Teaching Wireless Networking Technologies in the Internet-of-Things Using ARM based Microcontrollers

Nannan He[1], Rajeev Bukralia[2] and Han-way Huang[1]
[1]Dept. of Electrical and Computer Engineering Technology, Minnesota State University at Mankato
[2]Dept. of Computer Information Science, Minnesota State University at Mankato
nannan.he@mnsu.edu , rajeev.bukralia@mnsu.edu and han-way.huang@mnsu.edu

***Abstract*— This paper presents the ongoing work of applying the project-based learning approach to teaching IoT technologies in an advanced embedded networking course, which is offered to electrical and computer engineering students. The emphasis of this course is on teaching the prominent wireless networking technologies IEEE 802.11 (WiFi) for the IoT and the development of the IoT applications. Microcontrollers have been used to teach fieldbus networks or distributed real-time control systems. However, conventional efforts of teaching regular computer networks (e.g., the Ethernet) mostly make use of either personal computers (e.g., desktop, laptop) or single board computers installed with Linux or Windows operating system. The unique feature of this ongoing work is to use existing ARM-based microcontrollers without complex operating systems to teach wired and wireless network technologies in the IoT. Our primary experiences indicate that ARM-based microcontrollers with networking connectivity provide the flexible, cost-effective, well-supported platforms for developing the IoT applications.**

***Keywords*— Internet of Things; Wi-Fi; microcontroller**

I. Introduction

An industry survey shows that the consistently increasing number of new embedded designs (i.e. ~60% by 2014) include networking capabilities [1]. As IPv4 is giving way to IPv6, every device on the Internet can have its own unique IP address. The number of connected devices is predicted to surpass 50 billion by 2020 [2]. Technically speaking, the Internet of Things (IoT) is the interconnection of uniquely identifiable embedded computing devices within the Internet infrastructure to provide the remote monitoring or control services.

The dramatic development of the IoT is mainly based on the advances in microelectronics, communications and information technology. To be specific, microcontrollers, communication modules and other electronic components are being increasingly integrated into one device referred to "Things", due to their decreasing size, falling price and reduced power consumption. Thus, such "smart" devices being computerized typically have not only sensory and actuator capabilities to sense and manipulate the environment, but also have the networking connectivity to communicate with each other, access Internet services and interact with people [3]. The IoT has the significant potential to transform how we live and work, while also deliver intelligent industrial applications like a smart grid to enable more connectivity throughout end consumers, power grid infrastructure and utility providers. As the IoT grows rapidly in industry, there is a great education need to equip students the basic knowledge of the IoT technologies so that they are capable of developing basic IoT applications and more marketable.

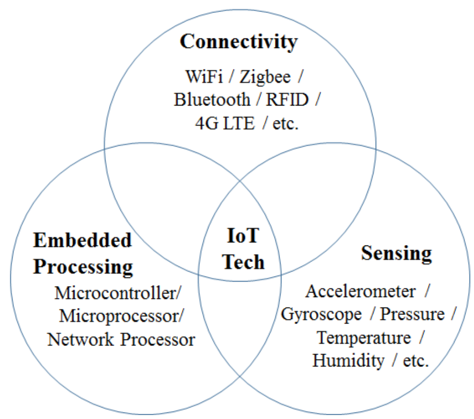

Figure 1. Three fundamental blocks of IoT Technology

The IoT enabling *technologies* are categorized under the three fundamental building blocks which are the sensing, embedded processing and connectivity as shown in Figure 1. Popular networking technologies for the connectivity are WiFi, Zigbee, Bluetooth and the cellular networks like the 4G LTE. And a wide range of sensing devices is used in the IoT such as gyro and accelerometer sensors for the motion tracking, temperature, humidity and light sensors for the environment monitoring, etc. To develop any IoT applications in practice, a *software development environment* is usually required, which ties the applications, sensing, users inputs, control, network processing and the security of each IoT device with the entire system [4]. As the importance of the software portion in the modern embedded systems especially the IoT has increased, more software and utility tools, device drivers are needed.

Our Advanced Embedded Networking course presented in this paper are offered to the electrical and computer engineering students at the senior level. Project-based learning (PBL) was chosen as the main learning paradigm and implemented to teach the widely used networking techniques in the IoT. The learning outcomes are created using Bloom's

Taxonomy, which provides a framework for aligning learning objectives with the level of cognitive complexity. This alignment is essential for ensuring that each course project is created and evaluated for pedagogical effectiveness. The following are the Bloom's Taxonomy levels in order of increasing complexity: *remember, understand, apply, analyze, evaluate, and create*. [22] The class projects emphasize different levels, including the higher *apply* and *create* levels, to build on conceptual knowledge imparted in the course. Each project is designed to present a realistic problem derived from actual engineering practice. In fact, the development boards, network-related hardware extensions and associated software packages used in this course are directly from the industry. To be specific, Atmel SAM D21 Xplained Pro kit (~$40) with a WiFi extension called WINC1500 has been employed. The extension is shown in the left side of Figure 2 (~$60) which builds on a single-band 2.4GHz IEEE 802.11 b/g/n network controller. The Texas Instruments'(TI) Launchpad EK-TMC1294XL (~$20) which includes a 32-bit ARM microcontroller integrated with 10/100 Ethernet MAC and PHY is also used to introduce basic IoT applications. These projects are organized into two phases. In phase I, students are required to conduct the basic projects of programming microcontrollers to control the networking devices. Each project covers some specific key concepts of the WiFi protocol, such as setting basic modes of a WiFi device - Access Point and Station. In phase II, the projects on programming common sensors in the IoT. Then, students develop some complete IoT application projects, which integrate the web development, sensors reading, embedded processing with wired or wireless networking connections.

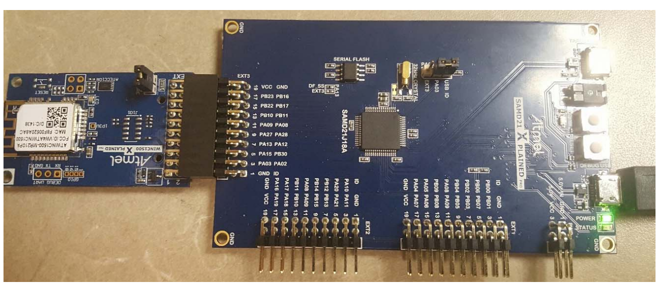

Figure 2. Atmel SAM D21 Xplained Pro with WINC 1500 WiFi extension

A. Related work

Recently, the pure lecture-mode approaches to teaching network technologies have been complemented or partially replaced by developing a network lab and a set of engaging laboratory exercises [5-7]. Some previous experiences of teaching networking techniques to science and engineering students have been surveyed, especially. In [5], to reinforce the theoretical networking topics to computer science students, authors designed networking laboratory exercises based on the ubiquitous Bluetooth wireless communications technology by means of active learning. In [6], authors presented a special topic course in mobile and wireless networks (i.e. IEEE 802.11) for the computer information technology major students by use of hands-on lab activities. Their results showed that students got ample opportunities to understand the underlying principles and concepts of wireless networks via hands-on labs. The paper [7] presents an application of project-based learning (PBL) paradigm to help electrical engineering students grasp the major concepts of Fieldbus networks.

In comparison, our work described in this paper also applied the PBL approach to designing hands-on lab projects for teaching major wired and wireless Local Area Networking (LAN) techniques. However, as our objective is to teach these techniques in the context of the IoT to electrical and computer engineering students, we make use of microcontrollers, network drivers, and various sensors and actuators to develop lab projects instead of using computers installed with full-feature operating systems. Authors in [8] developed a portable and reusable embedded software labware with hands-on labs in a relatively inexpensive box. The ultimate goal of our work is also to integrate the low-cost and portable microcontrollers, open-source device drivers, software tools and a set of lab exercises and lectures into a package to help schools that lack dedicated instructors with expertise in the IoT networking technologies. Authors in [9] presented their experience and evaluation of offering an integrated curriculum for the IoT to graduate students. Our work is mostly related to it, but has two distinct differences. Firstly, we taught the Ethernet and WiFi in detail, but they focused on different networking technologies such as Zigbee (IEEE 802.15.4) and 6LoWPAN instead. Secondly, students use the C language to develop basic IoT applications on two ARM Cortex-M microcontroller boards in our work. But an object-functional language *Scala* was chosen for developing IoT applications and it is not clear of the specific hardware platform applied in [9]. Finally, the work reported in this paper is based on our previous experience [10] but with the significant addition of teaching WiFi by the use of Atmel WINC 1500 board.

II. ADVANCED EMBEDDED NETWORKING COURSE

This section first presents student outcomes, course topics of this course. Then, a series of projects designed is reported. This course is organized as 3 hours of lecture and 2 hours of lab per week. The student outcomes are given in Table 1.

Table 1. Student outcomes

Student outcomes
O1. Can demonstrate the awareness of the origin and current status of the IoT in the industry and its major technology challenges.
O2. Can comprehend the common sensing techniques used in the IoT and the wired or wireless communication protocols for the IoT networking (i.e., HTTP, TCP/IPv4/IPv6/WiFi/Ethernet)
O3. Can develop basic IoT applications by using software tools to program microcontrollers, sensors, wired / wireless networking devices.

Guided by the student outcomes, the topics covered in this course as shown in Table 2 were prepared to achieve them. The outcome(s) associated with the weekly course topics are also indicated in the Table. Course materials have been derived from various resources, such as textbooks [11-14], industrial white papers [2, 4, 15-16], research papers [17-18], Code Composer Studio (CCS) and TivaWare software from TI, Atmel Studio and Atmel Software Framework (ASF) library from Atmel and industrial workshops [19-20].

Table 2. Week-by-week course topics details

week	Topics
1	Origin and evolution of the IoT; Multidiscipline technology challenges of the IoT development. (O1)
2	Basic electronic principles of common sensor technologies in the IoT; Sensors reading by programming microcontrollers. (O2 and O3)
3	Overview of application layer protocols (i.e., HTTP, WWW, DHCP) (O2)
4	Overview of transport layer protocols (i.e., TCP and UDP) (O2)
5	Overview of network layer protocols (i.e., IPv4 and IPv6) (O2)
6 - 7	Ethernet technologies (i.e., IEEE 802.3 MAC and physical layer standards, addressing, frame format, CSMA/CD architecture); switches (i.e., repeater/hubs; bridges, routers) (O2)
8-9	Overview of wireless networks for the IoT; wireless LAN (IEEE802.11 or WiFi) topologies; standards; network operations; mobility supports (O2)
10	Overview of wireless LAN transmission media; physical layer methods of IEEE 802.11b/a/g/n standards (i.e., high-rate direct sequence spread spectrum-HRDSSS, orthogonal frequency division multiplexing-OFDM, etc.) (O2)
11-12	IEEE 802.11 MAC layer fundamentals (i.e., challenges, MAC access modes and timing, contention-based access and data services using distributed coordination function; fragmentation and reassembly) (O2)
13	IEEE 802.11 MAC frame types (i.e., data, management and control) and their formats (O2)
14	IEEE 802.11 security fundamentals (i.e. authentication, WEP encryption and decryption); user authentication with 802.1x and 802.11i (i.e., TKIP and CCMP) (O2 and O3)
15	Practical issues of designing IoT projects (i.e., security, mobility, etc.) (O2 and O3)

Students are required to complete a series of projects by using two hardware boards respectively as shown in Table 3. The topics associated with each project are also listed in the table. The first three projects are based on the TI Launchpad EK-TMC1294X for developing Ethernet-based IoT applications step by step. Project 1 and 2 belongs to Phase I while the project 3 is Phase II. Students finish the project 1 so as to start with software development tools to develop basic sensing and embedded processing applications on the selected hardware platform. Project 2 serves the purposes of practicing the networking knowledge covered from week 3 to 5. Then, students are required to complete project 3 by use of a SensorHub BoosterPack which includes a variety of sensors such as temperature, humidity etc. and can be easily plugged to one of two Launchpad's boosterpack connection sites as shown in Figure 2(a). The MCU is interfaced with the SensorHub via the serial I2C interface.

Project 4 to 7 are all based on another hardware board SAM D21 and WINC 1500 WiFi extension from Atmel and build on each other. Project 4 to 6 are Phase I and each corresponds to one aspect of WiFi technology covered in the course. Afterwards, students are required to complete the project 7 in Phase II to develop a WiFi based IoT application. The capacitive touch devices have been employed to precisely obtain the users' inputs whose status can be monitored remotely from a smart phone APP. Finally, students should conduct a research survey and present their results in the class to the whole class so as to further encourage the student-centered learning.

Table 3. Course Projects and Their Learning Outcomes

Project Description	Learning outcomes
1. Design a software project in the CCS to program the microcontroller (MCU) to read sensor data from the SensorHub and generate output signals to control servo motors. (Week 2 topics)	- Create, build and debug MCU projects in the CCS; - Use TivaWare software libraries to program the MCU on the Launchpad to interface with the SensorHub.
2. Design a software project to set up an HTTP server from the MCU and program scripts to send HTTP request to the MCU and return the MCU response to the browser (Week 3-5 topics)	- Apply the open source software lwIP TCP/IP stack to construct an HTTP server from the MCU flash and edit the dynamic web page using HTML/Java script or CGI/SSI;
3. Develop an IoT application by using Ethernet as the networking connectivity to display readings of the SensorHub connected with the MCU and receive commands from the user to control actuators (i.e. electric fan). (week 3-7 topics)	- Apply software tools and libraries to tying together sensors, MCU and Ethernet connection for constructing IoT applications.
4. Develop a software project in Atmel Studio to program three basic operations of the WiFi device. (i.e. reading MAC address, configuring station mode and access point mode) (week 8-9 topics)	- Create, build and debug projects in the Atmel Studio; - Use ASF libraries for the WINC1500 WiFi device to configure and control its working modes.
5. Develop an MCU project to scan available wireless network services in the neighborhood and display their parameters (i.e., service identifier, security type and signal strength, etc.) (week 10-12)	- Apply software tools to program the MCU to control and configure the WiFi device attached.
6. Develop an MCU project to monitor the frames received and transmitted at the WiFi device and perform HTTP provision. (week 13-14)	- Apply software tools to program the MCU to monitor the real-time behavior of the WiFi device at the frame level and configure its association from the HTTP webpage at the smart phone.
7. Develop an IoT application by using WiFi as the networking connectivity to display the readings of the sensor device and receive users' request to control actuators. (week 13-15)	- Apply software tools and libraries to tying together sensors, MCU and WiFi connection for constructing IoT applications.
8. Conduct a research survey project of one wireless technology in the IoT (i.e. WiMAX, 3G or 4G cellular networks, Bluetooth, Zigbee, etc.)	- Develop the capability of studying a new networking technology and analyze the strengths and weakness of different technologies.

The web interface of an example IoT capstone project completed by students is shown in Figure 3. More details about this project can be found in [21].

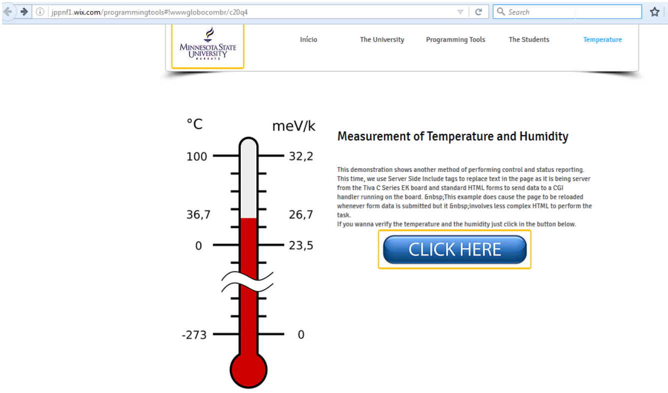

Figure 3. Example project

III. Evaluations

The course evaluations have been conducted to formally assess the teaching effectiveness of the networking technologies used in the IoT at the end of the semester. This course has been taught in two years, around 25 students each year. Furthermore, the graded projects, assignments and survey report and presentation have also been used to indirectly evaluate the effectiveness. Most students commented that the course projects provide the timely help on their learning of key networking concepts in the course. Results indicating that the level of understanding and applying networking technologies in the IoT and instructor's help in two courses are presented in Figure 4. According to the results of exams and course projects, all three student outcomes have been achieved, especially the application related outcome Q3.

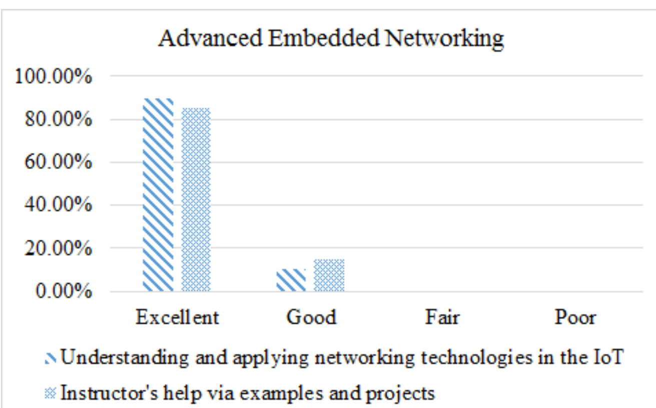

Figure 4. Students' assessment

IV. Conclusion & Future Work

This paper presents our experiences of applying the PBL approach to teaching electrical and computer engineering students the networking techniques including the wired and wireless networking in the Advanced Embedded Networking course. The course materials are derived from various resources from both industry and academy. The student outcomes, course topics, and projects design in this course have been reported. In the future, we will develop new course projects to teach Bluetooth and Zigbee using microcontrollers for the IoT applications.

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