of a wireless network, a firm understanding of the behavior of wireless links is of paramount importance. Without these links there is no wireless sensor network.

With this in mind we decided to let the students do experiments on communication between different Sun™ SPOTs and on the lower communication layers in the second assignment. This assignment started with some small tasks like collecting data on packetloss vs. distance, but quickly continued with more complex challenges using low level access to the radio hardware.

By letting the students read the datasheet of the CC2420 radio (1) and giving them example code from the Sun™ SPOT drivers, we let them make a frequency scanner. To complete this task students had to find registers in the datasheet and read RSSI values from these registers on the radio chip.

The results of this assignment demonstrated the interference between WLAN and 802.15.4 communication. Figure 3 shows what the students could expect to find. A graph like this gives a more intuitive demonstration of the effects than just looking at packet loss etc. The code to display the graph was included in the library we developed. This allowed the students to focus on the radio hardware instead of wasting time on the, for this course, irrelevant task of GUI design.

This assignment allowed students to gather experience with the same low level hardware access used in the previous years. The accessibility from a high level programming language and programming environment however reduced the complexity of this, for the students, new area.

5.3 Routing and topology

The MAC and the PHY layer cover only a part of the wireless links used in a WSN. Understanding of the complete

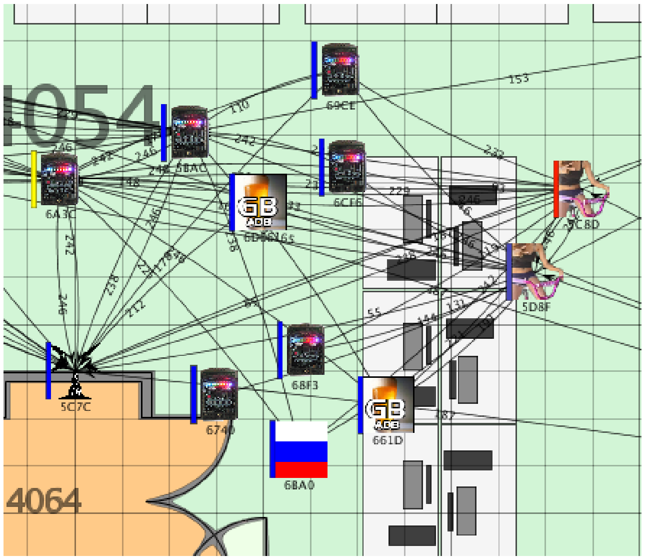

Figure 4. Subsection of the network topology GUI

topology of a WSN and aspects such as routing forms another important aspect of the challenge of communication. The assignments continued, in parallel with the lectures, with an assignment on topology finding and routing protocols.

The first task in this assignment was the design and implementation of an application running on a Sun™ SPOT that, in collaboration with our provided infrastructure, could find the complete network topology.

We provided the students with the message format and behavior of the infrastructure nodes on which they could base their design. Using service discovery techniques and periodic broadcasts the application could gather the required data.

In order to give the students insight in the network structure, we asked them to create a visualization of the network topology. To assist them in this task they were provided with a GUI capable of drawing a graph of the network.

We added an accessible element to the subject by the addition of personalized icons for the different network nodes. Each group could send us an image file which we stored in a database. By coupling this database with our administration keeping track of which group was using which nodes we could render each node with the icon of the using group.

So even though each group developed their own topology application, by using the provided GUI they were all able to see the personalized icons. The effectiveness of this small feature could clearly be noticed when the first group reached the point where a custom icon was visible in the network. Other groups soon noticed this and quickly send us their icons and put extra effort in getting their application to work.

By making the nodes used by groups recognizable, nodes sending erroneous information where quickly identified by other groups after which the group with the malfunctioning nodes could be informed of this fact. This greatly improved collaboration between the groups which leads to more effective learning (10).

A second part of the assignment asked the students to reason about the effects of blacklisting unreliable links in a WSN. For this task they could use the data found in the first part of the assignment.

5.4 Synchronization

The last of the smaller assignments involved designing and testing time synchronization algorithms. Time synchronization fitted the new goals of this course perfectly. Topics covered by this assignment include resource constraints, wireless communication and collaboration in a distributed task.

The students were required to make the effectiveness of their algorithms visible by making groups of Sun™ SPOTs blink their LEDs in sync. The students were free in their design, although we put some restrictions on their work-flow and made some functional requirements. We required for example that they started with a design that needed to be approved, before they commenced the implementation phase of the assignment. Furthermore we specified what should happen in case of a node leaving the network and restricted the amount of communication that was acceptable.

The visibility of the effectiveness of the designed algorithms made the students very appreciative of this assignment. Various groups put a real effort in visual effects with the 8 RGB LEDs present on the Sun™ SPOTs. Although this, of course, is not of any functional significance it helped to motivate groups to design a functioning algorithm.

Several of the groups asked to borrow more Sun™ SPOTs than we normally allowed in order to test the effectiveness of their algorithm in the presence of bigger networks. Since this was no part of the original assignment this clearly demonstrated the fact that the students were motivated and inspired beyond the objective of just passing the course.

5.5 Final project: Distance tracking

After having finished these first assignments the groups were asked to conduct a research leading to a distance measurement system for a walking person. We organized a final event were each group could attach several Sun™ SPOTs to a test person (in this case a member of the group) and the nodes had to report the walked distance. This distance could be derived from any combination of the available sensors on the Sun™ SPOT and from using the radio with an infrastructure network we provided. Upon a set distance, fifty meters during the final event, the Sun™ SPOTs should indicate that the person had to stop walking. If the given location was within arms reach of the location indicated by the Sun™ SPOT the students had achieved the goal.

The provided infrastructure periodically broadcasted messages including RSSI readings of all neighbor nodes in communication reach. The information in these messages combined with the RSSI readings of these messages could be used as an input to the localization algorithms introduced in the fifth lecture or some of the custom localization algorithms introduced by the groups.

The accuracy in the final event did not count for their final grade, this grade was solely based on a written report each group had to make. This report had to describe their experiments and research in a scientific way. The motivation provided by the drive to succeed at the final event however, led to a great collaborative effort in finding ways to measure the required distance. During several weeks students were doing experiments. Even outside the scheduled hours students were doing research and could be seen walking along measuring tape in the halls of the faculty.

Figure 5. In the middle a student that finished close to the goal, on the foreground an infrastructure node, on the background the rest of the students.

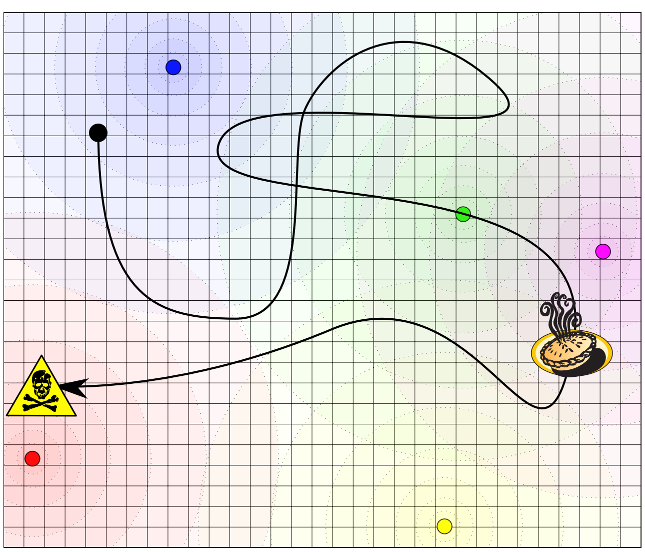

Figure 6. Image used in the description of the final assignment

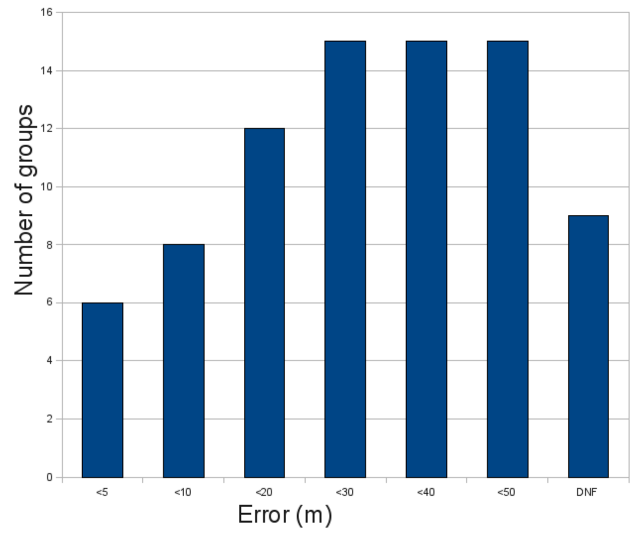

Figure 7. Results during the final challenge

Some of the more creative solutions included the implementation of a pedometer using RSSI readings between Sun™ SPOTs attached to the left and the right foot and the enhancement of the accuracy of a localization algorithm using a high hat that kept a clear line of sight to the infrastructure.

All of the groups investigated multiple possible solutions to the challenge which required them to think about communication issues, resource constraints due to complex algorithms and distributed reasoning. Even though not all the results during the final event were very exact (see Figure 7) the written reports show sufficient understanding of the material. A couple of the solutions showed such accurate results that they will lead to further investigation.

6. Experiences and future changes

After the first year with the new setup we have noticed some factors requiring small changes in the course. The main change needs to be in the programming environment. Although the combination of Linux and NetBeans was very promising and worked sufficiently, there were some driver related problems. The Sun™ SPOT SDK uses some libraries to enable Java to communicate with the serial ports and these libraries proved to be very sensitive to different versions of drivers and libraries. Since systems in our laboratory are used for a large variety of courses there is no complete control on all the software that is running on these systems. This posed some time consuming challenges for the people supervising the assignments and some minor problems for the students.

Although there were quick workarounds for all the problems with the lab systems the small delays experienced by the students led to some justified complaints in the beginning. Based on this we have decided to look into the possibility of running the lab environment in a virtual machine. If this proves to be a viable option we would have complete control over the used drivers and could extensively test the systems before the students start to work on them.

Figure 8. Student walking along the track with a Sun™ SPOT attached to his arm

7. Conclusion

Our preliminary conclusion after the first time this course is given is that the new setup is very successful. All students were able to complete the assignments, which clearly shows that the set educational goals were achieved. All students were able to apply their new knowledge in practical experiments and were able to do scientific research on a related subject in the final project. Their report writing skills improved with each assignment and these written reports showed clear understanding of a broad spectrum of the elements of Wireless Sensor Networks we aimed to teach. For Bachelor's students in their second year this is a satisfying result.

A clear indication of the enthusiasm with which the course was met, was the fact that the students increasingly spent time on the course, even outside the scheduled hours. For the final project the students could be seen conducting experiments in the faculty hall almost each day, not because they were short on time, but because they were motivated to achieve the best results.

Already, some of the students showed interest in additional projects in the area of Embedded Systems. Although only long term trends can show the final effects, we await these numbers with confidence. If we can repeat the success of this year we expect a rise in students following a Master's course in Embedded Systems.

Acknowledgments

I would like to use this opportunity to thank all the people involved in the creation of this course: Hans Scholten and Nirvana Meratnia for their cooperation in the initial planning of the course, Stephan Bosch, Berend Jan van der Zwaag and Thijs Mutter for their assistance during the practical sessions.

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