Teaching the Internet of Things with BLE and Zephyr

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Abstract

The Internet of Things (IoT) is an increasingly integral part of modern technology, which students should have the chance to study at university. This paper presents the design and implementation of a university course on IoT and wireless networks. The course combines interactive lectures on theoretical concepts with hands-on laboratory exercises and a project component. We detail the recent evolution of the labs to focus on Bluetooth Low Energy (BLE) and the Zephyr real-time operating system, a shift designed to align with current industry and research trends. Through a combination of problem-based learning in the labs and inquiry-based learning for the projects, students develop practical skills in building and evaluating low-power wireless IoT systems. An analysis of student feedback and performance indicates that while the hands-on approach is highly valued and effective in fostering engagement, the associated workload presents a considerable challenge. This paper concludes with a reflection on the lessons learned and outlines future improvements to better balance the course's demands with its learning objectives.

CCS Concepts

• **Social and professional topics** → **Computing education**; • **Networks** → *Sensor networks*; *Cyber-physical networks*; *Network protocols*.

Keywords

Education, University Course, IoT, BLE, Zephyr

1 Introduction

The Internet of Things (IoT) forms a significant and rapidly growing class of interconnected devices. With billions of devices already deployed [14] and the continued expansion, the ability to design and build IoT systems is an essential skill for the next generation of computer scientists. The field of IoT is vast, encompassing a wide array of hardware, from resource-constrained microcontrollers to powerful edge devices, alongside a diverse set of communication technologies, including short-range protocols like Bluetooth Low Energy (BLE) and WiFi, as well as long-range protocols like LoRaWAN and NB-IoT. This technological diversity, alongside numerous software stacks and operating systems, presents a challenge to educators seeking to design a comprehensive and relevant curriculum.

Our course, "Internet of Things & Wireless Networks," addresses this challenge by focusing on low-power wireless networking for microcontroller-based devices. The course is structured to provide a deep understanding of both the theoretical foundations and practical applications of IoT technologies. It combines traditional lectures with lab exercises and a student project. This blended approach enables students not only to acquire technical knowledge but also to gain hands-on experience building IoT solutions, deepening their practical skills.

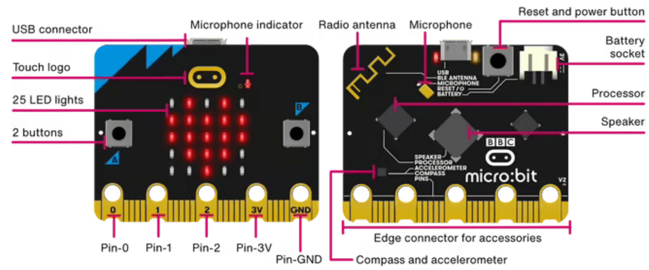

Figure 1: We use the micro:bit v2 as hardware platform for this course. Figure by Micro:bit Educational Foundation, CC BY-SA 4.0, taken from [5].

This paper presents the design and structure of this course, its learning objectives, and the pedagogical strategies employed. We provide a detailed outline of the curriculum, with a particular focus on the hands-on labs[1] that have been updated to emphasize Bluetooth Low Energy (BLE) and the Zephyr operating system [17] to reflect current trends in the field of low-power IoT. We discuss the student-driven projects and provide examples showcasing the practical learning outcomes of our course. Furthermore, we evaluate the course's effectiveness through student feedback and conclude with a reflection on the lessons learned and a discussion of planned revisions for future iterations of the course.

The remainder of this paper is organized as follows. Section 2 describes the core concepts and goals of our course. Following this, Section 3 provides a detailed examination of the course's structure, including the lectures, labs, and project work. In Section 4, we analyze the students' perception and evaluation of the course based on their feedback. Building on this analysis, Section 5 presents our reflections and outlines future improvements. Finally, Section 6 concludes the paper.

2 Course Concept

The course is based on a combination of three components: *lectures*, *labs*, and *projects*. Each component is designed with a distinct focus to create a multifaceted and in-depth learning experience.

- **Lectures** form the theoretical backbone of the course, providing in-depth discussions on wireless communication and networking for the IoT and presenting various solutions tailored for low-power devices.
- **Labs** are designed to provide students with hands-on experience, specifically focusing on BLE communication. These

[1]Lab materials available at: https://github.com/ds-kiel/iot-labs

practical sessions require students to solve realistic IoT communication problems through implementation, testing, and evaluation.
- **Projects** build upon the foundations laid by both the lectures and labs, offering students the opportunity to design and build an IoT system that is either useful or of personal interest to them.

The overarching goals of the course are to raise interest in the field of IoT and to activate students to not only apply the knowledge they have gained, but also analyze problems, evaluate potential solutions, and create new systems based on their own ideas. This pedagogical approach is designed to guide students through the full range of Bloom's taxonomy of learning objectives [1]. The central questions the course addresses are: What is the Internet of Things and its applications? How can we build reliable and resource-efficient IoT systems? And how do devices in the IoT communicate? Through this structure, lectures provide the required fundamentals, while labs and projects offer hands-on experience in developing IoT systems and exploring their real-world challenges.

3 Course Structure

The course has a scope of 8 ECTS credits, with a time allocation of 45 hours for lectures, 30 hours for lab sessions, 15 hours for project supervision, and an expected 150 hours of self-study. The self-study time is intended to cover lecture preparation, lab assignments, project work, and exam preparation. Below, we discuss the content of the lectures and labs, followed by the projects, including some sample projects done throughout the years. We close this section by discussing the exam.

3.1 Lectures

The lectures provide the foundational knowledge for the course, covering topics from introductory IoT concepts to advanced wireless communication technologies; see Table 1. The first four weeks are intensive, with two lectures per week to rapidly bring students up to speed on the basics of IoT systems, applications, real-world challenges, and the fundamentals of wireless communication.

Students entering the course have taken lectures on computer networks and operating systems and bring at least a basic understanding of network protocols and C programming. As the computer networks course at our university only covers wired networks, we dedicate the initial lecture time to the specifics of wireless communication and networking to set the foundation for subsequent lectures.

Following these introductory lectures, the course transitions to weekly lectures on routing and various low-power wireless protocols and technologies, such as IEEE 802.15.4, BLE, LoRa, and WiFi (see Table 1, weeks 5–11). These sessions equip students with a thorough understanding of different technologies, enabling them to make informed comparisons and design decisions when developing IoT solutions. The teaching style is interactive, fostering an active learning environment. We incorporate recap questions, open discussions of, e.g., advantages and disadvantages of protocols, and online quizzes to encourage active participation and critical thinking. We provide different means of learning materials, including lecture slides, recordings, and a course book (Schiller, Mobile Communications [13]).

Table 1: Topics of the lecture sessions

Week	Topic	Type
1	Introduction to IoT	L
	IoT Operating Systems	L
2	Wireless Basics I	L
	Wireless Basics II	L
3	Wireless Transmissions	L
4	Wireless Medium Access Control I	L
	Wireless Medium Access Control II	L
5	Routing, 802.15.4	L
6	802.15.4 & BLE, Position & Localization	L
7	Project Idea Presentations	SP
8	Position & Localization, Lora, VLC, ...	L
9	Cellular Networks	L
10	WiFi	L
11	WiFi, 6LowPAN	L
12	Final Project Presentations	SP
	Final Project Presentations	SP
13	Recap	L
	AMA	Q&A

3.2 Labs

A primary objective of the course is to provide students with hands-on experience in developing and evaluating IoT systems and to deepen their understanding of real-world challenges. Moving beyond pure theory, we adopt a problem-based learning approach [7], with students typically working in pairs. While each lab guides students with subtasks, it provides them significant freedom to explore and implement their own solutions. The deliverables for each lab consist of the implemented code and a presentation (either live or recorded) in which students explain and justify their design choices.

In previous iterations of the course, the labs centered on IEEE 802.15.4 using the Contiki-NG [11] operating system and the Cooja simulator [12]. Although this setup was beneficial for academic research on networking protocols and for experimenting with single-hop and multi-hop communication protocols, it no longer reflects the most common technologies used in commercial IoT systems and our own research. Therefore, starting in 2023, we shifted the focus to Bluetooth Low Energy (BLE), a protocol ubiquitous in consumer devices, and Zephyr RTOS [17], a modern and versatile operating system actively used in industry and our own research. This change also marked a move from primarily simulation-based work to hands-on development on hardware, supplemented by the Renode simulation framework [2] for controlled and reproducible experiments. Students are provided with Nordic nRF52840 development kits [8], and many also purchase their own BBC micro:bit v2 board [6], which offers additional onboard sensors (see Figure 1).

The lab sequence in the 2024 edition and their allotted time is as follows:

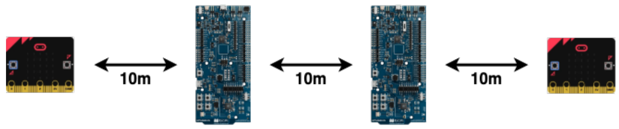

Figure 2: Topology for multi-hop communication in the labs. Both the BBC micro:bit v2 [6] and the Nordic nRF52840-DK [8] can be used interchangeably. In the case of simulation in Renode, only the nRF52840-DK is supported.

Prelab: C-Programming and Toolchain Setup (1 week)
Lab 1: Single-Hop Communication and Multi-hop Dissemination (2 weeks)
Lab 2: Multi-Hop Collection (2 weeks)
Lab 3: Build your own computer mouse (2 weeks)

3.2.1 Prelab. The prelab is a mandatory exercise to verify that students bring sufficient C programming skills for taking the course and to ensure that their toolchain is fully functional before the main labs begin.

3.2.2 Lab 1. This lab introduces fundamental network-wide communication patterns. Students implement single-hop communication between two BLE devices and multi-hop dissemination in a network of BLE devices in a line topoplogy (cf. Figure 2). In both cases, pressing a button on an end device propagates an action (e.g., turning on an LED) to all others. Students are free to choose how to implement their solution and whether they use BLE advertisements, the connected mode of BLE, or Bluetooth Mesh. A major component of this lab is to evaluate their solution's performance in Renode.

3.2.3 Lab 2. This lab builds on the previous one by focusing on multi-hop data collection protocols. A button press on an end node initiates network formation, after which each node periodically generates and transmits data to the initiator node. A key learning objective is to design for robustness, as the solution must operate reliably in the presence of other concurrently operating networks. In addition to evaluating their solution in simulation, students can participate in an in-class challenge where multiple groups' solutions are run simultaneously on hardware. This challenge is inspired by the *Industrial Communication Challenge* at TU Braunschweig [16].

3.2.4 Lab 3. This lab shifts the focus from custom networking protocols to standard application-level interoperability. Students create a BLE-based computer mouse capable of cursor movement, clicks, and an additional custom action, e.g., using the accelerometer of the micro:bit to control the cursor movement. This lab requires them to implement the standard BLE Human Interface Device (HID) Profile [4]. Moreover, lab 3 serves as a direct preparatory step for their final projects.

3.2.5 Lab Grading. For passing the lab section of the course, students must complete the mandatory prelab and earn at least 50% of the total points from the three subsequent labs. Each lab is worth a total of 10 points, with up to 8 points awarded for the technical solution and 2 points for the presentation. The grade for each lab is determined through a manual review of the submitted code and an evaluation of the student's presentation. This grading scheme offers students a degree of flexibility in managing their workload, as they can decide to work only on two out of three labs if their main objective is passing the labs. However, high performance in the labs can positively contribute to their final course grade (cf. Section 3.4).

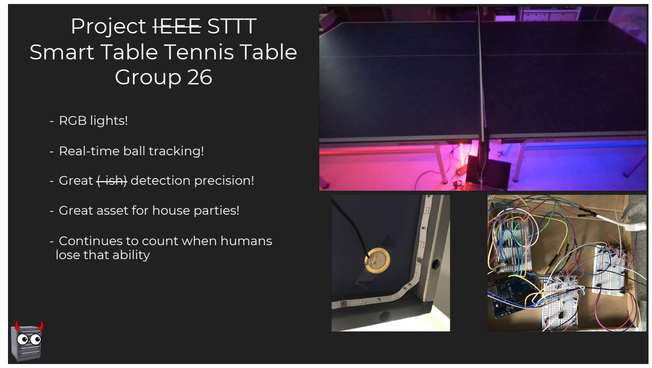

Figure 3: Madness Slide: Smart table tennis table

3.3 Project

Following the labs, students undertake a 4–5 week group project to further develop their skills by creating a complete IoT solution. We employ an inquiry-based learning approach [15], empowering students to define their own project goals and milestones, which in turn serve as the grading criteria. Each group proposes a 5-point, 10-point, and 15-point goal for their project. To ensure that the goals are realistic, students first present their ideas in a project pitch to instructors for feedback before commencing work. The project idea presentations and the final demonstrations are held during dedicated lecture slots (cf. SP in Table 1). To pass the project component, students must achieve a minimum of 10 points. Since a successful project pitch is awarded 5 points, this requirement is typically met by achieving their self-defined 5-point milestone. Like for the labs, high performance in the project can positively contribute to the students' final course grade (cf. Section 3.4).

A unique feature of the final project presentations is a "madness session," in which each group gets 45 seconds to present a single slide to persuade their peers to vote for their project as the best. This non-graded activity encourages creativity and communication skills. The instructors formally acknowledge the winning teams with certificates, adding a lighthearted competitive element to the final presentations.

Student projects are diverse and often highly creative. While some groups focus on protocol implementation in simulation, most involve hardware development. Past projects have often revolved around smart home applications, including notification-enabled letterboxes, automated plant watering and monitoring systems, smart locks for doors and sweet containers, or smart lighting. Other projects have explored themes like personal health (e.g., a pulse oximeter), locating their parked car, and interactive remote-controlled RC cars. Two notable examples include:

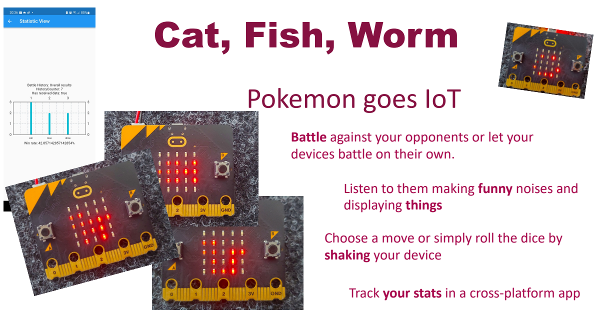

Figure 4: Madness Slide: Cat-Fish-Worm project

- A **smart table tennis table** equipped with contact microphones to detect ball bounces and automatically track and display the score during a game. In Figure 3 we show the "madness slide" of the group advertising their smart table tennis table.
- A **Cat-Fish-Worm** game (a variant of rock-paper-scissors), where two devices communicate via BLE to determine a winner and track game statistics (see Figure 4). The devices can automatically discover and connect to nearby players, and users can choose their action or have the device select one randomly.

These projects often push students beyond their comfort zones, particularly those with little prior hardware experience, but result in substantial learning and spark further interest in embedded systems and IoT. The project helps students gain valuable experience working with IoT systems, including the pitfalls of debugging embedded systems, in a way that traditional coursework cannot achieve.

3.4 Exam

The final course grade is determined by a final exam and student performance in the labs and project. The exam is typically written but may be changed to an oral examination if fewer than 10 students register. The exam covers the content of the lectures, with a focus on free-text questions and some protocol-specific diagrams that test understanding of concepts such as signal modulation techniques. To be admitted to the exam, students must pass the mandatory prelab and achieve at least 50% of the available points from both the lab assignments and the project. The final grade is calculated as the better of two options: (1) the exam grade alone or (2) a weighted average of 80% of the exam grade and 20% of the points from labs and projects, provided the exam itself is passed.

4 Student Feedback

This section summarizes student feedback collected through the university's official evaluation system (EvaSys [3]) from 22 participants in 2023 and 15 in 2024. The general sentiment is that the course has a high workload but is fun and interesting. This is encapsulated in one student's comment:

> “ My original plans had been to spend this term chilling at the beach. But then, IoT happened. It was a lot of work in the beginning. Finding our way in Zephyr was not always easy and I was sometimes afraid our team would fail the labs. Now we are working on our project and it is pure joy. I also feel that I learned a couple of useful things. In the end, I am happy to have chosen this course. ”

In the following, we highlight common feedback we received from students as part of the course evaluations and discuss the student rating of the course.

4.1 Positive Feedback

- Students consistently praised the course's clear structure, hands-on approach, and practical relevance, with one stating, "I feel that I learned something which might be useful for me in the future".
- The course was seen as effective at arousing interest and motivating students to engage with the content.
- The availability of lecture recordings was frequently mentioned as extremely helpful for reviewing material, with one pointing out that "It is really useful to have the lecture recordings. I usually need to hear things twice in order to memorize them. So, even if I usually come to the lecture, I still watch the videos."
- The project component was described as well-motivated and a key opportunity to implement their own ideas.
- The lectures were found to be lively and practice-oriented, and the use of the inexpensive and versatile micro:bit was appreciated.

4.2 Critical Feedback

- The most significant criticism was the high workload, especially for the labs. One student noted: "The labs are very much too time-consuming. Debugging costs so much time that we don't have".
- Several students felt that the workload in the first two labs was particularly unbalanced. For example "Lab-Workload was quite unbalanced (way too high in the first 2 labs). A lot of time for the labs was spent just 'setting up stuff'."
- A perceived disconnect between the broad scope of the lectures and the narrow focus on BLE/Zephyr in the exercises was a point of concern.
- Students expressed a desire for more guidance in the initial labs and more theoretical exercises to help prepare for the exam. One student wrote, "In order to create more coherence between the lecture and the exercise, more theoretical tasks are desirable in this case as an exception."
- The mandatory prelab in the first week was seen by some as a high-pressure start to the course.

4.3 Course Rating

Overall, the course is rated positively by the students, with an average satisfaction score of 2.1 in 2023 and 2.2 in 2024 (on a scale where 1 is best, see Figure 5). The course successfully activates student interest in IoT. However, the course evaluation also clearly shows that a majority of students find the workload for the labs to be high or too high, indicating a key area for improvement. In general, in most categories, the course was slightly better received in 2023 than in 2024.

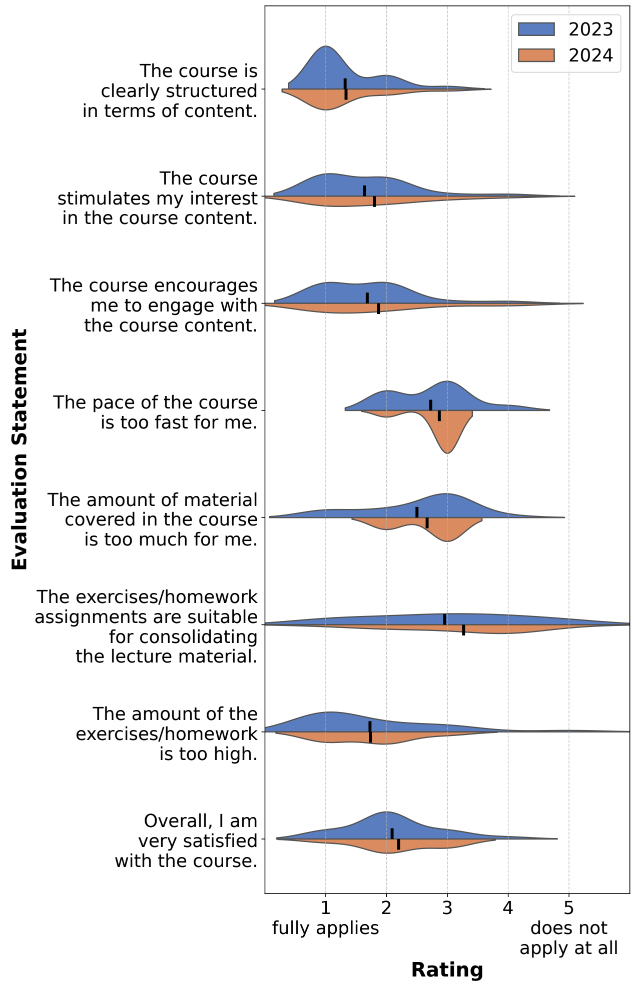

Figure 5: Student rating of the course. Mean highlighted in black. 2023: 22 evaluation participants; 2024: 15 evaluation participants.

5 Reflection & Future Improvements

Student feedback and our own observations confirm that the lab workload often exceeds a reasonable level for students, particularly those without a strong background in embedded programming. While the hands-on, problem-based approach is highly valued, its implementation needs refinement to ensure that the learning objectives are achievable without causing undue stress. The critical feedback regarding the high workload and the desire for more guidance is a primary driver for our planned revisions.

For the next iteration of the course, we intend to rebalance the lab workload and address the perceived disconnect between lectures and labs, especially in regard to exam preparation. Recognizing the skill gap in embedded programming, we plan to use existing, high-quality materials for the first two labs. Specifically, we will adapt and integrate components from the Nordic Developer Academy's courses on the *nRF Connect SDK* [9] and *BLE Fundamentals* [10]. This approach will provide students with a more manageable learning path, reducing the initial complexity and the time commitment. The prelab will also be revised to include more background material and a more flexible deadline. In contrast, Lab 3 will remain unchanged, as it is consistently well-received and serves as an effective stepping stone to the final projects.

To mitigate the perceived disconnect between lectures and labs, we will take a two-step approach. First, at the beginning of the course, we will more explicitly communicate the distinct pedagogical role of each component, with lectures focused on broad conceptual knowledge and labs on deep, practical application in a specific ecosystem. Second, to better support exam preparation, we will integrate exercises into the lab sessions that cover the concepts taught in the lectures and mirror the style of questions in the final exam.

6 Conclusion

This paper describes the design, implementation, and evaluation of a university-level course on the Internet of Things. By blending lectures with practical labs and a creative project component, the course provides students with a comprehensive and engaging learning experience. The evolution of the curriculum to focus on BLE and Zephyr ensures its relevance and practical value. Student feedback confirms that the hands-on, project-based methodology is highly effective for fostering practical skills and interest in the subject. However, it also highlights the critical challenge of balancing a demanding workload with pedagogical goals. Based on this analysis, we have identified concrete areas for improvement. Through continued refinement, we aim to offer a course that not only educates students on the fundamental principles of IoT but also empowers them to become capable creators and innovators in this vital field.

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