The Competence-Oriented Teaching of Antennas, Propagation and Wireless Communications: Enabling independent students

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***Abstract*—Competence-oriented education aims to teach individuals the cognitive skills to solve specific problems and the readiness to apply such solutions in versatile situations. We find that competence-oriented teaching is a promising paradigm in applied courses for antennas, propagation and wireless communications. Competence-oriented laboratory courses are easy to implement when mechanical facilities and equipment from laboratory courses are already available at the institute. Amateur radio equipment is used as an effective way to let students work on their own without risking damage to delicate equipment. In this paper, we describe several methods to modify lab courses towards competence-oriented academic teaching that we have found are popular with students and enhance their learning experience.**

***Index Terms*—Antennas, competence, education, propagation, teaching, wireless.**

I. Introduction

Simultaneously to the general trend in society, students increasingly move away from simple radios towards highly complex consumer devices which obscure the underlying technical functionality. Most students, that are currently at the end of their studies, have never experienced Morse communications. They might know it from movies. Students, that are now starting their university educations, have grown up with digital media such as DVD, cell phones and MP3 — many have never operated a radio. Analog communications is often unfamiliar to them and consequently they might not have an intuitive feeling for concepts like signal-to-noise ratio.

Policy makers in Europe are pushing towards competence-oriented higher education [1]. Competence-oriented education aims to teach individuals the cognitive skills to solve specific problems and the readiness to apply such solutions in versatile situations. To complement theoretical courses like network security, this has resulted in the creation of additional laboratory exercises [2], [3]. The starting position was different for technical courses, because these already contained practical exercises. We have found that a focus on competence further improves both lectures and laboratory exercises of our technical courses on wave propagation, centimeter- and millimeter waves, antenna design and realization, advanced wireless communications and short wave radio.

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The European Qualifications Framework (EQF) [4] has decidedly arranged work under supervision at education levels below university education. At bachelor's level students are required to solve *complex and unpredictable problems*. At master's level practical courses prepare students for *complex and unpredictable problems that require new strategic approaches*. It is no longer desirable that students learn based on scripted tasks and under supervision.

As a consequence, autonomy has been further increased in lab courses to allow students to find their own solutions to problems, unless supervision is required due to a risk of injury or the cost of the involved equipment. As an example, a traditional lab exercise might provide students with a detailed list of instructions and a workstation where the needed equipment is already pre-installed. The resulting tasks are simple and unforeseen problems usually don't occur. The equivalent competence-oriented university exercise might only task the students to characterize a given antenna. The students will encounter *complex and unpredictable problems* along the ways as they choose and apply methods and equipment on their own.

Three competence-oriented courses are described. The courses teach competences that are important for different aspects of academic education: general education, applied science and research. The example courses are taken from different levels of education and increase in complexity. Sec. II describes an exercise on modulation and coding schemes. The goal for students is to experience different schemes and practice using them. Scholars with higher education in the field of antennas and propagation are expected to be proficient in the most important modulation and coding schemes, including historic ones. In Sec. III it is demonstrated how an existing practical course on antennas can be altered towards competence-oriented education. The competence-oriented course on antennas treats a specific communications problem. It starts with the selection of a suitable antenna design by the students, and includes simulation, manufacturing and testing of the antenna as part of the complete system. The course has typical aspects of development in companies, especially the adaption to practical problems and limitations during development. Sec. IV showcases a laboratory course on wave propagation for centimeter and millimeter waves. The course goal is shifted to specifically teach students to independently perform wave propagation experiments and to model them mathematically. This is an important competence in the research focus of the institute and generally an important competence for independent researchers.

II. Experience Modulation and Coding Schemes

It is an important competence for any scholar in the field of telecommunications to be knowledgeable in modulation and coding schemes, and to have experience in using them. To teach this competence in a course, the exercises are done in small groups with around four people and usually last two hours. The group exercises start with oral exams on modulation techniques. Students are allowed to choose a favorite modulation scheme beforehand. They explain their chosen scheme to the peer group, which asks questions for clarification. The tutor guides the discussion and asks follow-up questions on topics that the testee avoided in their presentations. Typical follow-up questions involve basic circuits for de/modulation, general differences between analog and digital communications and what students expect that errors will look like without forward error correction. It is a premise of competence-oriented teaching, that students demonstrate to have successfully mastered the previous competence before students advance to further competences. Therefore, the oral exams are done at the beginning of the exercise. Only when students have shown, that they have understood the modulation and coding schemes theoretically are they allowed to participate further in the practical exercise. There was some concern prior to this change that students might no longer be interested in the exercise once the exam is over. On the contrary, it was found that students are very much engaged in the practical part and eager to experience the concepts that they had studied before.

Amateur radio is an excellent supplement for teaching [5] and offers a versatile way to operate in different modulation schemes. The exercise setup is a software defined radio consisting of a transceiver that is connected to a personal computer. The transmit antenna is either a software-reconfigurable Yagi-Uda antenna [6] or one of various student-built antennas from previous courses. The lecture starts with continuous wave (CW) Morse communications and moves to analog frequency modulation (FM), amplitude modulation (AM) and single-sideband (SSB) modulation. The first task is to tune to the right frequencies and to understand analog signals that are distorted by noise. Students listen and transmit at their own pace and overcome *Mikrofonangst* (German, the fear of speaking into a microphone to broadcast your voice to a large audience). This helps students to experience important concepts such as interference, signal-to-noise ratio, time-variant fading, the propagation conditions in different frequency ranges and great circle maps. Communication along great circles is counter-intuitive to most students, e.g. that antennas need to be pointed north-east in Vienna to reach Sydney. A demonstration with a globe and a rubber band as an analog computer for the shortest path between any two points on the globe has proven to be useful.

After some time, the lecture moves to digital modes without error correction. Radioteletype and binary phase shift keying (BPSK) are still popular among amateur radio operators and students can again work at their own pace. These modes help students to get familiar with coding, spectrograms, bit-errors, and automated-operation. Practical exercises help students to connect analog with the digital quantities, e.g. how a lower signal-to-noise ratio increases bit error rate.

In the last step, the students use digital modes with forward error correction. Popular amateur radio transmission schemes with modern forward error correction are available for Reed-Solomon codes [7] in JT65 [8] and low-density parity-check (LDPC) codes [9] in FT8 [10]. Software for these modes is intuitive to use and open source, e.g. Weak Signal Communication by K1JT (WSJT-X) [10]. Students find that messages with error correction are either correctly decoded or discarded. The displayed callsigns are correct and operators no longer send important information in triple. These modes teach about time-slots and synchronization. Young students are usually familiar with this kind of transmission as it is widespread in their personal lives. When they download an image from the internet, it is displayed without errors or not displayed at all. We plan to make amateur radio transmissions accessible in signal processing classes, such that students can decode real-world messages.

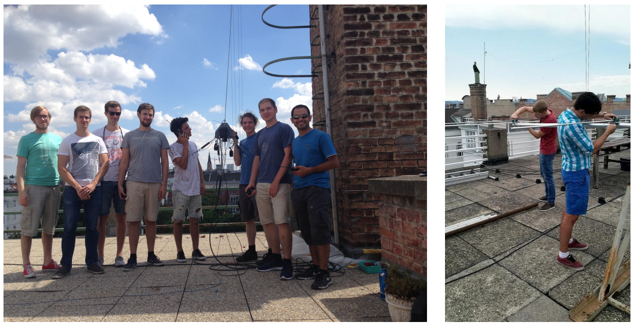
Required Course Equipment —

- Amateur radio transceiver
- Shortwave antenna; The students enjoy using student-built antennas from other courses.
- Coaxial cables
- PC or laptop for digital modes
- Software for digital modes (available for free): Fldigi, WSJT-X
- Lab room
- Students need amateur radio licenses to transmit in amateur radio frequency bands. It is worth asking the issuing authority for permits that allow students limited use of amateur radio frequency bands under supervision.

III. Students Can Use Their Antennas

Laboratory exercises for undergraduates are often structured as follows. First, the students simulate a desired antenna structure. Then, they build the antenna and measure it. At last, they derive performance quantities such as return loss, gain patterns, cross polarization and correlation, and they evaluate the antenna based on these quantities. From a student perspective this process feels unsatisfactory. Many students prefer to use their antennas as part of communication systems. However, large parts of the spectrum are sold and students are often not able to use the antennas that they build. As a result students lack the skill of testing antennas as part of the complete communication system — an important skill in industry where whole devices are evaluated with over-the-air testing (OTA).

The traditional antenna course is adapted for competence-oriented teaching. The new course follows the commercial development process. Students are tasked to select and design antennas for specific applications under practical limitations. Students design antennas for amateur radio frequency bands or industrial, scientific and medical (ISM) bands, such that the whole communication systems can be tested. From our experience, transmission tests are best done right after manufacturing the antennas, but before measuring and evaluating antenna performance — only antenna matching is measured before tests of the whole system to prevent damage to equipment. During transmission, the possibilities to more objectively quantify antenna performance usually come up in discussions and this motivates further measurements and evaluation of the antenna. Fig. 1 shows inverted-V and Yagi-Uda antennas [11], [12] that students have designed, assembled and tested.



(a) (b)

Fig. 1: Examples of antennas that students have dimensioned, built and tested. a) A triple arm inverted-V antenna for the 160 m/80 m/40 m frequency bands. b) A Yagi-Uda antenna for the 6 m band.

A course from 2016, where students built a triple band inverted-V antenna, is further described in detail as an example. The students were tasked with coming up with a replacement for the SteppIR, which was unavailable due to storm damage. The group decided that they want to build an inverted-V antenna and identified a part of the institute's roof as suitable construction site, for which the lecturers obtained permission. The chosen roof portion has a U-shaped courtyard with a chimney in the middle that is suitable to attach a mast. It was suggested by the tutor to built a multiband variant that could cover several amateur radio bands. The students decided for the 160, 80 and 40 meter bands and simulated the wire antennas with the software EZNEC [13], which is based on NEC-2 [14]. Inspection of the roof site later revealed that it was too small for an inverted-V at the 160 m band. The students went back to the simulation stage and determined the needed cable lengths to bend the arms of the 160 m antenna in a Z-shape instead of a V-shape. The group needed to determine if the three antennas could be used in parallel with a single feed, which they found to be feasible as the impedances of the unused antennas are quite high in the other bands. The students assembled the antennas and balun, including ropes, pulleys and clamps. For mechanical modifications, they can use a small workshop with reduced machinery that was specifically set up for student use. Before its deployment, the setup was checked by the lecturers. When the students needed to decide how to best span wires across the courtyard, they tied ropes to a football and shot it across the roofs. The finished antenna was tested as part of the universities amateur radio club station [15]. This was the last part for this particular course, as the antenna was too large to be measured in the anechoic chamber. Students were graded based on their contributions to the group project and their final lab report. The antennas are still functional and are used every year in the course in Sec. II.

Required Course Equipment —

- Expendable materials for antenna construction (a few hundred Euro depending on the project)
- Tools for cutting, drilling, crimping, screwing etc.
- Equipment for transmission and reception with the student built antenna (e.g. amateur radio transceivers, WLAN equipment, IoT devices)
- Permanent large installations on the roof might require a permit
- Radio transmissions require a permit by regulatory authorities. We use an amateur radio license for this purpose together with an experimental permit for limited use of amateur radio bands for students under supervision by a duly licensed operator.

IV. Experience Wave Propagation Phenomena and Test Propagation Models

The course modifications in this section aim to teach students to carry out experiments on wave propagation and to mathematically model their findings. These are paramount competences for researchers in the fields of wireless communications and propagation. Students work self-reliant in preparation for scientific career paths. The first subsections is a short summary of modifications to a course on short wave propagation. The second subsection gives a detailed description on how a course on millimeter waves is adapted for competence-oriented teaching.

A. Short Wave Radio

The Voice of America Coverage Analysis Program (VOACAP) was added to the course on short wave radio communications. VOACAP is a propagation prediction software for the high frequency bands and it is available online for free [16]. The theoretical part of the course teaches ionospheric propagation. Previously, the lab course was designed such that students become familiar with short wave radio operation. The competence-oriented practical part is now specifically designed with the goal that students can select propagation models that are suitable for their application, that they learn how to use those models by themselves and that they learn how to check the model for plausibility.

The session starts with a group discussion on short wave propagation. The examiner does not ask questions directly and instead moderates the discussion such that students can demonstrate what they have learned. Students are graded based on their understanding of propagation modes (e.g. line of sight, troposcatter, moon bounce, ionospheric propagation), suitable propagation models (e.g. explaining why Winner II and COST models are not suitable for short wave radio), typical effects in wave propagation (e.g. reflection, scattering, knife-edge diffraction) and model parameters in short-wave radio (e.g. time of day, frequency band, sunspot number, antenna gain). Then students are asked to predict the influence of these parameters. Their answers are graded qualitatively based on the students' line of reasoning. Students test the theoretical models that they have been taught, by testing the VOACAP prediction model in the universities' amateur radio club. The students keep tally sheets on the received countries and signal strength. They then compare them to VOACAP predictions and their theoretical understanding of skip zones, ionospheric layers, grey lines, etc. Digital modes work well for this purpose, because the software decodes all stations simultaneously. This gives a fast overview of the received countries and the received signal strengths.

Required Course Equipment —

- Amateur radio station: Transceiver, antenna, personal computer or laptop with internet access for VOACAP and connected to the transceiver for digital modes
- Lab room
- Radio transmission permit

B. Millimeter Waves

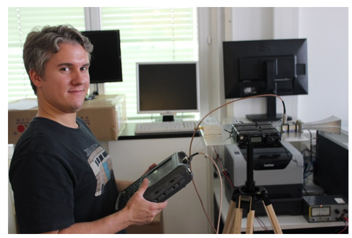
The competence-oriented course is intentionally unscripted. Students are tasked to measure a propagation effect in the high gigahertz range or for mmW. The students are given autonomy to choose which effect they want to measure, to devise a measurement setup and to assemble the RF hardware they need. They are given a list of fifteen tasks, from which they choose seven. The items on the list are considered to be suggestions and students are free to propose tasks.

1) Preparation in the mechanical workshop.
2) Transceiver assembly with coax relay.
3) Design and mounting for a parabolic dish.
4) Calculation of ideal horn antenna gain and pattern.
5) Calculation of link budget from station OE1XGA to OE1XTU.
6) Reception of OE1XGA beacon [17].
7) Measurement of horn antenna gain and pattern.
8) Assembly of transmitter with 4 W power amplifier.
9) Direct wavelength measurement (with standing wave).
10) Diffraction experiment with a large metallic plate.
11) Set up an analog outdoor SSB voice link.
12) Set up a digital link with a terminal node controller (TNC).
13) characterizing a transverter using a portable network analyzer (PNA) for X-parameters [18].
14) Measurement of radiation pattern in anechoic chamber.
15) Measurement of phase noise

The students need to find methods to fulfill their chosen tasks themselves. They need to plan the experiments, list the equipment that they require and check the equipment that is available at the institute. Students negotiate with the professor for funds to purchase additional equipment. Selecting appropriate equipment (e.g. choosing which antennas to buy or build) is an overwhelming task at first, and it is intentionally part of the course. With the wide range of technical equipment and methods and the loose formulation of the goals, the course easily fulfills the EQF requirement to create *complex and unpredictable problems that require new strategic approaches.*

The use of amateur radio equipment grants the students increased autonomy during the course. Such autonomy would hardly be possible with laboratory grade measurement equipment. Tutors only need to be constantly present during measurements with the PNA-X, because of its delicacy. Amateur radio equipment is more reasonably priced and can be replaced easily in case of irreparable damage. The increased autonomy results in longer lab durations for the students. The practical exercises typically take a few afternoons. Supervisors only need to be present when students ask for permission (usually if they are allowed to use certain parts), to check the setup before it is turned on and during measurements with delicate equipment.

Two student-assembled setups are shown in Fig. 2. In the first setup students used a UHF transceiver with a transverter to 10 GHz and a horn antenna, which they mounted on a tripod. A year later the students modified this setup with a self-built horn antenna that feeds an offset parabolic dish reflector. They also introduced a coaxial switch such that a single antenna can be used to transmit and receive.


(a)


(b)

Fig. 2: The students are allowed to assemble transceiver configurations and enjoy the increased autonomy. a) Students have assembled a 3 cm setup with an amateur radio transceiver, a transverter and a horn antenna. A student tests the antenna with a handheld analyzer. b) Another group used a self-built horn antenna to feed an offset parabolic dish.

So far groups have chosen to measure knife edge diffraction, wire grids, wall penetration loss and propagation loss in the outdoor urban environment. Two examples are shown in Fig. 3. Fig. 3a shows the group measuring knife-edge diffraction. They fixed a metal sheet on a cart, pushed it between transmitter and receiver, measured the sheet position with measuring tape and wrote down the received power for each position. Fig. 3b shows a student on the institute roof making contacts with other amateur radio operators. A laboratory protocol of around ten pages is the basis for grading a working group.

Required Course Equipment —

- Tools, preferably a small workshop
- Amateur radio transceiver; We have found that for millimeter wavelengths self-built kits or combinations of short-wave transceivers and transverters are the cheaper options.
- Measurement equipment: oscilloscope, vector network analyzer, PNA-X
- Components and expendable materials. Students enjoy to continuously improve the setup over the years. We budget about thousand Euros per year (e.g. parabolic dish, amplifier, transverter, tripod, cables).
- *Optional:* anechoic chamber

(a) (b)

Fig. 3: Students testing 10 GHz propagation. a) The students need to come up with their own solutions to practical problems. This group has decided to measure knife-edge diffraction by mounting a metal sheet on a cart that they push. They measure its position with measuring tape that the spanned across the room. b) A student has built a mobile setup and is transmitting on the institute roof to test urban propagation.

V. Conclusion

Practical courses on antennas, propagation and wireless communications are further improved by competence-oriented teaching. The courses teach specific competences that are useful to the students in their careers. Foci on general education, industrial development and scientific research are possible, as is demonstrated on the example of three competence-oriented courses. Competence-orientation requires the supervisors to design laboratory exercises to be less scripted and less supervised. Competence-orientation grants the students additional autonomy during the exercise and the certainty that they can apply their theoretical knowledge in practical szenarios.

For many students it was the first time that they transmitted with a radio. Besides in-depth theoretical analysis, they needed to design experiments, analyze and discuss their findings, and now have first-hand experience in signal-to-noise ratio, fading, interference, skip zones and many other important concepts. Students can test their own hardware in *real* two-way contacts.

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