Project Based Learning Methodology Applied to Radiofrequency Subject

Héctor Solar
Department of Electrical and Electronic Engineering
University of Navarra (Tecnun)
San Sebastian, Spain
hsolar@tecnun.es

David del Río
Information and Communication Technology Division
CEIT
San Sebastian, Spain
ddelrio@ceit.es

Andoni Beriain
Department of Electrical and Electronic Engineering
University of Navarra (Tecnun)
San Sebastian, Spain
aberain@tecnun.es

Roc Berenguer
Department of Electrical and Electronic Engineering
University of Navarra (Tecnun)
San Sebastian, Spain
rberenguer@tecnun.es

***Abstract*— The Project Based Learning (PBL) is a teaching method in which students gain knowledge and skills by working for an extended period of time to respond to a challenge. This methodology is being applied to the subject of Radiofrequency carried out by the students of Telecommunication Systems and Communication Electronics Engineering degrees at the School of Engineering (Tecnun) of the University of Navarra. This subject is devoted to the design of the analog front-end of transceivers for wireless communications. As part of the subject a project is included, in which the students are asked to design, simulate build and validate a LTE receiver (Rx) at the 800-MHz band.**

Keywords*— *Project Based Learning, Radiofrequency, LTE receiver

I. INTRODUCTION

The subject of Radiofrequency at the Technological Campus of the University of Navarra is devoted to the design of the analog front-end of transceivers for wireless communications. It is a 6^{th} semester subject for both Telecommunication Systems and Communication Electronics Engineering degrees.

The theory content is structured in such a way that the tools required to design a communication link complying with a specific standard are provided to the students. The main theory blocks are:

- Standard description: The students learn how to approach the physical layer of a standard, extract the main system parameters and translate them into requirements imposed to a transceiver aimed to fulfill that standard. Main topics are: network types, digital modulations, multiple access techniques, physical layer requirements and test, etc.
- Component performance: This part of the Radiofrequency subject reviews the main components of a transceiver chain and discusses their most important parameters, its role inside the chain, implementation issues, etc.

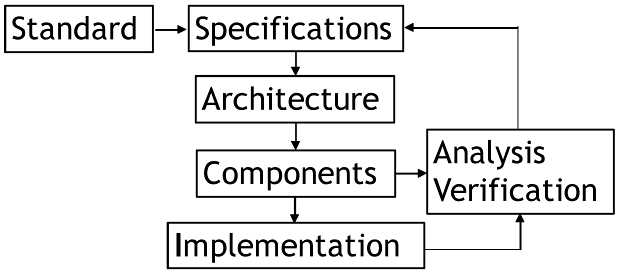

Fig. 1. Receiver design flow.

- Transceiver architectures: This aspect covers the main architectures employed for transceiver implementation and the criteria to choose the most convenient solution given the specific standard requirements.
- DCS 1800 case: The specific case of DCS 1800 standard is analyzed from the standard documentation to its translation into Receiver requirements in term of noise, linearity and dynamic range. An example of a Rx using actual Radiofrequency (RF) components is also given in order to introduce the students to the simulation tool. It serves as a first example for the students to perform their own analysis.

As it has been mentioned, the objective of theory lessons is that the students acquire the tools to carry out a specific project. The project is focused on the design of a RF Rx that has to fulfill a specific communication standard. The goal of the project proposed to the students is to go through the different steps of an actual Rx design: choice of the proper architecture, analysis of a communication standard and setting up of the component parameters and system simulation, test and validation of the Rx design. The project is introduced to the students as a challenge among different teams. The winner is the team that gets the best Figure of Merit (FOM) for their Rx design while complying with the chosen standard.

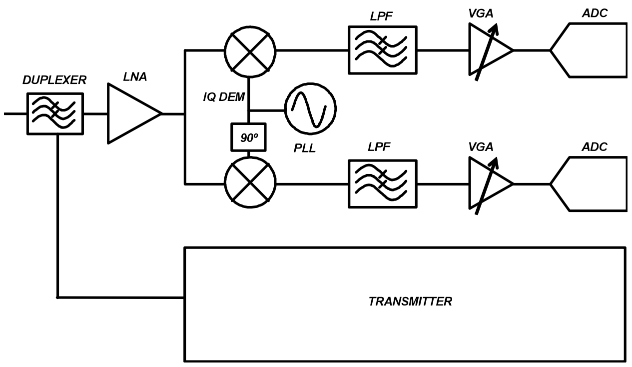

Fig. 2. Receiver architecture.

The rest of the paper is structured as follows. Section II gives a detailed view of how the project is structured and how it is carried out by the students. Section III summarizes the material that is used for the project. Section IV shows the results. Finally, Section V concludes the paper.

II. PROJECT DESCRIPTION

As it has been aforementioned, the project is carried out by the students in parallel to the theory lessons. The information about the specific standard, different milestones, templates is announced through the term. Introductory lessons inform them about the design flow that they will follow for the project realization, as shown in Figure 1.

A. *Communication Standard*

The DCS 1800 standard is used in sessions as first example. However, the students are required to work with a more modern standard. Specifically, the chosen standard is 3GPP LTE Release 11 (ETSI TS 136 101). It must be noted that the analysis that the students have to conduct is simplified. Namely, they are asked to extract information specifically for a fixed channel bandwidth of 10 MHz without Carrier Aggregation, using band 20 (800 MHz) and Frequency Division Duplexing (FDD) [1]. The students are provided with the actual standard documentation for the User Equipment radio transmission and reception along with relevant paper links, useful for the analysis [2]-[5].

B. *Milestones*

Project development consists on the following steps:

1) LTE requirements analysis

The students must translate the LTE requirements into Rx requirements in terms of noise, linearity and dynamic range. Specifically, Table I shows the list of requirements the students have to provide.

TABLE I. RX SPECIFICATION LIST

Component	Parameter	Description
Rx	NF	Rx Noise Figure
Rx	IIP3	Rx Third Order Intercept Point
IQDEM	IIP2	IQ Demodulator Second Order Intercept Point
PLL	Phase Noise	PLL Phase Noise
Duplexer/LNA/ IQDEM/PLL	Antenna Leakage	Rx Antenna Leakage
PLL	Spurs	PLL Spur level
VGA	ΔGain	VGA Gain Range
ADC	SNR	ADC Dynamic Range

The students are provided with a template document as a help to look for the information within the documentation and also to learn how to interpret the different standard sections so that Rx parameters are extracted. For example, as shown in Table II, the template helps them to extract linearity requirement from intermodulation, Tx leakage or cross modulation effect.

TABLE II. TEST CASES FOR IIP3, IIP2 AND PHASE NOISE

Parameter	Test Cases
IIP3	Intermodulation test Intermodulation of Tx Leakage + Out-of-band Blocker (OOB) Cross modulation of Narrow Band Blocker (NBB) with Tx Leakage Cross modulation of Adjacent Channel with Tx Leakage-Case1 Cross modulation of Adjacent Channel with Tx Leakage-Case2
IIP2	Tx Leakage In Band Blocking (IBB)-Case1 In Band Blocking (IBB)-Case2 Adjacent Channel-Case1 Adjacent Channel-Case2 Second order intermodulation
Phase Noise	Narrow Band Blocker (NBB) In Band Blocking (IBB)-Case1 In Band Blocking (IBB)-Case2 Adjacent Channel-Case1 Adjacent Channel-Case2

2) Architecture and Component selection

Next step in the design process is to choose the proper architecture for the Rx with its pros and cons. The Rx architecture is required to be compact and so a direct conversion Rx architecture is suggested, as shown in Figure 2. Along with this, students should choose the components that best fit the design of a Rx complying with LTE-Release 11 while maximizing the FOM. Students may choose components from a list of possibilities. Namely, the available components are the ones shown in Table III.

TABLE III. RF COMPONENTS

Component	Model	Supplier
Duplexer	B8622	TDK-Epcos
LNA	ADL5521	Analog Devices
LNA	TQP3M9036	Qorvo

Component	Model	Supplier
LNA	TQL9092	Qorvo
LNA	QPL9065	Qorvo
IQ Demodulator	ADL5380	Analog Devices
IQ Demodulator	ADL5382	Analog Devices
IQ Demodulator	ADL5387	Analog Devices
PLL	ADF4350	Analog Devices
PLL	ADF4355	Analog Devices
VGA	AD8366	Analog Devices
VGA	AD8372	Analog Devices
VGA	ADRF6510	Analog Devices
VGA	ADRF6518	Analog Devices

The components listed in Table III are available as evaluation boards. The main advantage is that the students save the time that would be needed for PCB design and fabrication, component soldering, error correction, etc. All these design skills are covered by other subjects through their Engineering degrees. In addition, evaluation boards come with 50Ω impedance matching at their inputs and outputs so that board connection is direct without worrying about impedance mismatches. A drawback is that input and output transformers added for impedance matching introduce extra losses that degrade the actual performance of components. However, as long as they have to characterize the components of their choice, they must take this into account.

In addition to RF components, the student must also choose a proper ADC in terms of sampling frequency, input swing and dynamic range.

3) Rx simulation

Based on the family of available RF components the students must now justify a correct design of a LTE Rx using Advanced Design System (ADS) Tool from Keysight [6]. The students have to validate it by carrying out ADS simulations that demonstrate that the LTE requirements have been fulfilled with the chosen combination of components.

There is an introductory laboratory session at which a Rx complying with the DCS 1800 standard is simulated. Therefore, the students learn how they should work in order to characterize their own architecture complying with the LTE standard.

4) Rx implementation and test

Once the students have validated their design they must implement it in reality. There are several laboratory sessions so that they first gain familiarity with the equipment and test procedures. In fact, the first session is an introduction to test equipment and test procedures in order to correctly characterize gain, linearity, noise and power consumption of components. Later on, they must be able to perform the characterization of the whole Rx. Next section details the equipment the students can work with.

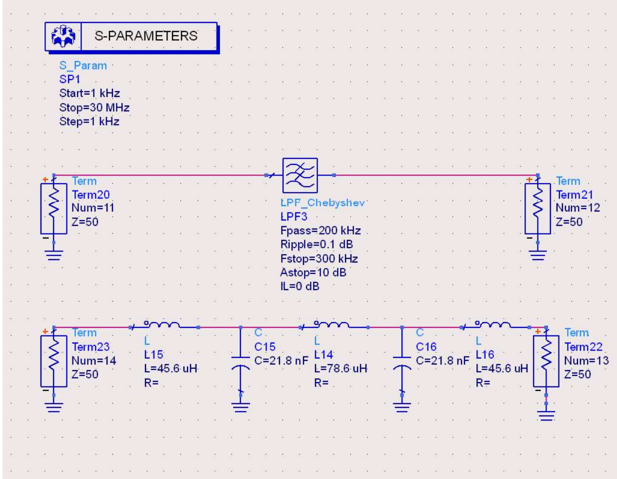

Fig. 3. ADS Schematic view of a simulated low pass filter.

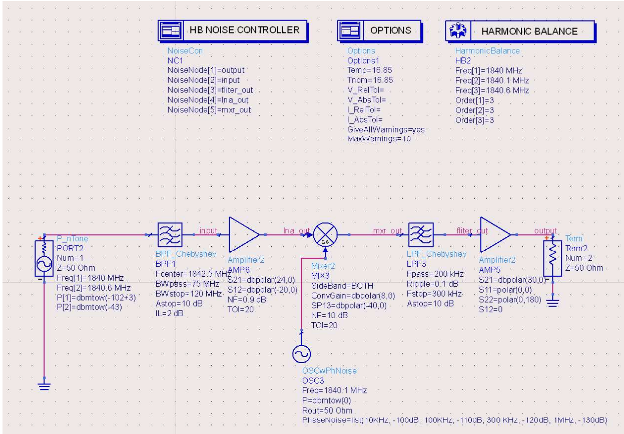

Fig. 4. ADS Schematic view of a simulated Receiver.

5) Low pass filter design and fabrication

Students are also required to design, fabricate and test a passive low pass filter of the type and order they consider the most suitable. In a previous subject they have learned how to synthesize a filter although online tools are also suggested [7]. They can implement, simulate and include their chosen filter in ADS, as shown in Figure 3. Later on, they fabricate the filter by means of surface-mount device (SMD) Inductor, Resistor and Capacitor kits available in the laboratory.

Implementation of the filter by means of commercially available inductor, capacitor and resistor values, makes them learn to adjust the final filter performance to components that are actually available in the market.

C. *Figure of Merit*

The FOM equation compares the quality of the design by using (1).

$$FOM=10^6/(Cost(€@1K)*\Sigma V_{DD}(V)*I_{DD}(mA)) \quad (1)$$

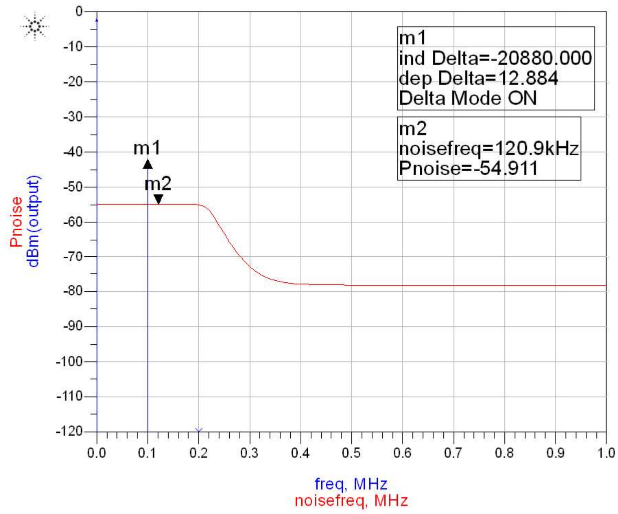

Fig. 5. ADS simulated results for sensitiviy.

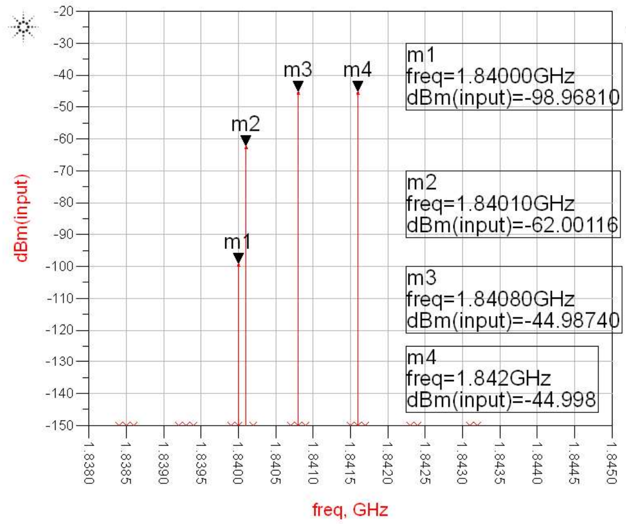

Fig. 7. ADS simulated results PLL leakage.

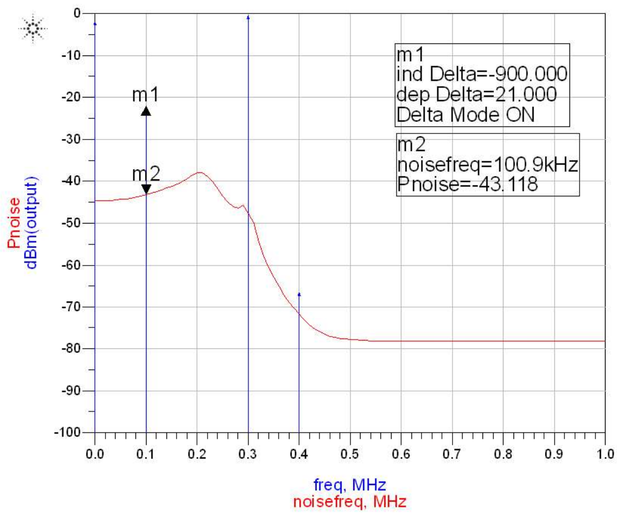

Fig. 6. ADS simulated results for noise and reciprocal mixing.

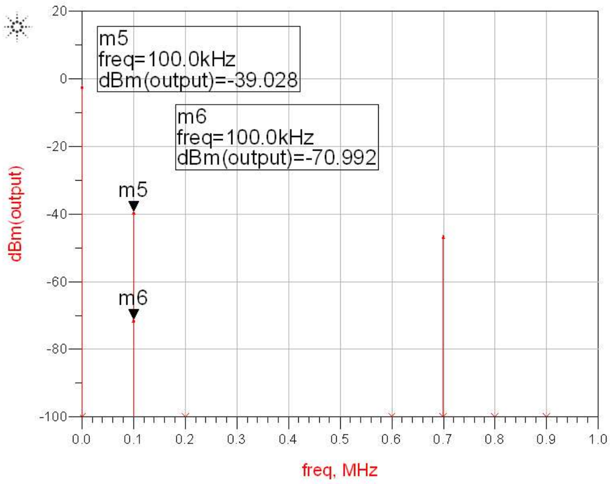

Fig. 8. ADS simulated results for third order intermodulation distortion.

It must be noted that solutions are not compared in terms of noise or linearity performance. All the proposed solutions must fulfill standard requirement, therefore the final winner is the one that achieves it with the least power consumption and cost. It is a good exercise not to just get the best solution in terms of RF performance but to take into account some other important aspects in the design process.

III. Project Resources

A. System Simulation Tool

As it has been already mentioned, the main simulation tool for the Rx performance simulation is Advanced Design System (ADS) tool from Keysight [6]. Students learn how to perform ADS simulations by selecting components from the available list and configure them in terms of gain, noise, linearity, isolation, etc. Noise, linearity and gain simulations are carried out by mean of the Harmonic Balance, Noise Controller and S-parameter simulation boxes.

An example of the schematics of a simulated Rx is shown in Figure 4. Several examples of simulations for the Rx are shown next. Figure 5 shows Signal-to-Noise ratio (SNR) results combining noise and the output channel modelled as a carrier signal with minimum input power level. Figure 6 shows the sensitivity degradation due to the effect of reciprocal mixing of the PLL phase noise with one of the interferers specified by the standard. Figure 7 shows the results of the PLL leakage at the antenna terminal. Finally, Figure 8 shows the signal to distortion ratio of the third order intermodulation test results at the output of the receiver.

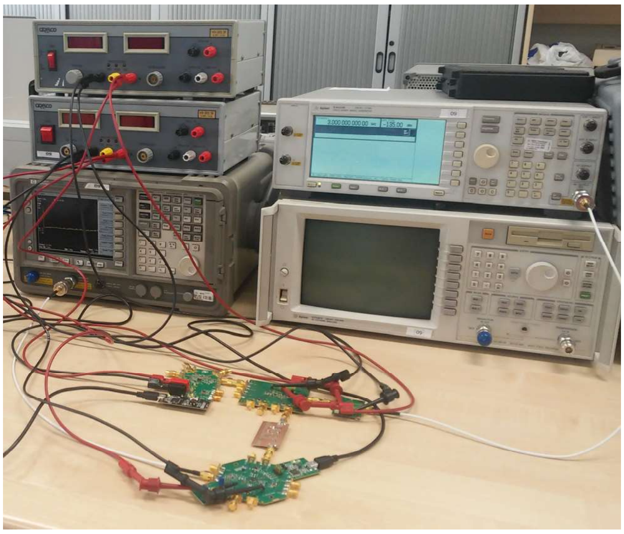

Fig. 9. RF equipment test bench.

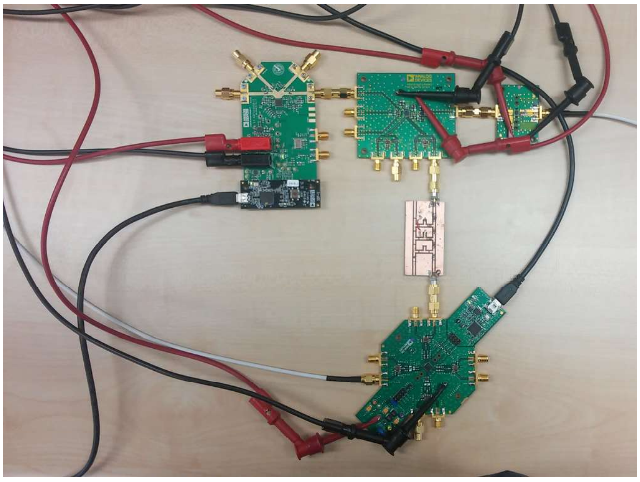

Fig. 10. Receiver hardware implementation.

B. Test equipment

Student teams have RF equipment available for the Rx testing and validation. The detailed list is shown in Table IV while a photograph of the laboratory test bench is shown in Figure 9. With the available equipment the students must validate the simulation results regarding noise, linearity and dynamic range of their Rx.

TABLE IV. RF EQUIPMENT

Equipment	Description
Agilent E4402B	Spectrum Analyzer
Agilent 8714ET	Vector Network Analyzer
Agilent E4432B	Signal Generator
Grelco VD 305	Power Supply
Agilent 346A	Noise Source

C. Test kit

The students have several test kits with material for the Rx test. Cables, adapters and connectors provided to them are based on SMA-type connector as it is the connector type for RF components commercially available. Table V lists the material that the test kit for each team contains. The quantities are calculated so the parts allow several teams to work in parallel with the different RF components. Students have to coordinate in order to optimize the testing time.

TABLE V. TEST KIT COMPONENTS

Component	Qty
SMA 50Ω load	7
SMA JACK to SMA JACK Connector	1
SMA PLUG to SMA PLUG Connector	7
N-PLUG to SMA-JACK Connector	6
N-JACK to SMA-JACK Connector	1
BANANA to Grabber Adapter Red	6
BANANA to Grabber Adapter Black	6
BANANA-BANANA Cable Red	6
BANANA-BANANA Cable Black	6
SMA-SMA Cable 50CM LENGTH	6
SMA-SMA Cable 15CM LENGTH	7
Power Splitter (MINICIRCUITS)	1
Calibration KIT SMA SHORT-OPEN	1
Calibration KIT SMA LOAD	1
Calibration KIT SMA JACK to SMA JACK	1

IV. RESULTS

Students have to report their achieved results for the project. They must first report the RF component requirements obtained from the LTE standard analysis. In addition, they must show a complete set of simulations in ADS that indicate that the choice of components for their Rx complies with the LTE specifications. Furthermore, the report must show the laboratory tests results, a comparison and discussion of the measured and simulated results. They need also to check component prices for potential fabrication quantities of 1K. Finally, they need to add their conclusions and the calculation of the FOM for their design. Figure 10 shows an example of an implemented receiver built by the connection of the evaluation boards and the fabricated low pass filter.

V. CONCLUSION

Students experiment the design process of a Rx covering its different steps: state-of-the-art standard analysis, architecture and component selection, filter design and fabrication and Rx simulation, test and validation. They also deal with the tradeoff of any design in terms of costs, power consumption and requirement fulfillment. Finally, documentation, components, software and equipment are chosen from the state of the art providers.

REFERENCES

[1] LTE Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception (3GPP TS 36.101 version 11.2.0 Release 11), ETSI Technical Specification, 2012.

[2] Third Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); LTE L-Band Technical Report (Release 10) (3GPP TR 36.813 V10.0.0 (2011-01)), ETSI Technical Report, 2009.

[3] Stefan Kählert, "Frequency Agile Filter Concept for Wireless Whitespace Receivers," Ph.D. Dissertation, Aachen University, Aachen, Germany, 2013.

[4] C.W. Liu and M. Damgaard, "IP2 and IP3 Nonlinearity Specs for 3G/WCDMA Receivers," High Frecuency Electronics, pp. 16–25, June 2009.

[5] St. Sesia, I. Toufika and M. Baker, LTE-The UMTS Long Term Evolution From Theory to Practice, 2nd ed., Chichester, UK, Wiley, 2011.

[6] Keysight Tech., Advanced Design System (ADS) software. [Online]. Available: https://www.keysight.com/en/pc-1297113/advanced-design-system-ads.

[7] Tony Fisher, LC Filter Design [Online]. Available: https://www-users.cs.york.ac.uk/~fisher/lcfilter/