Enabling Industry 4.0 Applications

Coaching a multi-national team with different disciplines to learn about Deterministic Networks for IoT applications

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Abstract

Connectivity is essential for enabling deterministic and reliable communication in Industry 4.0 applications. This paper presents our experience designing and delivering a 3 ECTS interdisciplinary course module focused on IEEE 802.15.4 Time-Slotted Channel Hopping (TSCH) and the open-source 6TiSCH protocol stack. Combining theoretical concepts with hands-on experiments and simulations, the course was offered within the EU-funded ECIU University framework, engaging students from five partner universities and diverse academic backgrounds. We discuss how the course was structured to address varying levels of prior knowledge, highlight the blended learning approach, and share key insights and challenges encountered throughout the course.

CCS Concepts

• **Networks** → **Link-layer protocols**; • **Computing methodologies** → *Modeling and simulation.*

Keywords

Coaching, interdisciplinary course, multi-cultural, 6TiSCH, Team-based Learning, Cooja simulator

1 Introduction

Connectivity plays a crucial role in advancing next-generation industrial processes. This module [1] introduces the fundamentals of communication technologies rooted in the IEEE 802.15.4 standard, tailored for Industry 4.0 applications [6].

Industry 4.0 applications, where feedback is tightly coupled with control commands, require deterministic communication characteristics in terms of delay and reliability [5, 7]. This cannot be achieved with random access methods such as WiFi, LoRa, or Bluetooth. The IEEE 802.15.4 Time-Slotted Channel Hopping (TSCH) mode provides such deterministic behavior. Therefore, this has been selected as the main topic of our course due to its foundation in open-source standards and its role in enabling a non-proprietary protocol stack known as 6TiSCH [9].

This course combines theoretical foundations and analytical approaches with practical experience through hands-on experiments and simulations using the IETF 6TiSCH protocol stack, offering an engaging and interactive learning experience.

The course was organised not just as a part of the computer science study program but also within the EU-funded ECIU University framework. ECIU brings together 12 European universities to offer joint micro-modules, short courses, mostly online with 1–3 ECTS, focused on group-based, interdisciplinary problem solving. In this course, students from five partner universities, including ours, and from diverse study programs such as mechanical engineering, electrical engineering, and mathematics participated, representing a wide range of coding skills and background knowledge in wireless communication and mathematical concepts.

In this paper, we share our experiences in conducting this course as a 3 ECTS module within an interdisciplinary setting. The following section describes how we structured the learning objectives to accommodate varying levels of students' prerequisite knowledge while aligning with the goals of the ECIU initiative. We then elaborate on the course design, which was delivered as a blended program, and present student feedback. Finally, we discuss the challenges encountered and the lessons learned.

2 Learning Goals

The course was organized to be an international and interdisciplinary teaching and learning experience in a very distinct subject issue. Therefore, the intended learning outcomes represent both transversal and subject-related competences.

Constructive alignment [4] as a guiding principle works under the premise that the learning goals can and should be decided beforehand in order to align them with learning

[1] https://engage.eciu.eu/micro-modules/b24edb90-2e3f-415b-96ab-19ed0261d5ed/enabling-industry-40

activities and feedback formats. This view brings a challenge for the course described here where the means of the learning process are provided, while it is mostly the students' responsibility to drive the learning in their teams with very diverse backgrounds and pre-knowledge. Activities and feedback formats were planed and conducted accordingly.

We clearly communicated the four learning goals of the course, outlining what students could expect to achieve:

(1) *Understand Industry 4.0 challenges and IEEE 802.15.4:* Explain how TSCH mode of IEEE 802.15.4 helps to achieve strict QoS of the industrial applications.
(2) *Think critically about network communication in Industry 4.0:* Bridge the gap between theory and practice by applying learned methods to real-world challenges, thereby gaining a practical understanding of the concepts of network communication in Industry 4.0, to develop skills in analyzing and synthesizing scientific research related to it, and leading to a broader and deeper understanding of the field.
(3) *Work in international, interdisciplinary teams:* Understand team roles, dynamics, online collaboration tools, and peer feedback.
(4) *Learn how to evaluate communication protocol performance:* Use performance metrics, analytical modeling, and Cooja simulations to assess protocol behavior.

3 Course Structure

Although our primary learning goals focus on the IEEE 802.15.4 TSCH mode, we extended the scope to include the 6TiSCH protocol stack, which builds upon IEEE 802.15.4. As illustrated in Figure 1, additional protocols used in 6TiSCH were provided as self-learning materials.

The core components—IEEE 802.15.4, the 6top protocol, and the Minimal Scheduling Function (MSF) [1] were taught in a blended format, combining online and in-person learning activities (Refer Figure 2). The module is divided into mainly three parts:

- Part 1 - Background knowledge: Core concepts introduced in the initial three online lectures are focused only on the link layer of 6TiSCH stack. Lecture contents consist of the following.
  - L1: Industrial IoT, introduction to low power wireless technologies and deterministic networks
  - L2: Introduction to IEEE 15.4 modes, depth analysis of TSCH mode, shared and dedicated scheduling
  - L3: Introduction to 6TiSCH, scheduling with 6top protocols
- Part 2 - Simulation and experiments: The learned concepts are systematically reinforced through practical simulations using the Cooja open-source simulator [8] and empirical experiments involving real-world hardware platforms.
  - A1: In the first assignment (Figure 3), students ran a simulation of a two-node network to understand the joining process in 6TiSCH stack. All nodes printed debug information in the console with relevant details such as the size of Enhanced Beacon (EB), frequency channels scanned before joining, etc. Students also recorded delays per packet as well as average values and compared the them to analytical expectations. Furthermore, a star network with two hosts connected to the sink was simulated to hint at the limitations of the communication on a shared cell (collisions).
  - A2: In the second assignment, dedicated cells were added manually to serve application traffic, and the changes in end-to-end delay should have been observed and explained using analytical model. A linear network with multiple nodes was simulated to teach the impact of network size on the delays and to motivate more flexible cell allocation.
  - A3: 6top (6P) protocol was introduced to manage the schedule at each node in this assignment. Students followed individual steps of a 2-step 6P transaction to understand how exactly distributed scheduling works and what are the potential limitations of randomized cell allocation.
- Part 3 - Theoretical analysis: In our fourth lecture, analytical techniques are employed to derive fundamental performance limits and evaluate QoS metrics. This approach ensures students are well-prepared to operate as competent network specialists in both current and emerging industrial applications.

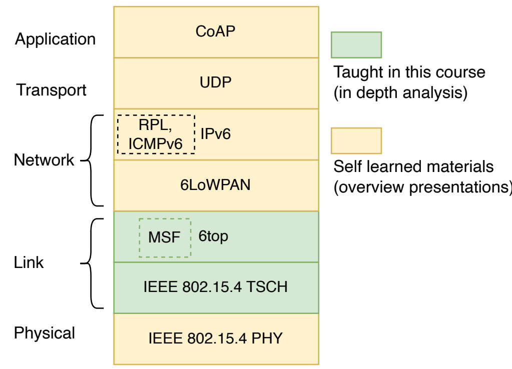

Figure 1: Course Topics

The main challenge in this course is adapting it to accommodate the diverse knowledge levels of the students. As a

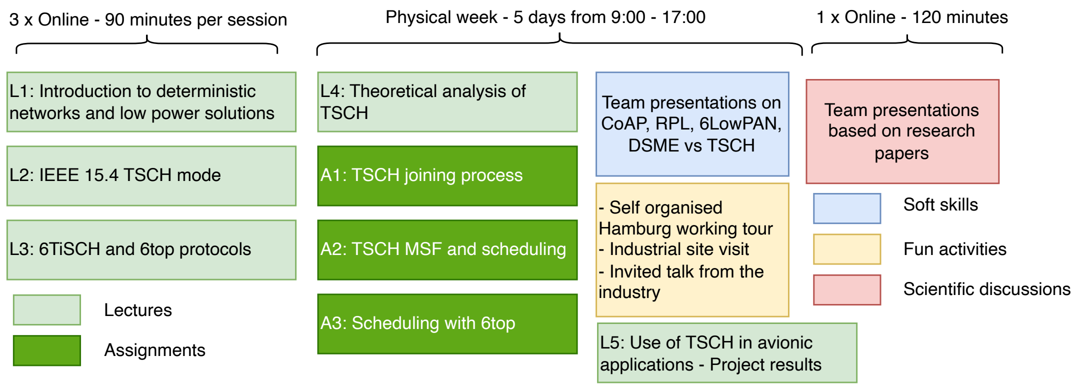

Figure 2: Course Contents - Online and Physical

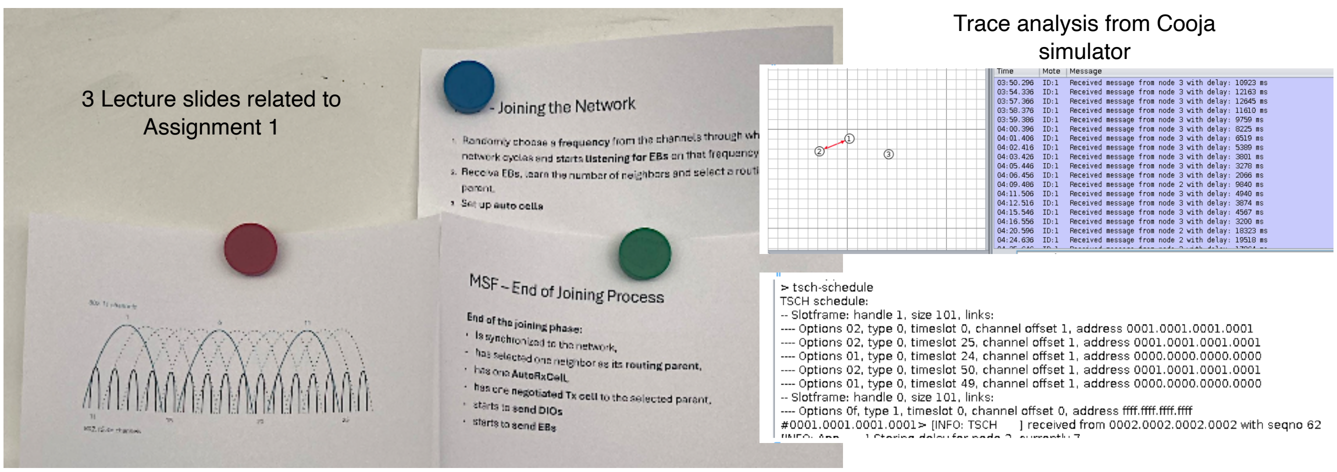

Figure 3: Conducting Assignment-1 to learn about TSCH joining process and MSF

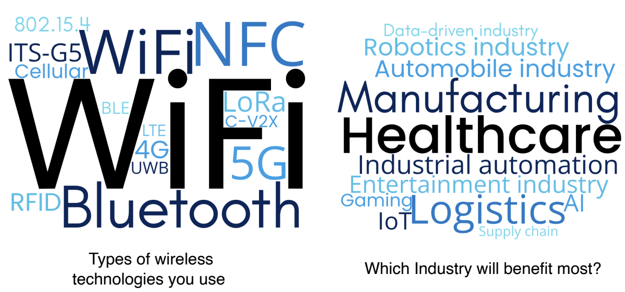

Figure 4: Pre-course survey - Students Opinions

preliminary step, we gathered information from students in a few of key areas to help them engage with the course material. Figure 4 presents their feedback, highlighting the types of wireless technologies they use in daily life and their visions for future applications based on wireless solutions.

This input guided the design of our first lecture, which provided an overview of technologies such as WiFi, Bluetooth, NFC, and RFID. Among the feedback, healthcare and manufacturing emerged as the two most commonly mentioned application domains. Therefore, we selected these areas to illustrate the importance of deterministic behavior and low-power solutions in real-world scenarios.

To support our efforts toward achieving *Goal 2* and *Goal 3*, we integrated breakout session discussions into our online lectures. These sessions are designed to spark students' curiosity and critical thinking before detailing into core concepts. Examples of such discussion topics include:

- "Why is WiFi not suitable as a low-power solution?" — discussion prompt before introducing IEEE 802.15.4
- "What factors influence the duration of a timeslot?" — This question encouraged students to work in small groups to explore the types of delays involved in data

transmission and to consider who is responsible for sending the link-layer acknowledgement.
- "Is TSCH channel hopping robust enough?" — Before covering the challenges of TSCH scheduling in the lecture, this question led students to reflect on potential failure points in the mechanism.

The course was co-taught by two lecturers. We actively participated in the breakout group discussions to judge students' levels of understanding and engagement. All lecture materials, including discussion topics, are available at [2].

The activities during the physical week focused primarily on collaborative, team-based assignments that fostered both hands on in learned concepts and essential interpersonal skills. We formed six groups, each consisting of three students, ensuring that no group included students from the same university. Additionally, we integrated four bachelor's students, encouraging them to work alongside master's students. Each team was paired with a "buddy team" to promote peer support — teams were encouraged to first consult with their buddy team when encountering challenges and to compare and validate their results collaboratively. Both instructors took on a coaching role throughout the in-person activities. These activities included:

- Completion of three assignments (each in three to five hours), followed by a justification of outcomes with the buddy team.
- Students were assigned to independently study additional topic areas related to 6TiSCH and present their findings in teams to the entire group (Figure 5). This approach promoted peer-to-peer knowledge sharing and encouraged a broader understanding of related concepts. Students were given dedicated study time and the freedom to organize and deliver their presentations in any format they preferred.
- L4 homework: This lecture was conducted during the physical week, featuring interactive sessions using a Jupyter notebook. Students explored the effects of varying parameters within the analytical model, allowing them to engage hands-on with the theoretical content.

During the physical week, students participated in various engaging activities, such as self-organized walking tours and attending local events. Additionally, an industrial visit to Airbus and a guest lecture from Bosch Research were arranged, offering students valuable insights into current industry developments related to the technologies covered in the course.

Following the physical week, the final lecture was conducted online, during which three groups presented their work based on research papers. The groups consisted of only local TUHH students, whom we had to grade specifically, unlike the pass/fail for the guest students.

The last session allowed students to apply the foundational knowledge they had acquired and demonstrated their ability to quickly comprehend and interpret relevant academic publications across different areas of Industry 4.0 applications.

4 Students Feedback

Traditional teaching evaluations often focus on recording student satisfaction with the teacher. However, we were looking for a form of teaching evaluation that promotes reflection on the learning process and at the same time provides as concrete an indication as possible of the connection between the intended learning objective/goals and the learner activity carried out in the heterogeneous student group, as well as providing potential for improvement.

We found this in the Bielefeld Learning Goal-Oriented Evaluation (BiLoe) [3], which was developed at the Center for Teaching and Learning at Bielefeld University and has since been used primarily in teaching-learning formats such as research-based learning or problem-based learning.

The BiLoe questionnaire begins with a request to formulate one's own learning goal for the course. This encourages a comparison of expectations. After evaluating how relevant the learning objectives set by the lecturers are for them, the students assess the perceived importance of three to four student activities that should serve to achieve the learning goal. The students reflect on their contribution to learning and the success of the course. Lecturers receive valuable feedback on where more explicit guidance or better integration of activities might be necessary. The evaluation we received for *Goal 1* is shown in Figure 6.

The questionnaire concludes with the following question: "What would you recommend to future students participating in this course?", thus maintaining the focus on the learning activities and the students.

17 out of 18 students completed BiLoe during the physical week. Participants found subject related *Goal 4 - Evaluate Communication Protocol Performance* important and felt they achieved it through understanding analytical equations, comparing analytical results to simulations, and discussing their understanding in teams. Most participants found the subject related *Goal 1 - Understand Industry 4.0 Challenges and IEEE 802.15.4* very important and felt they achieved it completely.

The course content and interactive discussions were effective in supporting this learning goal. Participants generally felt they achieved subject related *Goal 3*, particularly through online lectures and peer-assisted inquiries. Some found theoretical concepts challenging but appreciated the practical

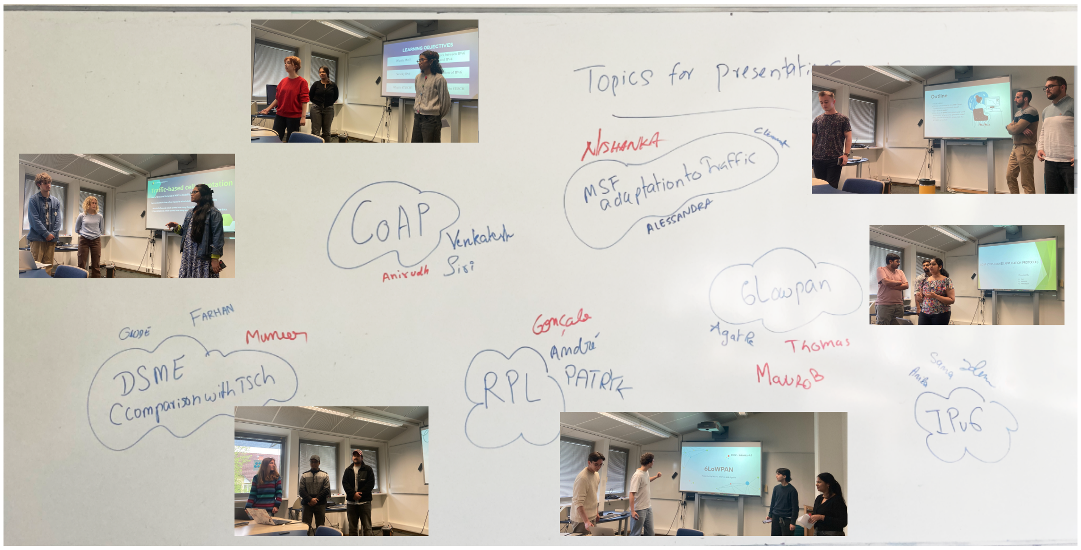

Figure 5: Presentations based on self-learned materials

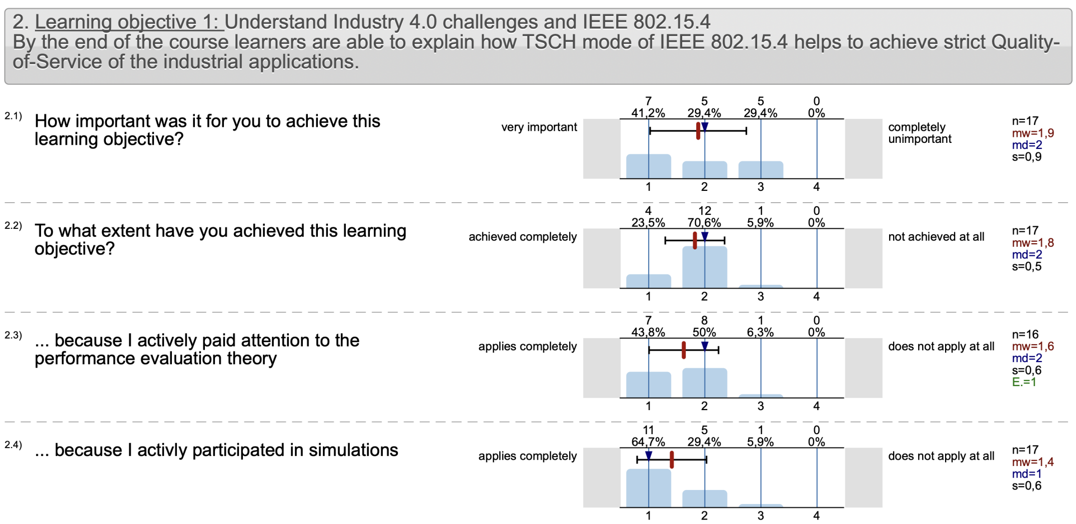

Figure 6: BiLoe based feedback on Learning Goal 1

applications. Learning to work in international teams, understanding different roles, and using tools for online collaboration was highly valued, and most participants felt they achieved it completely. The course structure facilitated teamwork and collaboration effectively.

Free text responses pointed out that participants started the course with various personal objectives, such as discovering wireless communications in Industry 4.0, other aiming for deep understanding IEEE 802.15.4, and other for improving seminar presentation skills. Some participants mentioned time constraints, lack of familiarity with network communication, and the need for more hands-on practice as reasons for not fully achieving their objectives. Future students are advised to be open-minded, have a good level of English, concentrate on tasks, discuss results as a team, and explore the Cooja simulator early. Anonymous students feedback is available at [2].

In summary, the course was well-received, with participants appreciating the structure, content, and interactive discussions. Hands-on activities and team-based discussions were highlighted as particularly beneficial. Some participants suggested more in-depth coverage of theoretical concepts and additional practical sessions to enhance understanding.

5 Summary and Outlook

Student selection was managed by our teaching center, ensuring that international students received funding to participate in the physical week of the course. Here, we summarize the technical challenges encountered during the course and the lessons learned.

5.1 Challenges

We used several communication tools throughout the course, including email, Zoom, Padlet, and Microsoft Teams. Both lecturers and students initially found it confusing to navigate these platforms and determine their appropriate use before, during, and after the course. However, Padlet emerged as a particularly effective tool, serving as a central hub for sharing the weekly and daily agendas.

As the course was conducted in an intensive format, especially during the physical week, it was challenging to minimize the time and effort required to install the Cooja simulator on students' laptops. We addressed this issue by providing extra laptops and limiting installations to student devices running Linux.

Engaging quieter students during online breakout sessions also proved difficult. However, the physical week significantly improved social interaction, allowing students to get to know one another and the lecturers better, which led to more active participation. Lastly, maintaining motivation across a diverse group of students remains a challenge. We recognized the need to incorporate a variety of activities to keep all students engaged.

5.2 Lessons Learned

This course was designed to achieve well-defined learning goals within a collaborative and international setting. As lecturers, we adopted more of a coaching role rather than following a traditional teaching approach. We ourselves learned to foster peer support among students, adapt lecture content to meet their needs, and define clear learning objectives along with appropriate evaluation methods.

For example, to help students intuitively understand how simultaneous access can cause packet collisions in WiFi networks, we designed an interactive classroom activity. Each student had to choose a random number within a short range and count down before saying their *favorite food* out loud. When many students selected similar number, they ended up speaking at the same time, making it difficult to understand any individual word, effectively simulating a collision. This playful approach led to a discussion on the importance of the backoff mechanism in WiFi, where choosing from a longer interval reduces the chance of such collisions. Below is a summary of the key lessons learned.

- Discussions in breakout rooms during online part were essential to keep students curious and trigger their prior knowledge.
- Assignments done physically activate and reinforce knowledge gained from online lectures.
- A mix of practical and theoretical materials provided a well-rounded overview of 802.15.4, making students aware of its potential for Industry 4.0.
- Clear instructions and controlled simulation environment is key to enable students focus on learning goals.
- Mixing local and international students in teams fostered more interaction and motivated them to perform better, since there was no "comfort zone"
- Self-study time and presentation assignments helped them digest accumulated knowledge and deepen the understanding by presenting assigned topics.
- The range of topics covered, along with optional tasks allowed to cater to students with varying levels of motivation.
- Invited speaker from the industry and shared experiences from our own projects highlighted the relevance of the communication for Industry 4.0.

Scalability-wise, we believe team-based assignments are perfectly suitable also for larger groups. While physical hardware can be a limitation due to quantity, simulations enable everyone to actively try the assignments on their own and solidify theoretical concepts from the lecture on practice.

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