A Practical Approach to Cellular Communications Standards Education

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***Abstract*—**The cellular communications industry is steadily growing and expanding to solve the needs of governments, businesses and communities. Standards are fundamental to enable cooperation while promoting competition. The companies involved contribute and agree on appropriate technical specifications to ensure diversity, compatibility and facilitate worldwide commercial deployment and evolution. The specifications of cellular communications standards are extensive, complex and intentionally incomplete to spur innovation and differentiation. This makes standards education a difficult endeavor, but it is highly demanded by the wireless industry. This paper describes a practical approach to teaching cellular communications standards. Our methodology leverages software-defined radio technology and uses the abstraction layer and operating environment (ALOE) to provide a practical learning environment that facilitates developing many of the needed technical and soft skills without the inherent difficulty and cost associated with radio frequency components and regulation. We define six learning stages that assimilate the standardization process and identify key learning objectives for each. We discuss our experiences when employing the proposed methodology at Barcelona Tech in Spain, compare the approach with an equivalent class at Virginia Tech in the US and make the following observations: (1) The complexity of standards need to be abstracted and presented in a form suitable for a given class. (2) Educating about cellular communications standards is most effective when students are immersed in the process. (3) Hands-on activities need careful preparation and close guidance.

1 Introduction

The wireless telecommunication industry has grown tremendously since the first cellular system was deployed in 1983. Digital techniques were introduced in 1993 to accommodate the huge boom in subscribers of portable telephone service in the mid 90's. Cellular communications systems evolved from providing voice in the mid 90's (2nd generation or 2G) to all-IP data services that are available since 2011 (4G). Advanced mobile broadband and real-time control will be enabled by future 5G systems. Wireless systems that provide personal and machine-to-machine communications currently constitute a major research area of vital importance.

Telecommunication standards have become a catalyst for technological innovation because of the way standards are defined. Standards become a tool to coordinate efforts of various stakeholders while preserving competition. They are necessary to ensure diversity, compatibility and facilitate worldwide commercial deployment and evolution. A company can take benefits of economies of scale, build or strengthen collaborations, and participate in the standardization process to impose its technology and grow its business. The potential of standards to spur economy and impact society is apparent more than ever in the increasingly globalized world. Standards developed by the 3rd Generation Partnership Project (3GPP), a consortium of several standard setting organizations (SSOs) that standardizes cellular communications, have led to an estimated global revenue of more than $3.3 Trillion in benefits and more than 11 Million jobs in 2014 [1]. A Billion human users enjoy wireless communications services today and tens of Billions of machines, cars, appliances, etc. will soon be networked.

Industry and academia collaborate on the evolution of cellular communications networks and on the design of next generation networks. Research, in part, shapes standards and helps refining them. While wireless communications technology is evolving towards 5G, 3GPP is finalizing the seventh major revision of the long-term evolution (LTE), which was introduced in 2008. LTE has created many new jobs in the wireless communications industry and is the de facto 4G mobile broadband standard. Implementing or evolving a complex standard, such as LTE, is challenging for anyone, but can be overwhelming for fresh graduates. The 3GPP specifications are written in an unusual language and are convoluted, requiring a steep learning curve. The technical reasons for specifying one parameter or technique over another are difficult to understand, since the standards do not provide explanations or justifications, and oftentimes have historical, political, or economical foundations. Typical parameter values that can be useful for implementing an algorithm are often difficult to find in the specifications, which encompass of many documents and scattered information. Despite the minimalistic and formal description, standards have been developed with implementation in mind, where those parts of the system that can create competitive advantages are intentionally left unspecified. All this makes the cellular communications standards education a difficult endeavor, but it is critical for the technological evolution and economic growth.

A standard is a tool that seeks transitioning from theoretical, simulation and experimental results to real-world implementation. It combines wireless concepts with system implementation and addresses conformance, interoperability, operation and management tasks. The specifications are a series of documents that define the standard and the operational modes of the system. The skills that are needed to implement a standard-compliant communications system are rare to find in fresh university graduates without industry experience. Even after completing a PhD degree in electrical engineering, graduates often lack implementation or advanced programming skills and have trouble assimilating the constraints of real-time systems. At the university, a student learns how to solve a particular problem, analyze the available solutions and develop alternative approaches. But, until actually implementing an algorithm and facing the practical challenges in terms of complexity and performance, the student does not fully understand the true differences and practical implications of selecting one algorithm over another. Standard-specific implementation, compliance and performance assessment would thus be a valuable addition to the electrical engineering curriculum.

We argue that the reasons behind the technical choices, their impact on the resource consumption and the performance versus flexibility tradeoffs are relevant for cellular communications standards education. Moreover, project management, team work, development of realistic expectations and practical solutions are skills that are much demanded by industry in addition to domain-specific technical specialization. We therefore propose a methodology for teaching standards that creates favorable conditions for developing those skills.

The combination of lecture-centered education [2] with laboratory-centered approaches [3], [4], has been adopted in the engineering curriculum when the *Conceive, Design, Implement and Operate (CDIO)* methodology appeared in the last decade. CDIO defines a structured methodology to translate the expected educational outcomes to the curriculum [5] - [7]. Whereas lecture-centered education is considered one of the most effective learning methods [2], it is often criticized for not helping students to transform their knowledge into skills. Laboratory work clearly enhances student skills and helps consolidating the acquired knowledge. Other cognitive techniques that help addressing the development of the required skills include (1) the *scaffolding* approach, where the students receive some support from the instructor, who incrementally reduces this support, (2) the *collaborative learning* approach, where the collaborative process gives students the possibility of sharing thoughts to approach a valid solution [8], and (3) the *student-centered learning* approach that attends the specific student needs [3].

Implementation-orientated active learning methods, such as project-based learning (PBL, http://www.bie.org), provide a student-centered learning environment appropriate for the purpose of cellular communications standards education. PBL follows a hands-on learning approach, where a group of students learns while doing and where each student contributes to the project by sharing experiences and learning perspectives. Diverse team members provide complementary skills that can be leverage in the teamwork. Learning by doing has been a major breakthrough in engineering education, inspired by how humans learn and what mechanisms they activate when thinking at a higher level [9]. PBL also has drawbacks. Students typically experience difficulties to initiate their project and do not reach the necessary depth when lacking sufficient background knowledge [10]. An interesting proposal to overcome this issue is the spiral step-by-step method [11], where information is grouped into stages and sequentially provided or acquired by the students.

We describe a PBL methodology for teaching cellular communications standards and apply this methodology to 4G LTE education. It is based on the standardization process itself and aims at guiding the student through it. We define our methodology around six learning stages—*context*, *design*, *expectations*, *implementation and testing*, *revision* and *presentation and evaluation*. We describe the stages, identify the key learning objectives for each, and specify the student and instructor roles. Our methodology leverages open-source software-defined radio (SDR) software that implements pieces of the standard. The use and development of this software by the students are aligned with the learning stages and objectives. This creates a practical learning environment that facilitates developing many of the needed technical and soft skills without the inherent difficulty and cost associated with radio frequency components and regulation, among others.

Our approach is based on our experience and belief that approaching standards education from a practical perspective is the most effective way of getting familiarized with the standardization process and the specifications of a standard. This is in clear contrast to alternative ways of teaching cellular communications standards, such as having the students read and summarize selected standards documents or having the instructor present the specifications. On the other hand, putting the focus on a narrow problem without providing the big picture is the risk of our method. Hence we propose a guided hands-on approach, where the instructor sets the expectations and provides background information at different stages of the learning process. The students use a rich set of tools that allow them to quickly immerse into the standard and develop, analyze, improve and present their solutions to the class.

Using only open-source software and commercial of-the-shelf computers, our software framework is portable and can easily be recreated at other educational institutions and adapted to their needs and constraints; the learning stages and objectives can be adapted as well. We discuss our experiences when employing the proposed methodology at Barcelona Tech in Spain, taught by one author, and compare the approach with an equivalent class at Virginia Tech in the US, taught by the other authors.

2 Enabling technologies

SDR technology and the availability of software libraries (Table 1) facilitate implementing and running a complete radio systems in class. These software libraries allow gaining experience with radio communications systems at low cost. But, unless actually modifying or complementing these software suites, e.g. by implementing features of newer releases, students do not become truly familiar with the standard, its specifications, and releases.

Table 1. Excerpt of SDR software libraries and frameworks.

Library/Framework	**Description**
liquidDSP	Open-source DSP library for building radio transmitters and receivers with support for various SDR/RF front ends
GNU Radio	Open-source framework for building radios in software with support for various SDR/RF front ends
REDHAWK/SCA	REDHAWK is an open-source framework supporting the development, deployment and management of SDRs. It is based on the software communications architecture (SCA), a set of specifications for building interoperable SDRs with support for distributed processing
ALOE	Open-source framework for real-time processing and control of waveforms with support for various SDR/RF front ends
openBTS	Software that allows implementing and running an GSM base station on a general-purpose processor interfacing an SDR/RF front end
Amarisoft	Software that allows implementing and running an LTE base station or user equipment on a general-purpose processor interfacing an SDR/RF front end
Open Air Interface	Open-source software implementing the LTE protocol stack on a general-purpose processor with support for various SDR/RF front ends, including an in-house developed custom board
srsLTE	Open-source software implementing the LTE protocol stack (base station and user equipment) on a general-purpose processor with support for various SDR/RF front ends

SDR technology intrinsically supports hands-on learning and enable rapid prototyping and practical analysis. We therefore advocate for using SDR tools to implement, validate, and evaluate the performance of a cellular communications standard. SDR development and implementation frameworks, such as REDHAWK or the software communications architecture (SCA)—primarily used in military radios [12]—, GNU Radio—primarily used in research and education (http://gnuradio.org)—, and the application layer and operating environment (ALOE)—also used in research and education (http://flexnets.upc.edu)—, have certain features in common with the specifications of wireless communications standards. SDR frameworks concatenate software modules and support access to external equipment though application programming interfaces (APIs). They facilitate building radios (GNU Radio), distributing the processing (REDHAWK/SCA) and dynamically reconfiguring the radio (ALOE).

ALOE is an open-source SDR framework that is specifically designed for the implementation of modern radio systems [13]. It takes advantage of the regular data flows of digital signal processing chains (waveforms). The framework abstracts heterogeneous multiprocessor platforms, provides a packet-oriented network with FIFO-based interfaces between processors, and coordinates real-time execution of the entire system. Its modular design and encapsulated services facilitate selecting only the desired framework functionalities. This customizability translates to low memory and time overhead [14]. ALOE monitors the computing cost of every processing module as well as other critical system parameters in real time. It facilitates switching from a simulated channel to over-the-air transmission by readily supporting external SDR front ends.

3 Cellular communications standards education: methodology

A wireless communications standard defines the physical and logical components of the system, their interfaces, the different processes, performance requirements, and so forth. The functionalities are split into basic functions which are formally presented in the specifications, only once, following the established document organization and indexing. These functions comprise algorithms, often expressed as one or more mathematical operations or one or more tables, and interact with other functions through well-defined interfaces to provide the desired functionality.

Instead of reverse-engineering the standard, building the standard out of fundamental building blocks aligns well with the human learning process. A student thus needs to analyze the basic functions first and combine them into a larger functionality to achieve the desired subsystem and, eventually system behavior. Many basic functions are introduced in prior undergraduate and graduate classes. The student can here focus on learning how to use these functions in concert to build subsystems and systems according to the specifications. The hands-on assembly of functions and the analysis of how these functions work together and how they affect the system performance allows gaining deeper insights into the standard.

Our methodology is founded on providing an initial and incomplete system implementation and defining assignments that lead to gradually building the system, validating and testing it for standard compliance, and evaluating its performance. Students obtain grades from measurable system performance results. The intrinsic motivation for students to make the system work helps them acquiring a solid background of the technical details and underlying fundamental technologies of a standard.

We propose to divide the class in groups of five or six students. Inspired by the *scaffolding* and *spiral step-by-step* educational methodologies, after providing a high-level overview of the standard under study in the first quarter of the class, we narrow down the focus and look more closely at specific parts of the standard. Once the implementation is complete and provides the desired functionality (about two quarters of the class period), the students investigate how the developed parts impact the overall system performance, measure and analyze standard compliance and discuss the technical decisions (last quarter).

The development and testing, which constitute the main part of the class, is regularly monitored by the professor and the students describe their progress and the troubles encountered during the weekly sessions, followed by discussions about the adopted solutions and the roadmap.

The student evaluation is proposed at two levels. The first level is related to the achieved results and the delivered documentation that describes the work done, justifies the decisions made, and analyzes the system performance. A second level of evaluation is provided by each team member. They, better than anyone else, know the level of commitment and responsibility of each participant. This aims at teaching cooperation, communication, and teamwork, which are all very important skills for future engineers, as well as researchers or developers.

The proposed methodology balances the teaching material and assignments to fit the available class schedule, while accommodating the specific learning objectives that the instructor considers of highest relevance. The overarching learning objectives are:

- Effectively read specifications and find the needed information,
- Design and implement a cellular communications system that is standard-compliant,
- Discuss the pros and cons of alternative technical solutions, and
- Debate possible evolutionary paths for the standard being analyzed.

We propose six learning stages with specific learning objective in each stage. These are described in continuation.

3.1 Context

The student needs to get familiar with the standard and the standardization mechanics. The instructor thus provides

a) A high-level description of the standard with certain details, describing theoretical concepts and employed technologies, identifying relevant working parameters and expected system behaviors,
b) The standard specifications and the relationships among the main and auxiliary documents, and
c) The introduction to the software framework to be used in the following stages.

According to our working approach and time limitations, we propose traditional tutorial sessions taking up no more than two or three lecture periods.

After completing this module, the student will be able to

- Identify, at a high-level, the critical components of the standard, the relations among key components of the standard as well as some of the important options and tradeoffs, and
- Formulate the information of interest using the standard’s terminology and identify the specifications that contain the relevant parameters.

3.2 Design

For wireless communications standards, the physical (PHY) layer is a key component of the system and is, therefore, a candidate for more detailed analysis. It is where the heavy processing takes place on real-time data. By abstracting the PHY, other parts of the standard can be analyzed, instead.

According to the project specification and milestones, defined by the professor, the student teams are tasked to develop a system model and document it properly. This model should identify not only the functional blocks and their interconnections, but also the working parameters and the resources needed. An initial implementation of the processing chain and its model are provided as a reference.

After completing this module, the student will be able to

- Assemble a model of the main processing chain of the standard-specific transmitter and receiver, and
- Discuss the processing tradeoffs and how they impact key performance parameters, such as synchronization, throughput, latency, and spectral efficiency.

3.3 Expectations

The complexity of modern wireless standards and the limited course duration require narrowing down the focus of the projects to specific aspects of the standard. Such focus could, for example, be on breakthrough technology that distinguishes this standard from its predecessors or emerging technology enabling the evolution of the standard. According to the specific project goals, students need to identify those parts of the specifications that require a deeper analysis. We suggest two main activities to be carried out by students under the close supervision of the instructor:

a) *Define Conformance Tests* to be able to later verify the suitability of the proposed implementation w.r.t. the project specifications, which are based on those defined in the standard, and
b) *Define Performance Tests* to analyze the impact of the chosen techniques on the overall system performance.

Along with defining those tests, the team develops a set of figures of merit (FOMs) for both types of tests and uses those to quantitatively characterize the performance of the system w.r.t. the project requirements.

Developing appropriate FOMs and test plans and analyzing how these are specified in the standard is a very valuable educational experience. Regulated tests allow interactions among the stakeholders (device manufacturers, network operators, service providers, etc.), enabling compatibility and interoperability of user handsets and cellular networks, among others.

After completing this module, the student will be able to

- Identify the key figures of merit (FOMs) for a system of interest, and
- Design performance and conformance tests based on the FOMs while taking into account the practical circumstances and limitation.

3.4 Implementation and testing

This is the core part of the proposed methodology, where the students implement part of the standard they have previously examined and designed and then analyze their implementation using the specified FOMs. The availability of a partial system implementation facilitates this phase and narrows it down to fit the course schedule. Students build the processing chain for their project from the standard specifications using the provided tools and the provided baseline implementation. The system components and the subsystems need to continuously *validated* for correct functionality using test vectors and known output statistics.

The second testing phase evaluates the system or subsystem for *conformance*, based on the FOMs defined in the previous stage. The results obtained from the conformance tests are validated by the instructor. In case of failure, an analysis of the implications on the overall subsystem performance follows. The team then makes a decision whether to continue or go back to prior stages to solve the problem at its roots.

Once the conformance tests are satisfactory, the third testing phase can be carried out. The *performance* tests benchmark the system. The results are analyzed by the team in two substages: (1) analyze the system or subsystem performance w.r.t. the expected performance and discuss the differences, if any, and (2) devise corrective strategies if system performance does not match the expected results and discuss alternative solutions to further improve the system performance.

In some cases, both conformance and performance test may require the use of simulated channels, whereas in other cases controlled over-the-air transmission and reception would be more appropriate.

After completing this module, the student will be able to

- Implement the design from available building blocks, and
- Test and evaluate the implementation in terms of functionality, compliance with the standard specifications (conformance), and performance.

3.5 Revision

After successful completion of all the tests, the students revise their system. In case of unsatisfactory results, an analysis is conducted to identify the cause. This could need a new design, new FOMs or tests, a revision of the overall project goals, or even a revision of the standard [15].

After completing this module, the student will be able to

- Identify where failures happened and discuss short-term remediation techniques as well as long-term solutions, and
- Revise the system or process, if needed, and design a possible system evolution.

3.6 Presentation and evaluation

The student teams document their work and provide a well packaged and documented software library. The report contains a general overview of their system and describes any relevant details and procedures. All student groups demonstrate the operation of their system to the class in a session that could be made open to other faculty and students.

After completing this module, the student will be able to

- Demonstrate how objectives have been met and what process has been followed in obtaining the results,
- Compare the achieved results with alternative solutions, and
- Properly document the project and effectively present it to others.

4 Cellular communications standards education: LTE case study

Wireless Communication has been taught as part of the Master of Science program at Barcelona Tech for more than 10 years. It applies PBL and teaches wireless communications standards, including 3G Universal Mobile Telecommunication System (UMTS), 4G Worldwide Interoperability for Microwave Access (WiMAX) and 4G LTE. The results presented in this section were extracted from the documentation presented by the students. In particular, we discuss the project titled “Computational cost of the LTE PHY,” which was carried out by multiple student groups in 2012-2014. Starting with a baseline implementation, the project objective was to implement the missing pieces of the physical downlink shared channel (PDSCH), the data channel of LTE, and analyze the impact of adaptive modulation and coding in terms of system performance as well as processing complexity. LTE defines nearly 30 modulation and coding schemes (MCS) and employs the turbo decoder, which is an iterative decoder based on two convolutional decoders.

The LTE base station, or eNodeB, assigns the mobile terminal, or user equipment (UE), the highest possible MCS according to the traffic conditions reported by the UE through a series of parameters. Changes in the MCS are notified to the UE receiver as part of the control signaling. The UE decodes the control messages and accordingly modifies the operational parameters of the receiver processing modules. We provide a simplified LTE PHY layer processing chain through ALOE, which features the eNodeB transmitter, UE receiver and a simulated channel. The students download and install ALOE on their computers and do not need any additional hardware.

4.1 General overview of 3GPP LTE

The learning process here follows a traditional approach, where the instructor provides an LTE tutorial in two or three sessions that covers the following:

- Overall LTE architecture description and functional split.
- Radio protocol architecture: A description of functionalities of user plane and control plane signaling.

- Fundamental resources, timing, multiuser access and scheduling.
- LTE PHY: Logical and physical channels and mapping to physical resources, synchronization, retransmission protocol, and so forth.
- System performance metrics.
- Conformance test and RF regulation.
- Organization of the LTE specifications.

The LTE tutorial includes a description of how LTE specifications are organized with emphasis on how the Technical Specifications Group on Radio Access Networks (TSG RAN) and their working groups (WG) specify the LTE air interface. A flavor of the information provided to the students is shown in Figure 1.

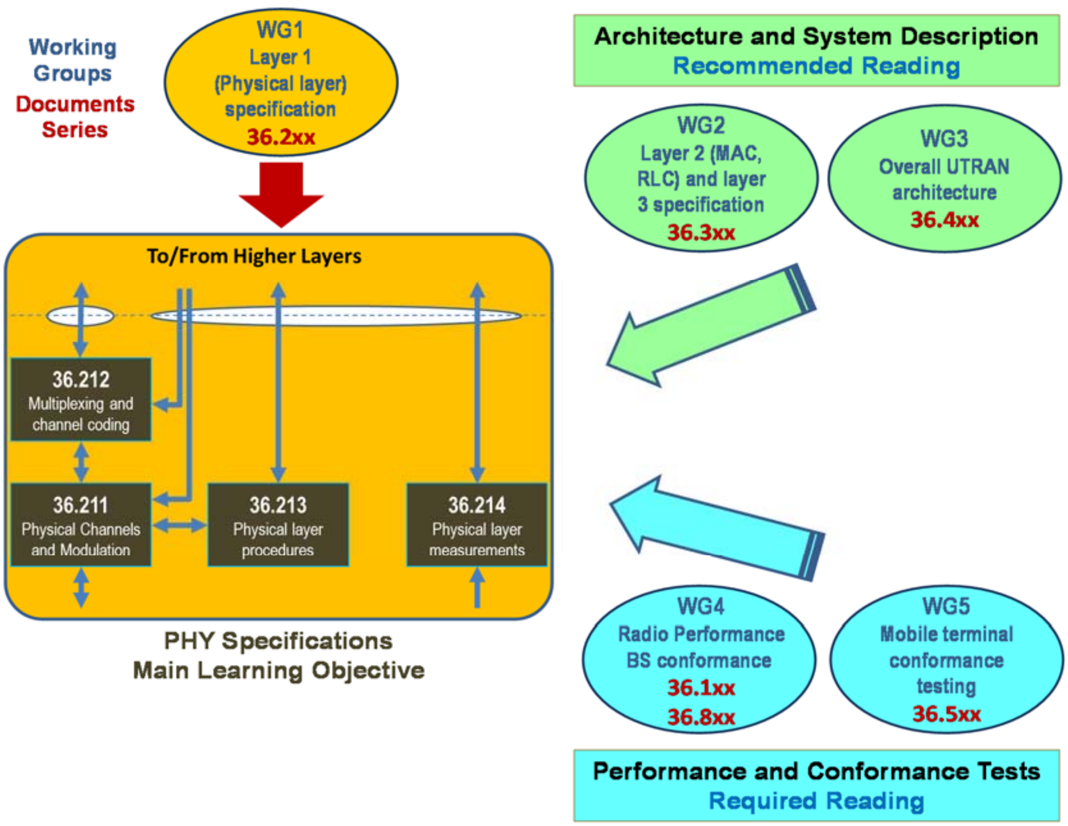

Figure 1. Working groups and documents specifying the LTE standard relevant to the class projects.

Observing the student progress over the years we found that the tutorials should be defined around a handful of key themes and involve the students. A technique that has worked well is having the students summarize each session based on a template and specific questions that emphasize the key take-home messages. This way the students obtain a general overview of the LTE standard, how the specifications are organized and how to search for details.

Following the LTE standard overview, a short ALOE tutorial provides the necessary resources for the students to start developing their projects.

4.2 Design: modeling the processing chain

Student teams develop a connected graph that illustrates the LTE PHY layer processing chain. One realization is shown in Fig. 2 and illustrates the simplified PDSCH transmitter and receiver. The blocks represent processing functions or processing chains and are specific to the LTE standard (http://www.3gpp.org/). A red circle indicates that the module is fully implemented, a green circle that only partial implementation is provided and no circle that the corresponding module needs to be implemented from scratch.

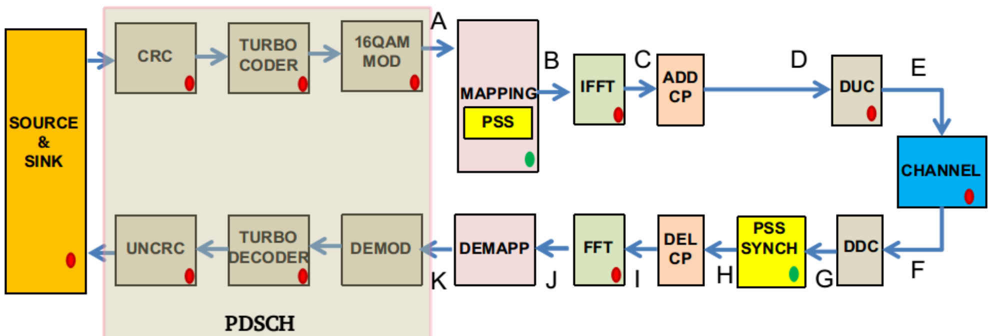

Figure 2. Modeling the PDSCH PHY layer processing.

Such high-level modeling along with the analysis of relations among modules and functionalities and the impact of some of the important parameters provide a good perspective for addressing the implementation and analysis of the system.

4.3 Expectations: validation, conformance and performance tests

One way of narrowing down the focus is analyzing the impact of the MCS on the LTE system performance. By measuring the computing cost, the system performance can be plotted over computing overhead to emphasize the growing importance of computing in modern wireless systems.

The student teams define the following tests to validate the system and analyze its behavior:

- *Validation tests:* These are defined to ensure compliance of the generated data and signals with those defined in the LTE specifications.
- *Conformance tests:* The second set of tests validates the system behavior using appropriate metrics.
- *Performance tests:* The performance tests measure the block error rate (BLER) and the computational complexity (processing time overhead) for a selected set of MCS values and different signal-to-noise ratios (SNRs) in a simulated channel.

4.4 Implementation and testing

After having defined the tests and FOMs in the previous stage, the students develop the partial system using a baseline implementation and perform the conformance and performance tests, after validation. The following figures and discussions, extracted from project documentations, provide insights about the quality of the work as an indicator of success of the proposed methodology.

A) System development and testing

Figure 3 shows the signals at the output of the MAPPING module (B in Figure 2) and at the input of the DEMAPPING module (J). We can compare both and notice similarities although the received signal is affected by channel noise. On the right side of Figure 3 we observe the correlation output of the synchronization module in the in-phase and quadrature channels. The subfigure below shows the spectrum of the generated bandpass signal ready for using an audio device for real transmission (sampling frequency 48 kHz). The terminal output at the bottom-left shows the instantaneous BLER and bit error rate (BER) values provided by the cyclic redundancy check (CRC) and the SOURCE&SINK modules respectively.

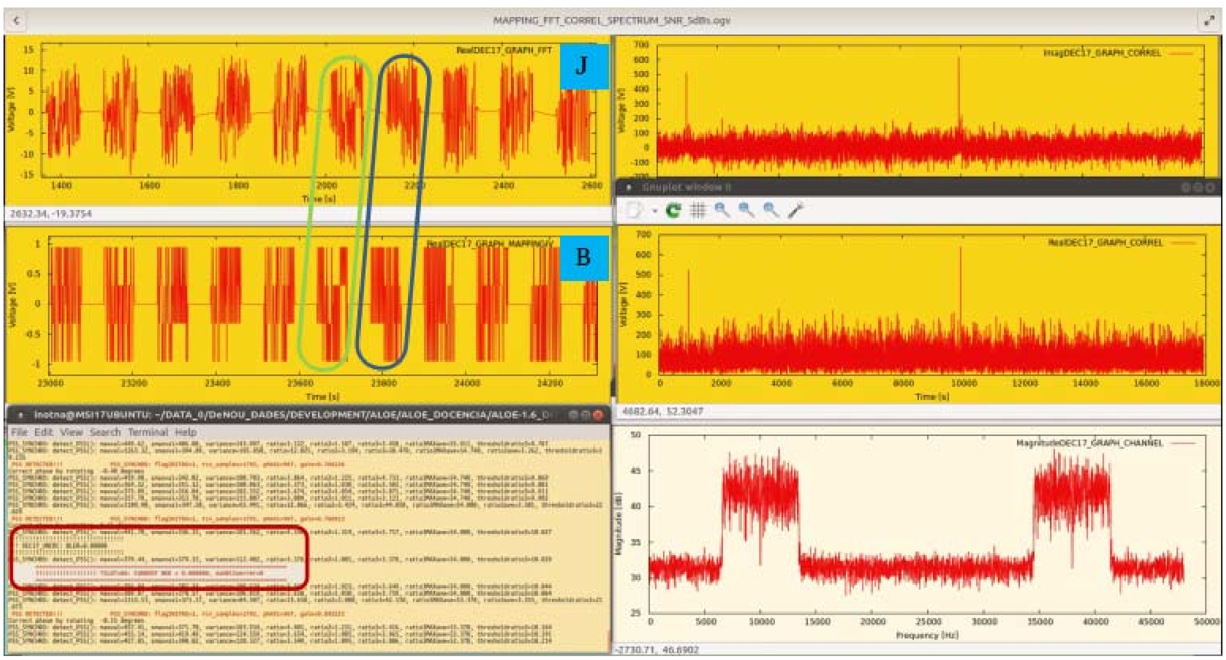

Figure 3. System operation.

The implementation process that follows evaluates the signals at appropriate points in the processing chain to check for the correct system behavior.

B) MCS and system performance

Figure 4 plots the BLER over MCS for different SNRs. It illustrates that the demodulation and decoding processes requires a minimum SNR to achieve the 0.1 BLER target, as suggested by the standard, and that this SNR is a function of the MCS.

The students learn how to use the iterative turbo decoder and they realize its relevance for error correction: When the receiver implementation does not fulfill the 3GPP LTE specifications, the number of iterations is increased.

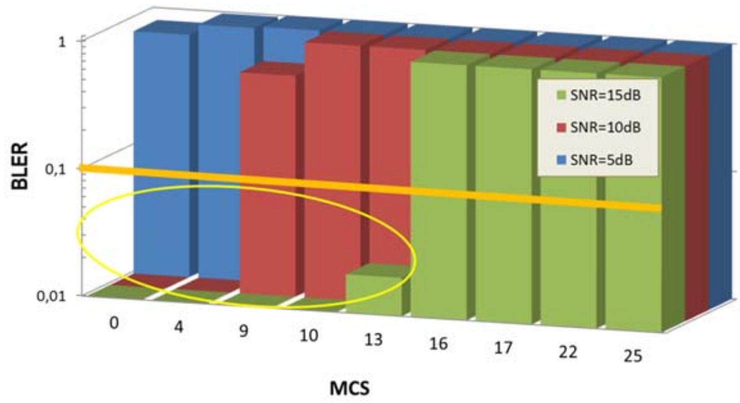

Figure 4. BLER over MCS for different SNR values.

C) MCS and computational cost

Figure 5 plots the user throughput and computing cost over MCS for 1.4 MHz LTE using the ALOE framework. These results were obtained with an Asus X200CA laptop (Intel Core i3-3217U) and the Ubuntu 12 operating system. Figure 5 is a result of analyzing the relationship between the transport block size—the number of bits transmitted in one transmission time interval—, the number of resource elements and the throughput. The nearly linear relationship between computational cost and MCS matches the expected behavior. According to the 3GPP specifications, an LTE UE can send one of 16 Channel Quality Indicators (CQI) to inform the eNodeB about the highest MCS that it can decode with a BLER not exceeding 10%. The students learn that multiple MCS values can meet the BLER target, but that each has a specific computational cost. Notice the elevated computational cost for MCS 17, 22 and 25, which employ 64 quadrature amplitude modulation (QAM).

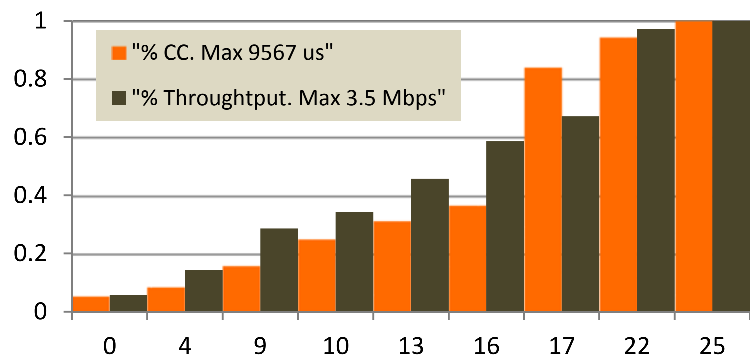

Figure 5. Computational cost and throughput over MCS (one decoding iteration). The PDSCH uses three modulation schemes, 4, 16 and 64 QAM, mapping 2, 4 and 6 bits to one modulation symbol.

4.5 Revision

The students revise their system implementation continuously, starting from the provided baseline implementation. Misalignments between the implementation and the specifications are analyzed and corrective measures discussed. Increasing the number of turbo decoding iterations has an impact on the BLER, but also the computational cost. The students experience such tradeoffs and discuss solutions from different viewpoints.

Improving the LTE implementation requires advanced skills and more time. Some of the aspects discussed by the different groups include a) speeding-up the processing requires an optimized implementation; b) more detailed documentation of the baseline implementation and the developed system facilitate making future changes to the code and adding more functionalities, and; c) mechanisms that identify bottlenecks in the development and any imbalance in the team member commitment early help achieving the project goals.

4.6 Presentation and evaluation

Student teams provide a comprehensive document summarizing the standard pieces they have analyzed in more detail, the phases of the project, the realized tests and accomplished results, conclusions, and suggestions for improvement. At the end of each semester, the student teams present their accomplishments with demos, videos, or posters in a demo/poster session. All class instructors and students assist this session, ask questions and make suggestions. The evaluation is, in part, based on how well a group presents their work with respect to the class learning objectives and the specific project objectives.

5 Comparison and observations

Classes that educate about the popular cellular communications technology and systems exist around the world. Two authors have taught the *Cellular Communication Systems* class at Virginia Tech. The graduate class offers a broad overview of cellular communications technologies and systems, and provides insights into important standards and the standardization process. It provides important knowledge to graduate students who wish to do research in wireless communications, or who wish to enter the telecommunication industry. The instructor reviews the fundamental theory and discusses how it is realized in practical systems and what the future trends are. The class mechanics are based on lectures that are interleaved with various in and out-of-class student activities, interactions and opportunities for research. Having successfully completed this course, the student will be able to:

- Design and compare different types of mobile, multi-user systems,
- Compare traditional and emerging cellular communications system architectures in terms of their components, interfaces, and interactions,
- Interpret the technical strategies in the design of LTE, and
- Debate technical features of emerging cellular communications technologies and systems.

These learning objectives are achieved through lectures and various assignments which allow specializing in certain aspects of a standard or technology. The semester class project offers the students the option to develop a system, such as the one described in the case study above, using a testbed [16] and software presented in Section 2. These projects are defined and developed by the students using the tools of their choice. The instructor provides guidance, but the projects are less structured when compared to the proposed methodology and case study presented before. In this class, students do public debates on competing standards. This is a competitive assignment that motivates the students to learn the standard they are defending and the pitfalls of the standard they are rebutting. Example debate topics from the past were on WiFi versus LTE in unlicensed spectrum or LTE-U versus licensed assisted access (LAA) versus MulteFire, the three variants of LTE in unlicensed spectrum [17].

Both classes emphasize group work, presentation of results and collaborative learning. The students in a class and across the two classes have different interests and prior experiences. Some are motivated and act as group leaders. Those students get most out of these classes. Other students deliver good work, but too narrow and specific. A balance is thus needed to gain broad knowledge without abstracting too many details. The Barcelona Tech class is providing this broader vision bottom up, where the students get exposed to a standard and connect to the fundamentals during all project phases and, especially, while conducting the analysis of their measurements during the testing, revision and evaluation phases. The Virginia Tech class follows a top down approach, where the instructor provides a broad overview and the students analyze some of the specifics of a standard trough different class assignments.

The two classes consistently achieve the expected outcomes in terms of student performance, learning objectives, and instructor and class evaluations. We could observe a high student interest in 4G LTE, reflected by the students' efforts in mastering the corresponding class assignments and project milestones. Interestingly, at Virginia Tech we observed that this motivation spills over into other blocks of the class that discusses theoretical concepts and pre-4G standards. We received very positive feedback from the vast majority of the students in both courses over multiple years.

Having taught both classes and taking careful notes at the end of each semester, our main observations can be summarized as follows:

1. The complexity of standards need to be abstracted and presented in a form suitable for a given class. This requires careful preparation.
2. Cellular communications standards education is most effective when students get involved in the learning process. This could be through hands-on projects, discussions, debates, student lectures, or other activities.
3. Hands-on activities need careful preparation and close guidance by the instructor to be effective. Otherwise, if the students cannot properly complete the task and achieve a meaningful or desired result, they may treat it as just another assignment to check off for passing the class.

It is worth noting that both schools have a dedicated SDR class [18], [19].

6 Conclusions

Testing a prototype or product for performance or standard compliance is a valuable experience for electrical engineering students looking forward to contribute to current and next generation standards. The telecommunication industry is constantly looking for graduates with strong theoretical background as well as hands-on experience. This paper presents a PBL methodology for teaching cellular communications standards. Our methodology is divided in several stages and makes extensive use of SDR technology and the ALOE framework, which provides an effective working environment and baseline implementation for the project development within the confined class period. We have identified the learning phases and the main activities of students and instructors, the major difficulties and the proposed solutions, and evidence of the suitability of the proposed methodology. Since standards are developed with implementation in mind, using the specifications to build a (simplified) product provides the best way of gaining a solid understanding of the standard. Since the class period is limited, care needs to be taken to put the developed system into context and discuss the overall standardization process and its scope.

It is worth mentioning that dealing with prototyping is always a huge endeavor and that the ALOE framework, which deals with concurrent processes and real-time execution, is not easily understood by the students. Nevertheless, the advantages of using SDR tools overcome their drawbacks: The availability of software modules, the capacity to work in parallel, rapid prototyping, switching between simulated channel and the use of real RF equipment, and the measurement tools embedded in the framework allow building standard-compliant systems and subsystems at low cost and with reasonable effort. The proposed methodology is based on the identification of some of the key skills that are demanded by the wireless industry and provides an effective learning environment for acquiring them.

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