Learning Mobile Communications Standards through Flexible Software Defined Radio Base Stations

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Abstract—Mobile communications are today widespread and contribute to the development of our society. Everyday new devices are including some means of wireless transmission, that is becoming ubiquitous with the Internet of Things (IoT). These systems are standardized by international organizations such as the IEEE, 3GPP or ETSI among others. Even though the knowledge of wireless standards is key to the understanding of these systems, wireless communications are quite often taught in Engineering degrees in a traditional way, without much emphasis on the standardization. Moreover, strong focus is often placed on the theoretical performance analysis rather than on practical implementation aspects. In contrast, most of the current applications make an intensive use of mobile data and the global users' satisfaction is highly correlated with the mobile data throughput. Thus, modern wireless engineers need to have a deep insight on the standards that define the mobile transmission systems, and this knowledge is not acquired following the traditional theoretical teaching schemes. In this paper, a new learning approach is described. This novel paradigm is based on a new flexible hardware/software platform (FRAMED-SOFT) that is also detailed. Although the paper is focused on two wireless standards, namely Global System for Mobile communications (GSM) and Universal Mobile Telecommunications System (UMTS), the work here discussed can be easily extended to other standards of interest, such as Long Term Evolution (LTE) and beyond, WiFi or WiMAX.

Index Terms—GSM, UMTS, LabVIEW, standards, USRP, cooperative education, flexible platform for learning, learning mobile communications

I. Introduction

Mobile communications are nowadays worldwide deployed and their applications are in continuous growth. In fact, our economy and everyday's life are conceived today around mobile communications. The Internet of Things (IoT) and the new generation of smartphones which include access to social networks are just two examples of how ubiquitous communications have become and this trend is foreseen to continue in the future.

However, a reliable yet efficient and universal wireless technology is not easy to design, deploy and manage. In this heterogeneous scenario, many different wireless systems will cooperate and interact. Indeed, the mobile engineers of the future will have to start from the traditional and current communications standards and evolve them towards a new generation. For this purpose, they need to have a deep knowledge and insight on wireless standards and their practical implementation. Specifically, in this paper we focus on two well established wireless standards, namely, Global System for Mobile communications (GSM) and Universal Mobile Telecommunications System (UMTS). Anyway, some of the work that we discuss can be easily extended to Long Term Evolution (LTE), or even to other wireless systems such as WiFi or WiMAX.

According to our experience, it is highly demanded that new communication engineers have a good experience in practical aspects of wireless communications, besides a very strong theoretical knowledge of these technologies. This insight can only be acquired through the laboratory work and practical experience. In this sense, Software Defined Radio (SDR) can be a good option for the students to approach the real world in the industry, and prepare them for the professional requirements they will face after finishing their studies. This requires a new learning paradigm where flexible equipment is used by the engineering students and instructors, including cooperative education which ensures that the students will be able to perform a team work.

Some previously published papers highlight the benefits of teaching practical communications with SDR platforms. In [1] the work developed in six U.S. universities is presented showing how they have integrated in their curricula the SDR, most of them including a significant laboratory component. The authors of [2] focus on the practical challenges found in designing and implementing wireless communications that are overlooked when focusing only on the theory. They show how their students have improved their skills when working with the Universal Software Radio Peripherals (USRPs) of National Instruments (NI). [3] describes the development of a hands-on open-courseware using very low cost SDR devices such as the RTL-SDR, which can be used in combination with Matlab to enhance the teaching of the principles and applications of digital signal processing and communications theory. [4] presents a summary and comparative of hardware and software alternatives by examining four case studies of application of SDR in industry, academia, and government. All these works show experiences of using SDR in teaching focusing on the principles and fundamentals of communications. Also recently, some commercial communications design frameworks are starting to include some libraries that cover standards such

as GSM or LTE. However, their focus is on the commercial system development and not on learning. Therefore, many important practical aspects are already solved and they are not illustrative for learning purposes.

Complementary to these approaches, in this paper we present our experience, where we have prepared and exercised with the students some practical work based on well-known wireless communications standards. After discussing the available platforms and recent work, we explain our proposal: a novel SDR-based platform denoted as Flexible Radio Access Mobile Environment Defined by SOFTware (FRAMED-SOFT). We provide a detailed description of the hardware, the developed software and the contents of the practical work performed by the students. The paper finishes with some conclusions about the learning methodology and the students perception of the experience.

II. HARDWARE/SOFTWARE PLATFORMS AND RECENT WORK

The use of SDR is rapidly expanding and these devices have become a very useful tool to prototype new algorithms and evaluate them in a real-world environment [4]. The following SDR platforms are of widespread use: Ettus USRP N200/N210, ZedBoard with Xilinx Zynq-7000 FPGA & AD-FMCOMMS5-EBZ, NooElec NESDR Mini SDR USB Stick and Ettus USRP E300. A detailed comparison of them can be found in [4]. Besides these platforms, there exists a programming system called RF Network-On-Chip (RFNoC) developed at Ettus Research to ease large SDR designs implemented in Field Programming Gate Array (FPGA).

NI offers the NI USRP-2920 which is functionally equivalent to Ettus USRP. It is equipped with two antenna ports that can be independently used for transmission or reception. The Digital to Analog Converters (DAC) and Analog to Digital Converters (ADC) are 400 Msamples/s with 16 bits per sample and 20 MHz of bandwidth. The operational frequency ranges from 50 MHz up to 2.2 GHz. These values enable the implementation of transmitters and/or receivers with enough quality and fidelity for many of today's communications standards, including GSM or UMTS.

The USRP needs to be handled with help of the Laboratory Virtual Instrumentation Engineering Workbench (LabVIEW) software which integrates all the tools that engineers and scientists need for the implementation of a wide range of applications. It is a graphical development software that easily allows the description and implementation of a complete system.

Within the LabVIEW interface, the NI LabVIEW MathScript RT allows the use of Matlab code directly into the LabVIEW designs. This is especially useful when students are not very familiar with LabVIEW, since they are generally familiar with Matlab. It is also practical when a complex algorithm is evaluated and refined first in Matlab prior to its hardware implementation.

Alternatively, open source software tools for SDR prototyping are currently also used because they potentiate a quick development leveraging a high community of users.

They include OSSIE [5], CubicSDR, ALOE [6] and the GNU Radio project [7]. However, due to our large experience with NI LabVIEW, their extensive range of products and their comprehensive and timely support, we selected LabVIEW to develop our platform.

Using these types of SDR hardware and software, several universities and some research institutions are including practical teaching for their students to better understand the communications concepts.

- The instructors of University of Strathclyde propose in [3] an open-courseware for SDR using the cost-effective RTL-SDR. With this receiver they can scan the RF spectrum and digitize I/Q signals within the range 25 MHz to 1.75GHz. The software used is Matlab and Simulink.
- El-Hajjar et al. in [2] propose a practical session using USRP and LabVIEW, where the students must build a Differential Quadrature Phase Shift Keying modulation (DQPSK) receiver. Besides, they present additional work that consists on building a PSK using Pilot Symbol Assisted Modulation (PSAM).
- Prof. Robert Heath uses NI USRPs and LabVIEW to teach digital wireless communication concepts at the University of Texas at Austin.
- Prof. Joseph Camp designed a course based on FPGAs and the FPGA-based hardware platform Wireless Open-Access Research Platform (WARP), for the School of Engineering at the Southern Methodist University.
- [8] shows the procedure to provide some wireless communication knowledge to engineering students with backgrounds in other areas. It is based on USRP and Lab-VIEW. In fact, they explain that they are replacing the WARP boards by NI USRP due to their enormous development in last years.

All these constitute successful experiences of teaching the principles of wireless communications in a practical way. They present the main building blocks of a generic wireless system, without particular focus on a given standard. Against this background, the proposed FRAMED-SOFT offers the possibility of working with real communication standards and real base stations, as it will be shown in section IV. This is indeed the innovation of our approach, namely, the focus on learning by experience the telecommunication standards. Our platform integrates a complete communications chain, including the bit generation, framing, modulation, coding and transmission of two representative examples of current mobile communications standards, such as GSM and UMTS. It is a flexible and modular platform that promotes cooperative learning among the students and is scalable to include additional building blocks of the system. Moreover, the student contributions are included in the platform to be used in the following years, promoting a continuous improvement of the platform.

Working with real standards prepares the students for the industrial experience. It also motivates them because they can practice with devices that they use in their everyday's lives. The course is oriented to undergraduate students. It shows

Fig. 1. The developed BTS including the hardware part with NI USRP (dashed box) and software part composed of the computer and the LabVIEW design

them some of the recent improvements in the evolution of the wireless communication systems, encouraging them to explore their own ideas. FRAMED-SOFT uses the NI USRP-2920 and LabVIEW as the hardware and software components.

The paper is focused on learning the portion of the GSM and UMTS standards related to the physical layer. However, higher level procedures established by the standards could also be envisaged to be dealt with our platform. In fact, those procedures are usually addressed by students in their Master Thesis, also using the platform here described. However, for the sake of conciseness, the details are not included in this paper.

III. CONCEPTS LEARNED WITH FRAMED-SOFT

As mentioned before, engineers need to have a deep insight on telecommunications standards because they will probably need to implement, improve or manage systems and services based on them. However, the standards documents are not easy to read and/or understand. More specifically, the portion of the standards related to the physical layer is hard to learn, not only because of the complexity of the specifications, but also because there are many external and internal factors that are involved and multiple disciplines that are required. Interference, handovers, coexistence among standards and technologies, signal processing, communication theory and hardware design are key ingredients to be considered.

Practical knowledge of the standards is often not included in the curricula of engineering. In fact, the traditional way of teaching the telecommunications standards relies on describing, with higher or lower detail, how the frame structure is formed and the modulation used for transmitting the signal. Besides, the channel coding and other procedures such as authentication, ranging, paging and resource allocation are also theoretically explained. All these explanations are necessary. However, often the knowledge is neither assimilated nor remembered by the students because of the high complexity and abstraction level of the topics.

When there is a chance to illustrate telecommunications standards with practical classes or laboratory sessions, showing how the signal is built and transmitted, the learning of these concepts is highly improved. Indeed, based on our experience, if these concepts are supported by current standards, students pay more attention. In order to consolidate this knowledge, realistic practical experience is needed to be offered to the future engineers. Moreover, industry is demanding engineers with these practical skills, a good knowledge of standards and the understanding of implementation issues [8].

In our practical work, students get familiar with the specifications of the standards and learn how to browse throughout them. They are able to find and understand the parts of the documentation describing what they want to implement. Besides, the students understand the importance of standardization in telecommunications experiencing two practical situations: they can implement a standard-compliant receiver that can be used with a working system, and, because of the interoperability allowed by standards, they realize it is straightforward to integrate different parts of a system performed by different students.

The FRAME-SOFT platform allows understanding the main concepts related to the implementation according to the standards of wireless communications systems as follows:

- **Transmission and Reception:** This includes all the aspects related to, among others, the concepts of pulse shaping, sampling, interpolation, bandwidth, amplifier design and automatic gain controllers. Working close to the real implementation, students need to deal with them and design algorithms to carry out the required tasks. They can check what happens when changing their parameters and they get more insight into real physical aspects related to transmission.
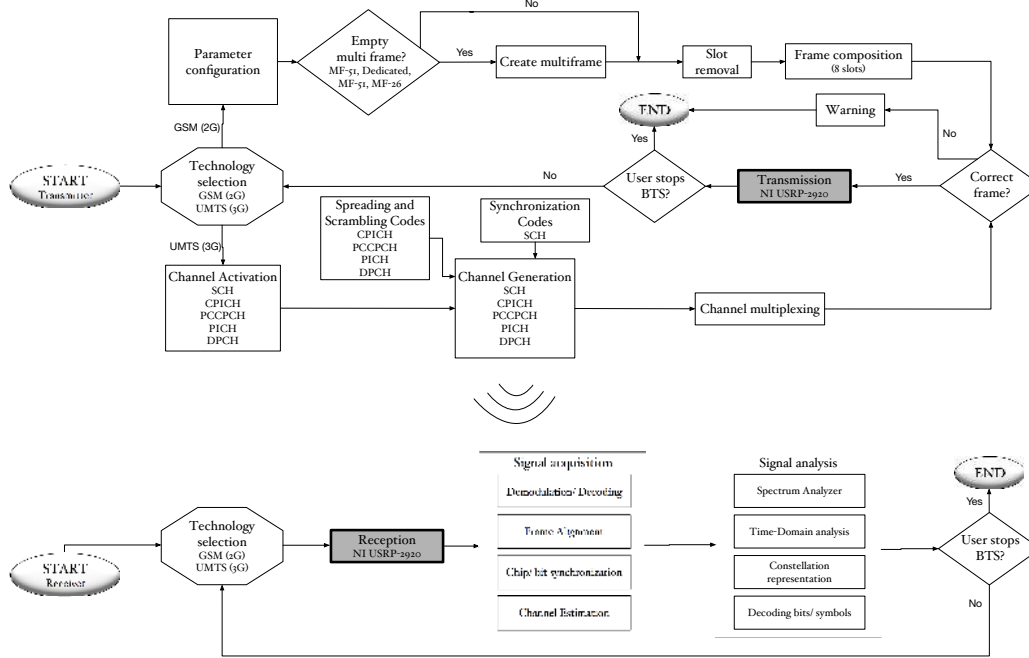
Fig. 2. Simplified FRAME-SOFT Diagram for GSM and UMTS laboratory.

- **Multiplexing and multiple access:** In the design of multiplexing/demultiplexing, students are dealing with the frame structure, frame detection and alignment and slot duration. According to our experience, this part is usually very time-consuming for the students due to the variety of schemes and algorithms that are involved.
- **Modulation and coding**: This deals not only with the modulation scheme, but also with other signal processing procedures associated to the transmission, e.g. spreading and scrambling in the case of UMTS. Block coding, turbo coding and advanced coding schemes for the new mobile standards must be considered. When designing each of these blocks, they are aware of their complexity and the interactions among blocks, as well as memory issues, overflows, etc.
- **Receiver algorithms:** Synchronization and channel estimation algorithms need to be designed and implemented to align signals in time and compensate the effects of the propagation channel. Although there are several algorithms already implemented in the platform, they can always improve them or design new ones. The delay is another important parameter and students realize here how it can compromise the performance and the quality of experience.
- **Signalling:** There are procedures in wireless mobile communications such as channel request, channel assignment, authentication, control signalling transmission and reception, resource allocation/management, etc. that the student will use and implement in the FRAME-SOFT platform.

Thus, after finishing our practices, the students are aware of the importance of standards and they are better prepared to join the industry, being used to working with them.

IV. THE FRAMED-SOFT PLATFORM

In order to support the new concepts and pedagogy described above to learn the wireless standards and in particular the physical layer, new tools and platforms need to be developed. These architectures must be flexible to allow the fast implementation of different standards yet powerful enough to be able to implement either the base stations or the mobile terminals.

SDR platforms such as the USRP-2920 from NI [9] possess those characteristics and thus, are perfect for our purpose. Two of these devices can be seen in Fig. 1, where the developed base station is shown (highlighted in a dashed box).

Thereby, an implementation with these tools will be composed of two parts, namely, the radio frequency and the baseband. The first one are the USRPs, and the second one is implemented in a host computer with a LabVIEW design.

By using the above described USRPs, the FRAMED-SOFT platform has been designed and implemented (see Fig. 2).

Although the same USRP could work simultaneously as transmitter and receiver (one antenna for transmission and the other one for reception), our design uses two different USRPs connected by the provided interconnection wire. In this way, the design is simpler, it allows the use of less powerful computers for controlling the USRP and it is not highly demanding for each USRP. Thus, it allows us to modify or optimize the transmission/reception parts independently.
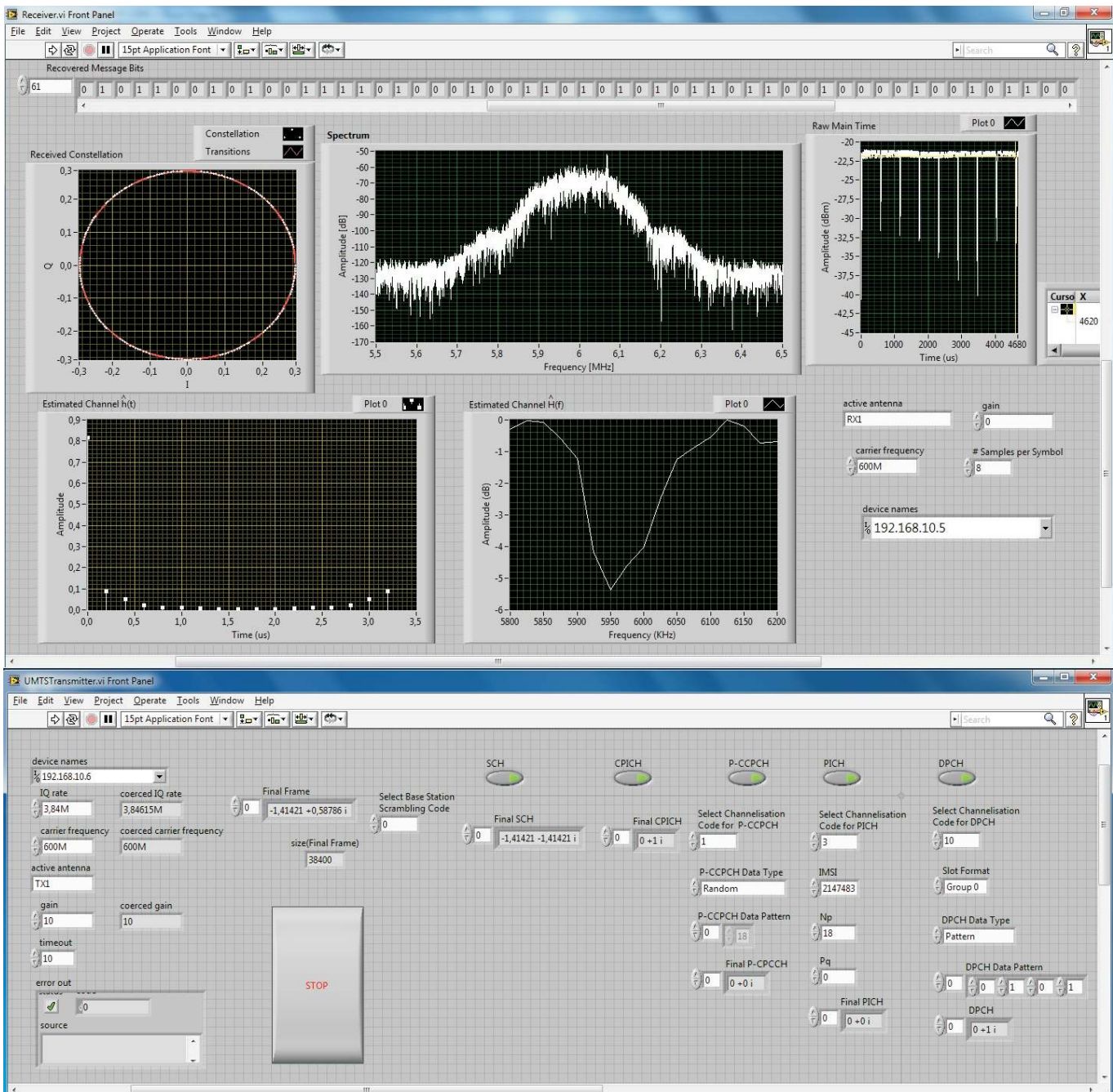
Fig. 3. Two examples of Front Panel for the FRAMED-SOFT tuned to 600 MHz. Upper part: GSM receiver showing constellation, frequency and time signal, channel estimation and received decoded bits. Lower part: UMTS base station showing the main transmission parameters that can be configured.

The software implementing the base station allows one to select the GSM or the UMTS standard. Depending on which one is chosen the adequate LabVIEW design is executed.

Since both standards are completely different from the physical layer point of view, two different designs have been implemented. However, from the logical point of view, both of them have several similarities. For example, both have a collection of specific channels for synchronization and channel estimation purposes, or for transmitting information or for control tasks[1]. All of these channels have been included and can be enabled or disabled. Since the platform is focused on the physical layer, the vocoder has not been implemented and it is emulated by random bits. However, since the platform is modular and flexible, higher layer procedures could also be easily included.

For the GSM standard [10] FRAMED-SOFT includes the formation of the different multiframes (MF-51, Dedicated MF-

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[1]Besides, there are many procedures, such as the paging, the resource allocation, the synchronization or the handover among others, that are very similar between technologies and all of them can be implemented in FRAME-SOFT.

51 and MF-26) following the instructions of burst composition and its corresponding information. The following channels are developed: FCCH, SCH, BCCH, AGCH, PCH, TCH/FS, SACCH/TF.

To build the main functionality of the UMTS base station, the following physical channels are implemented: DPCH, P-CCPCH, CPICH, PICH and SCH. As UMTS is based on WCDMA, the concatenation of specific spreading (channelisation) and scrambling codes is implemented for each physical channel according to [11] and [12]. Additionally, the SCH is generated to contain the synchronisation codes [11].

In Fig. 3, the front panel of FRAMED-SOFT is captured, where it is shown that in GSM, the multiplexing/demultiplexing is performed in the time domain (upper part of Fig. 3), while in UMTS it is carried out in the code domain. The different channels for UMTS that can be fully configured are shown in the lower the part of Fig. 3.

V. LEARNING AND GETTING EXCITED ABOUT THE PHYSICAL LAYER OF TELECOMMUNICATION STANDARDS

This section explains how the FRAMED-SOFT platform is used for introducing a new paradigm in the learning of the telecommunication standards. It is a complement and reinforcement to the traditional teaching. The students practice with the physical layer implementation, experience the concepts that they have previously seen in the theoretical classes and establish connections among concepts that were distant before.

The main idea is to involve the students as much as possible into their learning process. They are provided with the knowledge and tools and they are given some challenges to be solved while acquiring a realistic and practical insight. At the same time, we have seen that this methodology makes them enjoy while they learn.

Students involved in the course have full access to the complete LabVIEW version because of the existing agreements with National Instruments [13]. Thus, they can install the software at home. In this way, the students can implement their solutions at home and come to the laboratory to test their prototypes in the hardware. The platform also allows saving or loading signals from files. This allows, for example, the group working on the receiver to have access to a signal saved in electronic format at the transmitter side and be able to check their progress.

The variety of laboratory sessions is very rich. Some students can work with the transmitter while other students can deal with the receiver. They can choose between GSM or UMTS for their experiments. Moreover, once they have selected the element to work on, they can even focus more on which aspect to tackle.

Since the number of possible tasks is very large, the probability of plagiarism is considerably reduced, and this impacts in the learning improvement too.

A. Cooperative problem solving

The students can work on a stand-alone problem. For example, one student can deal with the channel estimation

and equalization at the UMTS base station, whereas another student can decide to improve the rake receiver. Both of them work separately at the beginning and cooperate at the end to obtain an improved equalizer. Besides, they can cooperate with another student that may have chosen to cope with the synchronization, obtaining in that way a much better receiver. The platform is flexible and modular to give these opportunities.

B. Cooperative Challenge

If the instructor and the class agree, they can organize a competition to see who is able to better improve the system: the class is divided in groups of several students and then, one of the standards is chosen (GSM or UMTS). The different groups will work on the diverse parts of the system in order to enhance them. They must cooperate with each other because at the end, the winner team will be the one that produces the whole system with the best performance, measured either in terms of error probability or throughput. This ranking will be considered for the grades. The results from the current and previous years can be accessible for students. Thus, they can know how close they are to the previous or current teams.

C. Real Base Station

The platform offers the possibility of implementing part of a realistic receiver. The advantage of using designs based on real standards is that the student can implement a receiver to detect a signal that is transmitted by a real base station from a telecommunications operator. They can even extract additional knowledge from the signal. For example in UMTS, the scrambling code being used and the channelization codes can be found, or the information in the broadcast channels can be decoded. In GSM, they can obtain information about the organization of the cell and the cell size by obtaining the timing advance parameter from the broadcast channels, the number of neighboring cells or even the standards being used, i.e. GSM, General Packet Radio Service (GPRS), Enhanced Data rate for Global Evolution (EDGE), as well as the exact localization by measuring the received power and signal quality in different points, or to decode the information from the operator that is transmitted in the common channels. The improvements at the receiver in channel estimation, synchronization, diversity and detection will play an interesting role when working with these real signals.

Some examples of these configurations can be seen in Fig. 4 where, as explained before, all of them can be simultaneously given in the same class.

D. Organization and Scheduling of the laboratory work

In the following, data obtained during the academic years 2013-14 and 2014-15 in the Mobile Communications course [14], within the degree of Engineering in Communications Systems at the University Carlos III of Madrid, will be briefly described. A set of laboratory sessions have been organized where two different and complementary practical works have been introduced, one related to GSM and the other one to UMTS.
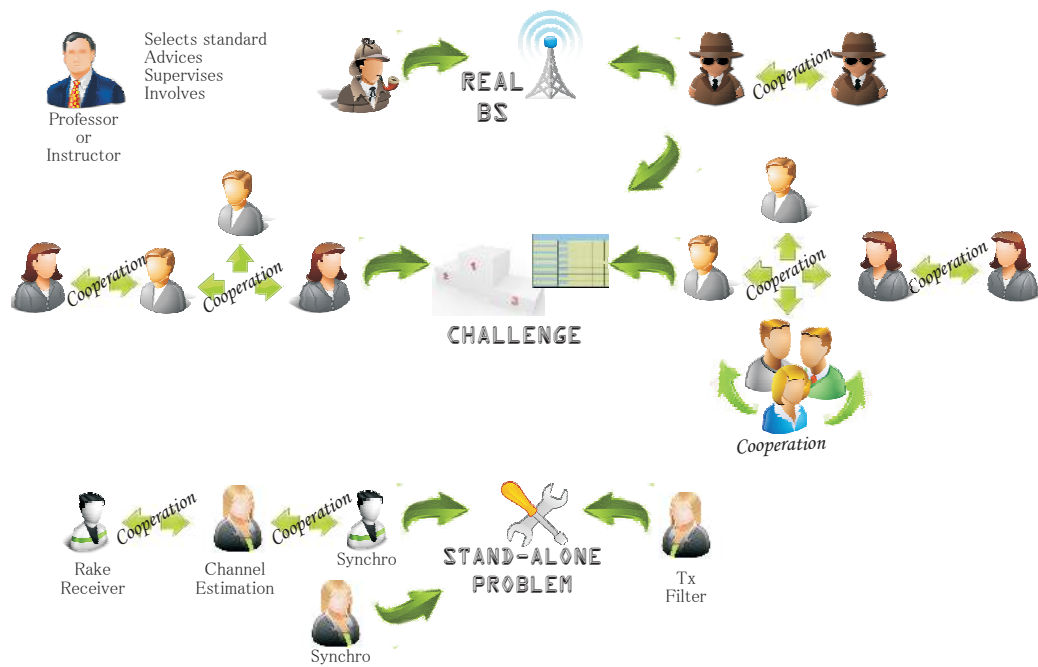
Fig. 4. Examples of classes' configurations, roles, scenarios and interactions among students

The laboratory contents are summarized as follows. When focusing on GSM, the purpose of the session is the generation of several GSM control channels along with a traffic channel. The main aim is that the students learn about the whole procedure starting from the source information bits until the information is transmitted. Concretely, two control channels and one traffic channel have been examined in detail follows these steps:

- Generation of two control channels:
  - FCCH (Frequency Correction CHannel).
  - SCH (Synchronization CHannel): to generate the encrypted bits (78 bits). Each group has different parameters.
- Generation of one TCH (Traffic CHannel): to create the end information bits (114 bits).
- Creation of bursts: The idea is to generate a module which receives the bits obtained before and conforms the bursts by including a training sequence and some tail bits (148 bits).
- Integration of all the modules created previously and transmission of the generated signals with a USRP transceiver. Afterwards, reception of these signals with another USRP transceiver and analysis of the frequency spectrum, the time domain signal and the constellation.
- Preparation of a written report with the explanation of all the steps followed, the achieved results, conclusions and difficulties found.

When the focus is on UMTS, the goal is the generation of very specific UMTS control channels, including:

- Generation of the SCH by using LabVIEW, including the SCH codes. Synchronization data are different for each group.
- Generation of the Common Pilot Channel (CPICH) in-

cluding the spreading and the scrambling codes for the specific cell.
- Multiplexing of both channels and transmission by the USRPs.
- Signal reception by an additional USRP and analysis of the quality of the received signal.
- Preparation of a written report with the explanation of all the steps followed, the obtained results, conclusions and difficulties found.

To speed up the learning curve of LabVIEW and USRPs for the students, a tutorial has been elaborated and an introductory laboratory training session has been scheduled. After these two laboratory sessions the students are familiar with the environment and mobile communications standards. As [4] states, an open-ended design experience improves the students learning. Thus, several challenges are proposed such as the creation of a synchronizer, equalizer, channel estimator, or the extraction of base station information. The students, organized in groups, design and implement a part of the communication system from scratch during several laboratory sessions. Detailed material is available in [14].

E. Project Outcomes

After the first experiences with the new teaching methodology and the developed platform, several important lessons have been learned. The most important one is that this new practical work requires more effort from both sides, students and teachers. From the students, because they have not been exposed to LabVIEW before, they are not familiar with the tool either and the way of describing algorithms and procedures in a real prototype is new for them. From the teachers, because they also have to get used to the tool and because of the wide range of questions and troubleshooting that are often

encountered when dealing with real systems. Besides, we have to consider the amount of work devoted to the design of the practical work in the first year.

According to the students, who have answered to a survey, their experience was very positive (95 % of satisfaction). They agreed that the laboratory sessions with LabVIEW and the USRPs allowed them to learn both a completely different programming language and how to use new hardware devices which together allowed them to understand better the real problems associated with the implementation of communications standards. With this practical work, they have been able to understand the process of prototyping and the advantages of using SDR. Now they are ready to tackle the development of standard-compliant communications systems, and also, they are aware of the importance of standardization. We would like to highlight that most of the students considered this practical work more difficult than the traditional one based on simulations with Matlab (80 %). They evaluated as very important the initial tutorial taught at the beginning of the course (100 %), although the practical work implied more workload compared to the traditional methods.

From the instructors' point of view, the development of the new practical work entailed an important effort. From now on, this effort will be lower as only some continuous improvement and update of the practical work will be needed. The amount of feedback received from the students has increased, which is important and valuable from the point of view of improving their learning.

Another important and interesting outcome is that after the introduction of this practical work into the Mobile Communications course, many students have decided to carry out their bachelor thesis by using this platform. This is of great interest because their results will help to improve the existing practical work and develop new laboratory sessions. In fact, a simple LTE version is being developed.

VI. CONCLUSIONS

In this paper the architecture and functionalities of a new flexible platform, denoted as FRAMED-SOFT, have been explained. By using this platform, new concepts and learning methodology have been explored, giving as a result an improved way of learning the telecommunication standards. We have focused on two of the main cellular standards nowadays. Besides, these possibilities can be extended to also cover other wireless systems that are currently being deployed. The main outcome of the proposed methodology using FRAMED-SOFT is that the students get involved in their learning process and enjoy the physical layer of mobile communications based on standards. Indeed, the study of standards that usually is found boring by students becomes an exciting part because they can

understand and implement them. The fact that they can work in realistic scenarios adds value to their learning. Moreover, several students have decided to carry out their bachelor and master thesis in the field of wireless communications and specifically using and improving our platform. Other students had interesting ideas on how to improve the standards. With the FRAMED-SOFT and the practical work carried out, the students have learned about some of the most important aspects in these standards, such as transmission and reception, multiplexing, modulation and coding, synchronization and channel estimation. They have done so using current standards, which has allowed them to experience their implementations with real world signals. Any instructor may use our platform upon request as explained in our website [14].

REFERENCES

[1] S. G. Bilén, A. M. Wyglinski, C. R. Anderson, T. Cooklev, C. Dietrich, B. Farhang-Boroujeny, J. V. Urbina, S. H. Edwards, and J. H. Reed, "Software-defined radio: a new paradigm for integrated curriculum delivery," *IEEE Communications Magazine*, vol. 52, no. 5, pp. 184–193, May 2014.

[2] M. El-Hajjar, Q. A. Nguyen, R. G. Maunder, and S. X. Ng, "Demonstrating the practical challenges of wireless communications using USRP," *IEEE Communications Magazine*, vol. 52, no. 5, pp. 194–201, May 2014.

[3] R. W. Stewart, L. Crockett, D. Atkinson, K. Barlee, D. Crawford, I. Chalmers, M. Mclernon, and E. Sozer, "A low-cost desktop software defined radio design environment using Matlab, Simulink, and the RTL-SDR," *IEEE Communications Magazine*, vol. 53, no. 9, pp. 64–71, September 2015.

[4] A. M. Wyglinski, D. P. Orofino, M. N. Ettus, and T. W. Rondeau, "Revolutionizing software defined radio: case studies in hardware, software, and education," *IEEE Communications Magazine*, vol. 54, no. 1, pp. 68–75, January 2016.

[5] M. R. et al., "OSSIE: Open source SCA for Researchers," in *Proc. SDR Forum Tech. Conf.*, vol. 47, 2004.

[6] I. Gomez, V. Marojevic, and A. Gelonch, "Aloe: An open-source SDR execution environment with cognitive computing resource management capabilities," *IEEE Communications Magazine*, vol. 49, no. 9, pp. 76–83, September 2011.

[7] E. Blossom, "GNU Radio: Tools for Exploring the Radio Frequency Spectrum," *Linux Journal*, no. 122, p. 4, 2004.

[8] M. Petrova, A., Achtzehn, and P. Mähönen, "System-oriented communications engineering curriculum: teaching design concepts with SDR platforms," *IEEE Communications Magazine*, vol. 52, no. 5, pp. 202–209, May 2014.

[9] National Instruments, "Universal Software Radio Peripheral (USRP)," http://www.ni.com/usrp/esa/ (Accessed on February 7th, 2017).

[10] ETSI, "Mobile technologies GSM," http://www.etsi.org/technologies-clusters/technologies/mobile/gsm, (Accessed on February 6th, 2017).

[11] 3rd Generation Partnership Project, "Spreading and modulation (FDD)," 3GPP TS 25.213, Tech. Rep. V 7.7.0, March 2007.

[12] ——, "Physical channels and mapping of transport channels onto physical channels (FDD) (Release 5)," 3GPP TS 25.211, Tech. Rep. V 5.0.0, March 2002.

[13] N. Instruments, "Student and professor program of national instruments spain," http://spain.ni.com/academia/programa-estudiantes-faq (Accessed on February 7th, 2017).

[14] GCOM, "Mobile communications course's web page," http://gcom.tsc.uc3m.es/en/teaching/mobile-communications/, (Accessed on February 6th, 2017).