ON TEACHING ALWAYS-EVOLVING WIRELESS TECHNOLOGIES

O. Sallent, A. Umbert, J. Pérez-Romero, R. Agustí
Dept. of Signal Theory and Communications
Universitat Politècnica de Catalunya (UPC)
Barcelona, Spain
E-mail: [sallent, annau, jorperez, ramon]@tsc.upc.edu

Abstract

Teaching on wireless telecommunication networks faces a number of challenges, such as the fact that contents are dynamic in nature, the resulting framework is complex and heterogeneous, design principles can largely vary from one system to another, etc. In order to cope with these challenges, novel and advanced methodologies have to be implemented so that the expectations placed by students and industry are met. In this context, this paper will stress the relevance of exploiting the always-evolving wireless technologies to introduce concepts to students in a non-disruptive way, so that novel concepts associated to newly introduced technologies can be presented on top of previous concepts associated to previously existing technologies. In addition, the integration of theoretical contents and practical experience as key enablers of the learning process will also be stressed.

Keywords
Teaching Wireless Communications, GSM, UMTS, Measurement equipment, Laboratory sessions.

1. INTRODUCTION

Wireless telecommunication networks have faced an impressive grow, progress and evolution over the last two decades, becoming wide-spread around the world. By the end of 2008, there were more than three billion people world-wide with mobile subscriptions. The rapid pace of global adoption and diffusion of mobile communications has revolutionized economic and social life.

Since early 90's, more than 700 GSM (Global System for Mobile communications) mobile phone operators have deployed their networks across more than 200 countries. GSM is the most popular standard for 2G (second generation) mobile phones in the world [1][2]. Similarly, since 2003, the so-called 3G (third generation) technologies, which enable network operators to offer users a wider range of more advanced services, have already been deployed. UMTS (Universal Mobile Telecommunications System) networks based on WCDMA (Wideband Code Division Multiple Access) technology have exceeded 300 million subscribers [3]. At this stage, standardization fora led by industry are already defining the so-called 4G (fourth generation) mobile systems, which promise impressive data transmission capabilities reaching up to 1.000 Mbits per second.

Focusing on the technological dimension of this evolution, wireless telecommunication networks have become extremely sophisticated and complex. This is further enforced by the fact that wireless networks are heterogeneous in nature and, usually, different systems have been conceived, designed and implemented following different principles and targeting different objectives.

In this context, teaching on wireless telecommunication networks faces a number of challenges, such as the fact that contents are dynamic in nature, the resulting framework is complex and heterogeneous, design principles can largely vary from one system to another, etc. In order to cope with these challenges, novel and advanced methodologies have to be implemented so that the expectations placed by students (who show high interest in these subjects) and industry (who demands skilled engineers in this field) are met.

This paper will discuss how the always-evolving technologies can be introduced to the students in a non-disruptive way but building novel concepts associated to newly introduced technologies on top of previous concepts associated to previously existing technologies. Furthermore, this paper will stress the relevance of the integration of theoretical contents and practical experience as key enablers of the learning process. Arguments in this paper will be sustained on a success case story, which has been implemented at the Universitat Politècnica de Catalunya (UPC) and analyzed along the last 5 years. To this end, the methodological approach has been built upon: (1) theoretical sessions on general wireless network design principles, which establish common aspects that are technology-independent, (2) theoretical sessions on specific wireless network systems (e.g. GSM, UMTS), which allow the introduction of novel concepts (associated e.g. to UMTS) by remarking the differences with previous technologies (e.g. GSM), and (3) practical sessions with the help of real mobiles phones and test equipment, to analyze in the laboratory the different wireless technologies behavior in terms of physical layer parameters and signaling procedures, which allows a better understanding of the principles underlying in the considered technology.

The rest of the paper is organized as follows. Section 2 presents the first of the abovementioned steps, dealing with theoretical sessions on general wireless network design principles. In turn, Section 3 addresses the theoretical sessions on specific wireless systems, while Section 4 presents the corresponding practical sessions. Finally conclusions are summarized in Section 5.

2. THEORETICAL SESSIONS ON GENERAL WIRELESS NETWORK DESIGN PRINCIPLES

Given the rapid evolution in the mobile communication arena, where the life-cycle of a novel technology lasts for a decade before its replacement in the best case, it is prime important to provide general concepts and design principles, these being as technology-independent as possible, before the student is introduced into specific systems. This principle will ensure that the knowledge gained in wireless communications courses is a solid background facilitating the student's evolution in its professional career.

The design of a complete communication system involves a number of engineering techniques to be incorporated into the different elements of the system. The resulting system design is highly influenced by the media between the transmitter and the receiver, which is known as communication channel. In wireless communications, the communication channel is given by the propagation of electromagnetic waves over the air. The behavior of electromagnetic waves is established by Maxwell's law, which would provide the exact form of the magnitudes (level of electromagnetic field, received power, etc.) for certain contour conditions. At this stage, and given the complexity of a pure theoretical and mathematical approach, students are introduced into a series of propagation models, this constituting a good example of engineering, where simplified though sound characterizations are usually considered to represent the real world.

As a constant methodology across the theoretical sessions, students are motivated to anticipate the most relevant parameters and environment's aspects influencing the propagation conditions, thus constituting the basic parameters to be included in the propagation models. Afterwards, different propagation models are presented in a formal way, justifying the statistics used to characterize the different phenomena. Following with propagation aspects, and claiming for general procedures applied in engineering fields where the wide range of practical situations use to be simplified with a reduced number of representative scenarios, a number of propagation environments are presented (e.g. urban area, rural area, etc.).

At this stage, it is possible to introduce one of the key concepts in wireless communication networks: coverage. It is discussed that coverage in practical deployments has to be measured in statistical terms, this being consistent with the fact that the propagation models introduced before are statistical. Using these models, coverage is defined in a formal way with a reduced number of mathematical equations. These concepts are illustrated with several numerical examples, in order to familiarize the student with the typical orders of magnitude for the different parameters considered. Furthermore, some references to practical tools, used by network operators in order to predict the coverage provided by its deployed network, are given.

With solid foundations on the characterization of the communication channel and a suitable perspective on the disturbance that the different propagation phenomena tend to introduce into the wireless communication, different engineering techniques can be envisaged in order to minimize the channel effects (e.g. noise, distortion).

The need to introduce a certain multiple access technique arises when considering several mobile terminals who wish to connect to a given base station. Multiple access techniques allow several users to share the communications means with a given base station, then allowing the support of different connections simultaneously. Besides, the key aspects to be solved for the practical implementation of the different solutions are identified and the historical evolution of their corresponding use is highlighted. Arguments from the technical, economical and regulatory perspectives are described, then providing a broader perspective to students, who get familiarized with the eco-systems where systems are developed, deployed and exploited and get some insight on the complexity of the wireless communication business environment.

Moving towards a framework closer to real networks, several base stations and several mobile terminals operating at the same time are considered. In this view, inter-cell interference is defined as the major limiting factor in wireless communication networks. Emphasis is placed in the concept that wireless systems become interference-limited and, therefore, all efforts towards an efficient exploitation of radio resources have to be made in order to deal with interference in the best possible way. This is formalized with the definition of frequency-reuse and cell cluster concepts. Some formulas are derived for the case where cells are assumed to be hexagonal, which is a classical way to characterize cellular systems from a theoretical point of view.

The last step in the presentation of the general wireless design is to introduce the key distinguishing factor in wireless compared to fixed networks: mobility. Certainly, the fact that at least one of the two communication ends moves around the scenario introduces relevant design challenges and makes wireless networks particularly complex. The need to support seamless handover (i.e. the capability to transfer a given connection from one cell to a neighboring one when the user moves far from the current cell and approaches the neighbor cell) is firstly discussed. Before entering into modeling and mathematical characterization of the mobility factor, students are requested to anticipate what the major system aspects are causing a higher number of handover procedures to be performed in a wireless network. Afterwards, a simple mobility model, introducing some randomness into the trajectories that users describe across the network, is developed. This provides some supporting formulation that results useful to gain insight into the problem. In particular, a mathematical expression is derived for the handover probability (i.e. how likely it is that a handover is performed), which depends on the above identified aspects (mobile speed, cell radius and connection’s duration).

After all the above foundational aspects have been developed, students are ready to face the design methodology for a wireless communication network. First of all, the design criteria fixed by the operator deploying the network are identified and discussed. Several examples are given to illustrate that the operator’s targets use to be contradictory among them. Conclusion reached is that the network design has to be understood as a whole. Then, a detailed methodology is introduced, with a clear identification of the inputs needed to apply the methodology and the outputs obtained as a result.

With all the above aspects, students are in the position to get a solid understanding and background of the difficulties faced in wireless communication networks, the engineering solutions to be incorporated to enable the establishment of wireless connections, and the methodology to be followed for a proper network design. It is worth remarking that the concepts presented along these theoretical sessions are rather general, this enabling an ulterior intensification towards particular systems and technologies. Last but not least, it is worth remarking that the knowledge acquired during these sessions should let the student to clearly identify the major trade-offs arising in the radio network design and deployment, namely coverage, capacity and quality, as illustrated in Figure 1.

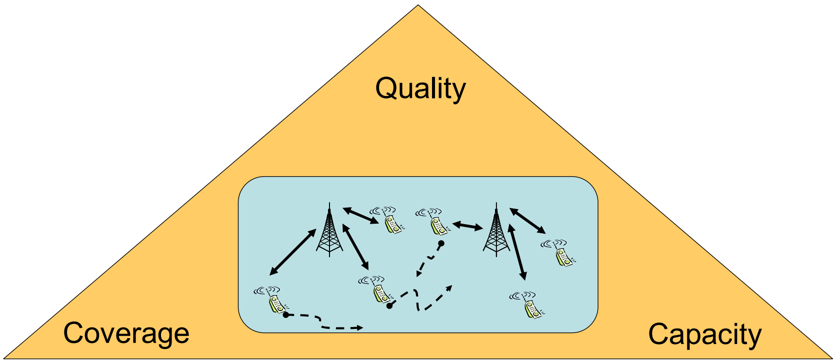

Figure 1.- Trade-offs arising in wireless network deployment

3. THEORETICAL SESSIONS ON SPECIFIC WIRELESS NETWORK SYSTEMS

With solid foundations on basic design principles in wireless communications, the description of specific standardized systems can be accomplished. A standard technology can be seen as a particular realization of a number of generic functionalities necessary to establish and maintain a communication between two end-nodes (either a person or a machine).

In general, a top-down approach is followed for the description of a given standard. That is, even though the focus is on the wireless segment of the communication, an overall view of the system architecture needs to be firstly provided, including the nodes forming the network and the interfaces between them. Afterwards, the emphasis is placed on the radio interface, which allows the mobile terminal to communicate with the fixed infrastructure. In this respect, the multiple access technique (which enables the sharing of scarce radio resources among an as large as possible number of users) is a major driver of the radio interface design. That is, different multiple access techniques will come up with totally different radio interface designs.

The evolution on wireless cellular communication systems from an European perspective has drawn the vision depicted in Figure 2. The adopted terminology uses “generation” to refer to a system with certain capabilities. In pursuing ever increasing system capabilities (support of diverse services, higher data transmission rate, etc.), the industry has come up with the following digital generations:

- 2G, GSM in Europe. GSM is based on TDMA (Time Division Multiple Access) technique. Mainly designed for voice service. Low transmission bit rates.

- 3G, UMTS in Europe. UMTS is based on CDMA (Code Division Multiple Access) technique. Designed for voice and data services. Higher transmission bit rates.

- 4G, LTE-A (Long_Term Evolution - Advanced) in Europe. LTE-A is based on OFDMA (Orthogonal Frequency Division Multiple Access) technique. Extended range of supported services. Very high transmission bit rates.

Certainly, every generation brings a more sophisticated system and air interface design, since the requirements fixed at the time of conceiving a future system are increasingly demanding. Besides, the possibilities offered by chip-industry substantially improve year by year, e.g. in terms of the processing capabilities. Therefore, with the definition of a new generation, a number of engineering techniques that were not implementable in the past due to complexity problems become feasible and can be included in the system design. As a result, it can be clearly stated that UMTS is a far more complex system than GSM, in the same way that LTE-A will be far more complex than UMTS.

As for GSM, a (simplified) picture of the structure of the theoretical aspects to be discussed can be as follows:

- System architecture – circuit switched
- Physical channels
- Logical channels
- Procedures

As for UMTS, a (simplified) picture of the structure of the theoretical aspects to be discussed can be as follows:

- System architecture – circuit and packet switched
- Physical channels
- Transport channels
- Logical channels
- Procedures
- Radio resource management
- UMTS evolution
- UMTS in heterogeneous networks

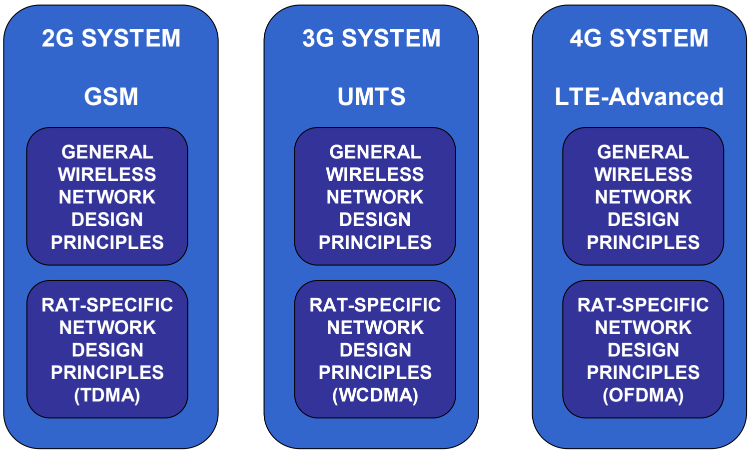

Figure 2.- Wireless systems technology evolution

In a first bunch of theoretical sessions, GSM system is described, according to the items listed above. A rapid comparison with the corresponding UMTS items allows identifying commonalities in the structure, reflecting that, being both wireless communications systems, their specifications share many aspects. Nevertheless, as stated above, the 3G system is adding new features and characteristics, which can be more easily understood and placed in context with a solid previous knowledge on 2G system. In this respect, the methodological approach followed in the second bunch of theoretical sessions describing UMTS is strongly sustained on building novel concepts associated to 3G on top of previous concepts associated to 2G. In this way, the rationale behind technology evolution is substantially enforced. In particular, when describing UMTS, it can be better introduced the need for:

- An evolved system architecture, comprising a packet switched core network (able to efficiently support data traffic) in addition to the GSM circuit switched network (able to efficiently support voice traffic)
- Transport channels, in order to enhance the flexibility offered by the radio interface, in a way that user traffic can be transmitted in a variety of different forms (in contrast to GSM, where user traffic is always transmitted in the same form)
- Advanced radio resource management strategies, as a result of a much more sophisticated radio interface that must be properly managed in order to achieve a suitable efficiency

On the same basis, once the so-called UMTS Release 99 (the first version of the UMTS standard) has been outlined, the need for further enhancements and system capabilities is drawn and, therefore, the UMTS evolutionary path can be introduced in a natural way. In this sense, the following items are also discussed:

- UMTS evolution, to provide short term evolution (e.g. HSDPA, High Speed Downlink Packet Access, which is currently operative) as well as long term vision. Long term vision is only introduced to give a wider perspective in the wireless arena, though it is considered that a detailed description of some of these systems is neither needed nor appropriate (since some of them are still in the standardization phase) at this stage.

- UMTS in heterogeneous networks, to place in context that operators use to deploy UMTS networks after several years operating a GSM network. Therefore, it is important to highlight that the proper management principles are neither the ones to be applied to a GSM-only network nor the ones to be applied to a UMTS-only network but should be based on the joint consideration of the deployed overall capacity (i.e. that resulting from the GSM plus the UMTS resources).

4. PRACTICAL SESSIONS

Wireless telecommunications systems have lots of parameters that determine the performance of the physical layer, such as the transmitted power, the used modulation, the frame and burst structures, etc. All these parameters must be carefully studied and properly designed, since the correct performance of all the higher level protocols relies on the help of the physical layer to generate and transport the radio signals. Furthermore, also important signaling procedures supporting the mobile service are implemented with the defined protocols and signaling messages in any wireless system. This includes e.g. the paging mechanism to inform a terminal about terminating calls, the access mechanism used by the terminal to indicate its willingness to transmit, etc. Nevertheless, in spite of the importance of these parameters and procedures, introducing them in the teaching room has been traditionally something difficult, because in general students tend to find them a bit boring, so that keeping their attention and motivation in this area turns out to be an important challenge. Of course, the use of references to the daily procedures the students themselves use to carry out with their wireless devices, trying to go one step beyond the simple description of the message flows on some slides, can help in making the theoretical sessions more attractive. However, in order to consolidate the transmitted knowledge and to even reinforce the motivation of the students, the use of practical sessions turns out to be a good solution. In that respect, the ideal practical session would be to make use of real devices, i.e. a mobile phone similar to the one that any student may find in a shop, so that the physical layer parameters and the signaling procedures can be illustrated with different test equipments in the lab.

As it has been mentioned in the previous sections, even if the different mobile systems have been conceived, designed and implemented following different principles and targeting different objectives, these always-evolving technologies can be more easily introduced to the students if the concepts of the newly introduced technologies are based on top of the concepts associated to the previous technologies.. This is the case of e.g. the transition from second generation (2G) systems such as GSM towards third generation (3G) systems such as UMTS, in which many of the signaling procedures were based on prior GSM procedures, with the corresponding additions to cope with the requirements of the new developed technology.

Under the above considerations, different practical sessions are being used in the Universitat Politècnica de Catalunya (UPC) to introduce the physical layer parameters and signaling in both GSM (as 2G mobile system) and UMTS (as 3G mobile system).

4.1 Analysis of the GSM physical layer

This practical session makes use of the HP8922H radiocommunication test set [4] to analyze different parameters and procedures of the GSM physical layer such as power control and power limitations, burst structure, frequency errors and FDMA/TDMA components. The HP8922H radiocommunications test set is used world-wide for applications development and validation, for the production of RF modules and complete mobile terminals for GSM, DCS 1800 and PCS 1900 systems. Figure 3 illustrates the connection of the mobile phone to the HP8922H equipment to carry out this practical session.

The equipment generates all the signals that are necessary in order to make the test of the mentioned elements. By means of this equipment automatic tests of the mobile terminal, power measurements, change of frequency, calculation of the error probability, etc. can be carried out. It also permits the emulation of a base station, permitting functions such as calling generation, calling reception, call ending, etc. Also this test set has oscilloscope and spectrum analyzer functions, permitting the temporary and frequency analysis of the GSM signals. This is particularly relevant in order to reinforce the learning of FDMA and TDMA concepts, and from a more general perspective the multiple access techniques, which constitute one of the driving mechanisms in the evolution of wireless communications systems.

Then, as result of this practical students can see the bits in a normal burst, can measure the slot, frame and multiframe duration, can find out the FCCH peak in the beacon frequency spectrum, etc. In short, they can experience with real equipment all the GSM physical layer parameters.

Moreover, the appearance of the digital systems introduced a new concept in the transmission of information: for the maintenance of a good quality of information it must be ensured that bit error rate is below certain limits. Being GSM a system that uses a digital modulation, it is important to know how information is transmitted and how this information is protected This error rate will be different according to the level of protection used and will depend in great measure on the received power by the mobile. In this context, the last part of the practical is devoted to the evaluation of the bit error rate observed in the mobile for different channel conditions. Moreover, thanks to the use of real equipment, students can easily get the idea of how their own voice degrades when passing through the equipment for different bit error rates, representing different channel conditions.

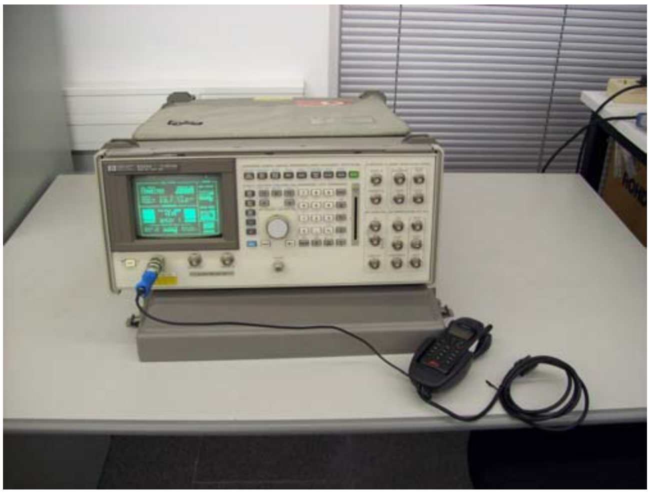

Figure 3. Equipment to analyze GSM physical layer parameters

4.2 Analysis of the GSM signaling

Once the concepts related with the physical layer have been studied, a second practical session enforces the analysis of the signalling procedures, based on the HP37900D equipment. It is a general purpose protocol analyzer that can also emulate a mobile terminal. It could decode any protocol with the appropriate interface card and emulate any signaling node. The objective of this practical session is to study the signaling in a GSM network, thus the HP37900D equipment will be used with specific cards and software to this end. After getting in touch with the equipment, students will go into the radio interface signaling analysis in depth. The analysis can be done not only for the radio part but also for the interfaces between network nodes, such as the A-bis interface that communicates the base stations with their controller.

In order to monitor the radio interface between BTS and mobile station, the HP37900D is connected to the HP8922H that generates the entire radio interface signaling through a rear port connected to a HP37900D Datacomm Card as shown in Figure 4.

The structure of this practical session is divided in two main parts:

1. - To get in touch with the HP37900D equipment. To identify the different parts, explore the different menus and their possibilities.

2. - HP8922H and HP37900D connection in order to monitor the radio interface. To study the typical GSM signalling procedures.

In this practical students analyze the messages and primitives involved in the location updating procedure which is carried out by the mobile either at switch on or when changing the location area. The same procedure is analyzed for both the radio and the A-bis interface.

Figure 4. HP8922H connected to HP37900D to analyze GSM physical layer signaling

4.3 Analysis of the UMTS physical layer

The Rohde Schwarz CMU-200 equipment [5] is a Universal Radio Communications Tester that can be configured to work with different mobile communication systems, and is in particular used in this practical session to analyze the UMTS physical layer.

The practical session makes use of the signaling mode of the equipment, which allows an operation equivalent in essence to the one that a mobile terminal would experience in the real network. In this mode the equipment is able to generate the needed signaling in order to establish a communication with the test mobile. To do that, not only the physical layer aspects must be taken into account (i.e. generation of channels CPICH, SCH, P-CCPCH,…), but also the signaling associated to higher layers, related both with the Access Stratum and Non Access Stratum, that allows establishing and releasing calls with different characteristics. Thus the mobile terminal acts similar than if it was in a real UMTS network. In this mode, it is possible to capture the involved signaling from an external PC, and analyze it a posteriori.

The objective of this practical session is to analyze the UMTS FDD physical layer parameters. Following the methodology used in the theoretical sessions in which 3G concepts relay on the prior knowledge of 2G systems, this practical session assumes the students have a solid knowledge on the GSM systems, acquired in the previously described practical sessions, and focuses on the main differential aspects in UMTS. More specifically, the following physical layer measurements are studied in the practical session:

- Power measurements: they allow measuring the mobile terminal received power and simulating the power control.
- Spectrum measurements: they allow visualizing the mobile terminal transmitted signal spectrum, as well as the level of interference introduced in the adjacent channels.
- Modulation measurements: they allow characterizing the transmitted signal phase and frequency errors.
- Code power measurements: they allow characterizing the channelization codes used in the transmitted signal. It is worth mentioning that this is a particularly key feature, since it

illustrates the CDMA technique, which constitutes one of the main differences with respect to the access techniques FDMA and TDMA used by 2G systems.

- Error measurements: by means of transmitting signals in closed loop, it is possible to perform error measurements over the received signal, as well as to visualize the quality parameters reported by the mobile terminal.

The hardware configuration used in this practical is shown in Figure 5.

Figure 5. Rohde-Schwarz CMU-200 with 3G mobile to analyze UMTS physical layer parameters

4.4 Analysis of the UMTS signaling

Finally, after the student has familiarized with the physical layer procedures of UMTS, the aim of this practical session is to analyze some signaling procedures used in UMTS, like the initial mobile registration, or the call execution. Again, it should be stressed that signalling procedures in UMTS retain many similarities with those of GSM, since they were essentially originated from the same mechanisms and updated in order to cope with the new functionalities and requirements of the new system. Then, it is important for the student to stress those signaling aspects that mainly differentiate from those studied in the previous sessions on GSM. This has two main advantages in the learning process: on the one hand it allows a better understanding and consolidation of the GSM procedures, and on the other hand, by justifying the reasons for the differences in the procedures of the two systems, the students can strength the evolving vision of wireless communication technologies.

In order to carry out this practical session, the Rohde Schwarz CMU-200 equipment must be used in signaling mode, and the signaling will be captured with an external PC for a posteriori analysis with the Message Analyzer as shown in Figure 6 and Figure 7 for a mobile terminating call (MTC).

In this practical the following UMTS procedures are studied in detail: Initial Registration procedure, Mobile Terminating Call, Interfrequency Handover, and Vertical Handover from UMTS to GSM1800. It is worth mentioning that the vertical handover procedure is also one of the key aspects of the coexistence between different technologies, enabling the capability to switch from one to the other depending on the different conditions.

The used Rohde-Schwarz Message Analyzer shows the captured logfiles in two different views. The first one (Figure 6) includes the involved lower layer, the Service Access Point (SAP), the service, the primitive, and the Payload Data Unit (PDU), as well as number and time references where each message is transmitted.

In turn, the second view (Figure 7) shows the flow message diagrams, so that students are able to follow the messages exchanged between the lower UMTS layers in the radio interface. It is also very important to mention that the messages are captured while passing through the different layers of the protocol stack (e.g. physical, MAC, RLC, RRC, etc.), and the graphical representation of the message flows makes easier the understanding of this layered structure, which on the other hand reveals to be as one of the toughest aspects in the learning of mobile systems operation.

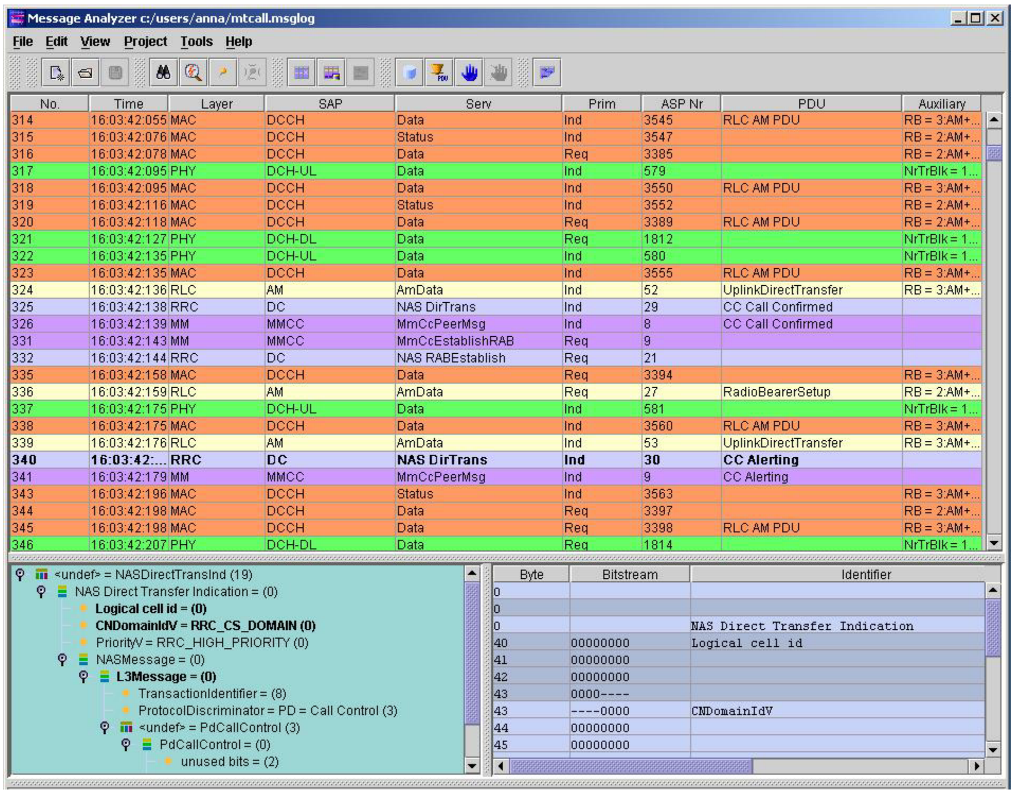

Figure 6. Message Analyzer (view 1) to study UMTS physical layer signaling

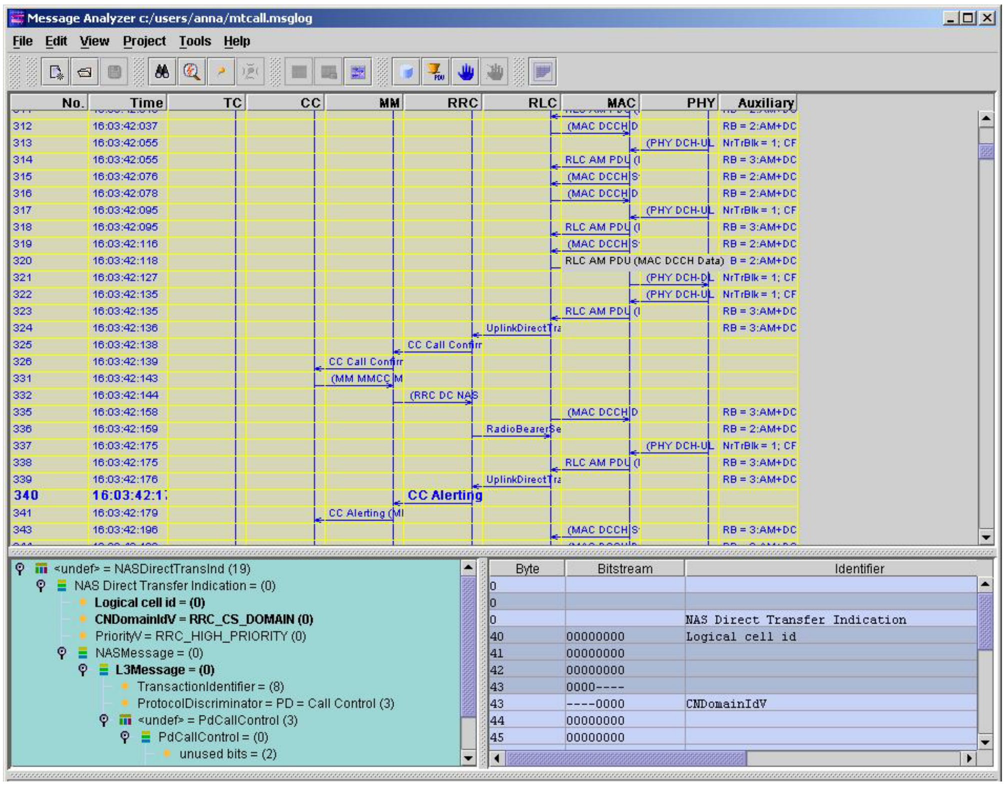

Figure 7. Message Analyzer (view 2) to study UMTS physical layer signaling

5. CONCLUSIONS

Within the telecommunications field, the rapid evolution in the mobile and wireless communications systems together with the world-wide penetration of wireless systems such as GSM, UMTS, Wi-FI, etc., has motivated the need for skilled professionals with solid technical background in this area. This learning process presents a number of challenges due to the dynamical nature of the contents, the complexity of the heterogeneous systems and the multi-disciplinary nature of wireless systems, covering multiple aspects of the telecommunications (e.g. from services down to signaling protocols and radio transmission technologies). Even if the different mobile systems have been conceived, designed and implemented following different principles and targeting different objectives, their evolving nature starting from similar fundamentals on wireless communications, enables a teaching methodology in which presented concepts for each technology can be consolidated based on the acquired knowledge from its predecessors.

Under this framework, this paper has stressed the relevance of exploiting the always-evolving wireless technologies to introduce concepts to students in a non-disruptive way, so that novel concepts associated to newly introduced technologies can be presented on top of previous concepts associated to previously existing technologies. This is the case of e.g. the transition from second generation (2G) systems such as GSM towards third generation (3G) systems such as UMTS, in which many of the signaling procedures were based on prior GSM procedures, with the corresponding additions to cope with the new requirements of UMTS. In addition, the integration of theoretical contents and practical experience have been presented as key enablers of the learning process.

To this end, the methodological approach presented in this paper has been built upon: (1) theoretical sessions on general wireless network design principles, which establish common aspects that are technology-independent, (2) theoretical sessions on specific wireless network systems (e.g. GSM, UMTS), which allow the introduction of novel concepts (associated e.g. to UMTS) by remarking the differences with previous technologies (e.g. GSM), and (3) practical sessions with the help of real mobiles phones and test equipment, to analyze in the laboratory the different wireless technologies behavior in terms of physical layer parameters and signaling procedures.

Arguments in this paper are sustained on a success case story, which has been implemented at the Universitat Politècnica de Catalunya and analyzed along the last 5 years. Conclusion reached after this experience is that students exhibit a high level of satisfaction with the applied methodology and the learning process is significantly improved.

Acknowledgements

The experience reported in this paper has been supported by Fundación Vodafone España.

References

[1] M. Mouly, M.B. Pautet, *The GSM System for Mobile Communications*, published by the authors' company, Ceel & Sys, 1992.
[2] S.M. Redl, M. K. Weber, M.W. Oliphant, *An introduction to GSM*, Artech House, 1995.
[3] H. Holma, A. Toskala, *WCDMA for UMTS*, John Wiley & Sons,2nd edition, 2002.
[4] "8922H GSM Mobile Station Test Set" information available at http://www.home.agilent.com/agilent/product.jspx?cc=US&lc=eng&nid=-536900809.536879669.00&pageMode=OV
[5] "R&S CMU200 Universal Radio Communication Tester", information available at http://www2.rohde-schwarz.com/product/CMU200.html