

## An Example from the Basic Engineering Project Subject at the UPC Telecom-BCN School: Learning Radiofrequency Links, Antennas and Amplifiers with the Help of Recycled Materials

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**Abstract.** The Basic Engineering Project is a third-year subject and the second of four stages tackling design-implemented subjects in the 4-year Telecom BCN curricula. The Introduction to Engineering subject is the first stage and the degree Thesis is the last one. The Basic Engineering Project focuses on technical design, construction, measurement and validation of guided system blocks, which are part of a complex ICT system. The current implementation of the subject enables the students to choose among four different complex system orientations according to the chosen major, namely: (i) sound amplification (electrical engineering specialization), (ii) sound characterisation and enhancement (audiovisual systems), (iii) network protocols and mobile apps (networks engineering), and (iv) WiFi radiolink (telecom systems).

This work addresses the latter specialization, which includes the design of antennas with low-cost/recycled materials and matching a microwave amplifier with adhesive stubs.

**Keywords.** Design-build subject, hands-on-lab, project-based learning, telecom engineering.

### 1. Introduction

The Basic Engineering Project is 6-ECTS subject, part of the 4-year-long bachelor degrees at the Telecom Barcelona (BCN) - Electrical and Telecom Engineering School of the Technical University of Catalonia (UPC), started 2010-2011 and implemented according to Conceive-Design-Implement-Operate (CDIO) standards. A detailed description of the four design-implemented subjects, Introduction to Engineering (6 ECTS), Basic Engineering Project, Advanced Engineering Project (6

ECTS), and thesis project (24 ECTS), in the degrees' pathway can be found in [1-3].

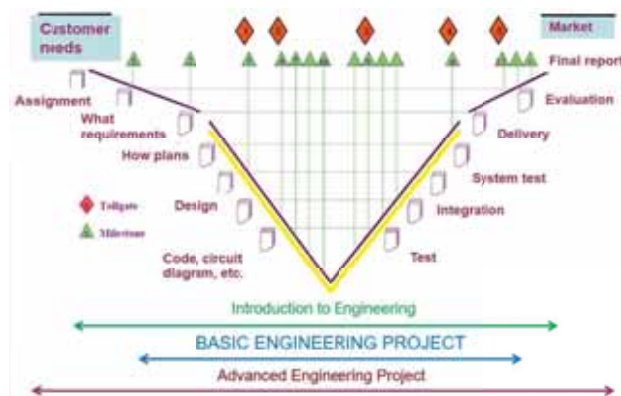


Figure 1. The V-shaped diagram in the LIPS project cycle (adapted from [6])

Central to the CDIO strategy is the breakdown of a complex system into smaller parts or subsystems, which enable the students to work in teams and to be exposed to different implementation possibilities [4-5]. In the case of the Basic Engineering Project the project is narrower in scope (i.e., implementation possibilities are lesser and the system breakdown is defined by the faculties) but conveys higher technical difficulty. Figure 1 illustrates the project formulation in comparison to the other two design-implemented subjects, Introduction to Engineering (wide scope - low technical difficulty) and Advanced Engineering Project (wide – high).

Table 1. Targeted skills in the Basic Engineering Project [2]

| #  | Generic Skill   | Exposed | Stressed | Assessed |
|----|---|---------|----------|----------|
| 1  | Innovation and entrepreneurship   | X       | X        | X        |
| 2  | Societal and environmental context  | X       | X        | X        |
| 3  | Communication in a foreign language (English)   | X       | X        |          |
| 4  | Oral and written communication  | X       | X        | X        |
| 5  | Teamwork  | X       | X        |          |
| 6  | Survey of information resources   | X       | X        |          |
| 7  | Autonomous learning   | X       |          |          |
| 8  | Ability to identify, formulate and solve engineering problems                         | X       |          |          |
| 9  | Ability to Conceive, Design, Implement and Operate complex systems in the ICT context | X       | X        | X        |
| 10 | Experimental behaviour and ability to manage instruments                              | X       | X        |          |

Targeted generic skills in the Basic Engineering Project are summarised in Table 1. Assessed skills are highly variable among the different project teams (4 students per team)

since the faculties act as both “clients” (project specification) and “technical consultants” (coaching students).

In addition to these skills, *learning outcomes* include: a) on the technical side: (i) multi-disciplinary knowledge about the project topic (students revisit and intensify concepts learnt in specific subjects along the curriculum or being taught during the same academic year), (ii) design and simulation tools, system characterisation, instrumentation and measurement techniques, and (iii) fabrication skills; b) on the transversal side, focus is on project documentation and technical writing.

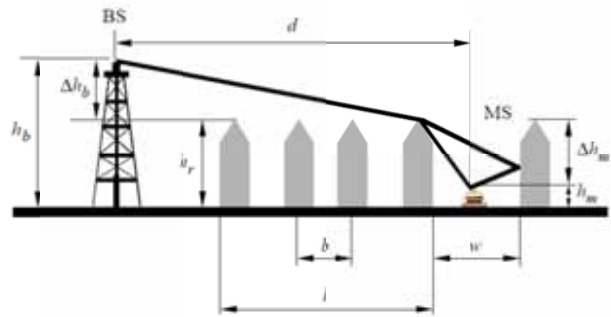
## 2. Course implementation

The Basic Engineering Project subject comprises two *tracks*: A 2-ECTS track on the regulatory aspects of ICT projects (which is an important part for ICT practitioners in Spain) and a 4-ECTS track (3 h/week of the lab activity plus 4 h/week of autonomous work) focusing on the complex-system project chosen according to the degree’s specialization. For the *major on telecom systems* the proposed project deals with the *design of a short-range radiocommunications link in the 2.45-GHz WiFi band (the “WiFi radiolink” in what follows) by using recycled materials to build the antennas* [7]. The lab. group assembles a maximum of 20 students organised in 5 teams of 4 students each.

The *course schedule* is shown in Table 2 and it is explanatory of the break-down of the complex system under study.

The first block (weeks, w1-3) addresses basic concepts in radiocommunications (free-space, Line-of-Sight and Non-Line-of-Sight propagation, Figure 2, and key related subsystems) around short expository instruction time from the lecturers’ side (30 min/session), Moodle-based course materials, and guided reading [8]. Hands-on instruction and *learning outcomes* aim at:

- engaging the students to program their own radio-propagation link-budget simulator in Excel™ (milestone M1), and
- familiarising with transmitters (TX) and receivers (RX, Figure 3a,b), digital modulations and performance (Binary Error Rate (BER) measurement, M2).



**Figure 2. ITU-R 1411-1 model: Example of definition of parameters for the Non-Line-of-Sight transmission case in a short-range outdoor radiocommunication system [8]**

The second block (w3-8) is aimed at the construction of five different types of antennas (horn, corner reflector, patch, Yagi, and helix; one for each lab team) by using low-cost / recycled materials. Although a key output of this block is the antenna prototype by itself (M3) hands-on learning involve:

- getting acquainted with antenna simulation software either academic- [9] or professional-oriented (NEC) [10].
- one-port measurements with the microwave Vector Network Analyser (VNA) with a view to antenna impedance matching (M4),
- antenna pattern measurements (M5).

Block two is the most demanding one and hence, the lab teaching strategy essentially combines individual coaching and supervision of each lab team combined with short expository-time guidelines from the lecturers’ side.

The third block (w8-11) tackles impedance matching of a microwave amplifier (Figure 3c, to be integrated as an optional block of the WiFi link in reception) using adhesive stubs. Learning goals target:

- to know how and to simulate maximum-gain and minimum-noise amplifier matching techniques with simple CAD microwave software (M6) [11].
- to perform two-port S-parameters measurements with the VNA with a view to amplifier matching (M7).

The last block (w12) wraps up the whole WiFi-link project by carrying out range- and received-power tests outdoor in the Campus with low- and high-speed beacons. By this means, each lab team has the opportunity to revisit and validate their own power link-budget assessment (first presented in the Preliminary Design Review (PDR), w3) by assimilating their antenna and amplifier parameters measured so far.

Project documentation encompass PDR, Critical Design Review (CDR, w8) around the antenna design, and Final Design Review (FDR, w13). A guided outline for each of these deliverables is provided along with indication of the maximum no. of written pages in order to foster succinct scientific writing. Documentation format is a simplified mix of adapted European Space Agency (ESA) templates and the LIPS standard [6].

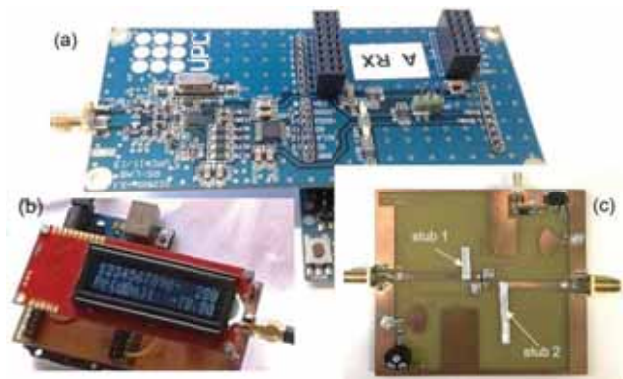
**Table 2. Course schedule (telecom systems track, WiFi radiolink; “M” indicates milestone)**

| w    | ACTIVITY   |
|------|--|
| 1    | Course introduction (tasks and deliverables). Link-budget (I): Foundations                                     |
| 2    | Link-budget (II): Simulation (M1). Wireless transceiver (CC2500): BER assessment (M2).                         |
| 3    | (PDR) Link-budget deliverable and oral presentation. Antenna design principles                                 |
| 4, 5 | Antenna design and manufacturing. Antenna lab tests: Impedance matching (M3-4).                                |
| 6, 7 | Antenna outdoor measurements: Far-field radiation pattern and gain (M5)  |
| 8    | (CDR) Antenna results, prototype & presentation. Impedance matching: Simulation with PUFF                      |
| 9    | Impedance matching with PUFF: Revision. RF amplifier (I): Matching networks for max-gain design                |
| 10   | Foundations of the Vector Network Analyser (VNA). RF amplifier: Matching networks (w. stubs) (M6)              |
| 11   | RF amplifier: Matching networks (w. stubs) & VNA test (M7). RF amplif. (II): Minimum-noise design (simulation) |
| 12   | WiFi link: Outdoor measurements & validation (M8)  |
| 13   | (FDR) Final design results and oral presentation   |

Students are assessed on a progressive basis: PDR (10%), CDR (25%), FDR (50%). The remaining 15% of the mark accounts for the achieved team work in the lab.

The course runs in the radiofrequency (RF) teaching lab of CommSensLab (UPC), which includes basic RF/microwave instrumentation (two VNAs over 3 GHz, one noise figure meter, spectrum analysers, RF synthesizers) and a

small anechoic antenna test chamber though only the VNAs are of concern for the present project. The lab is also equipped with a workbench and tools, 10 computers, and RF simulation software already mentioned. Key start-up items delivered to each lab team are summarised in Figure 3 in addition to connectors and cables to build the antenna. The UPC shield CC2500 enables direct interface with Arduino UNOTM and hence, a wide range of configuring possibilities of the RF transceiver (Sect. 3). A limited stock of PVC tubes (e.g., to build the Yagi antenna boom), RF connector pigtails, aluminium ground planes and aluminium foil tape, and copper rods (e.g., to build the dipoles) are also available.



**Figure 3. Start-up items. (a) UPC-designed TX/RX system based on the low-cost low power CC2500 radiofrequency transceiver. (b) Similar TX/RX operating as power meter. (c) 2.4-GHz amplifier (position/size of adhesive stubs 1-2 to be found by the students)**

### 3. Example results from the WiFi-link project

Next, example results are shown for selected milestones in Table 2. Results have been compiled and adapted from selected students’ FDRs and do not intend to be exhaustive of the whole course syllabus.

#### 3.1 Preliminary WiFi-link performance

The first example (M2, Table 2) aims to study the performance of the WiFi link over a 35-m path between bldgs. C3 and A3 over “Plaça Telecom” square (North Campus, Telecom-BCN School), which is to be set up by the students during w6-7. At this preliminary step (w2), which is carried out in the lab (outdoor test is postponed until w6-7), the link performance is studied in terms of the byte error probability (as a proxy of the BER) between two CC2500

transceivers (Figure 3a). One transceiver is configured as TX and the other one as RX, both interconnected by means of a 70-dB attenuator chain. The TX transmits a pre-defined known 10-byte digital sequence (0123456789) in endless loop fashion, which is later used to statistically estimate the error rate. The 70 dB figure is representative of the expected TX-RX losses (incl. free-space propagation losses). Figure 4 results show that FSK-2 modulation outperforms OOK and that performance is poorer for high-speed beacons, which is in agreement with theory.

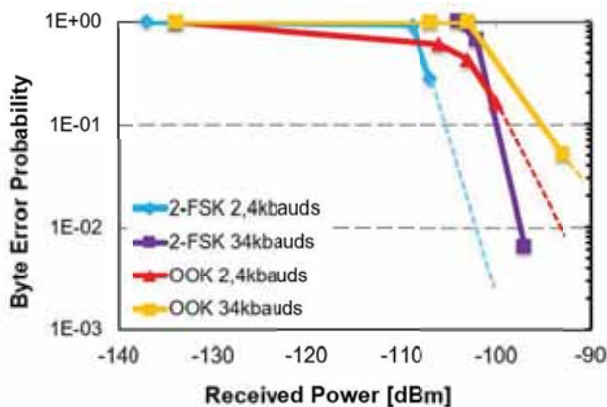


Figure 4. Byte error rate for the lab. Transmission. (Adapted from A. Gonga, A. Pérez, A. Roig and V. Wasmer, FDR, spring 2018)

### 3.2. Antenna block

A detailed technical procedure on the implementation of the different types of antennas can be found in [7]. The students recycle or buy for themselves the rest of low-cost materials (Sect. 2) needed to fabricate their antennas (M3, Table 2 and Figure 5), which is a good exercise of planning and creativity.

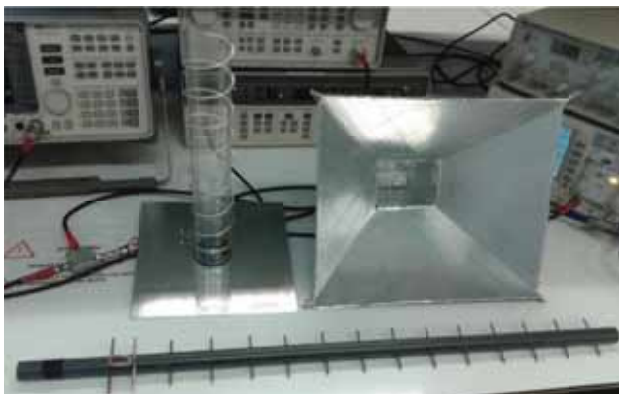


Figure 5. General view of the helix (left, second plane), horn (right) and Yagi antenna (first plane)

For the horn antenna, examples or such recycled materials include a milk tetra brick, which is used as waveguide, foamcore (i.e., a board of polystyrene foam clad with an outer facing of paper on either side) and aluminium tape to make all the walls conductive.

Another example is the helix antenna consisting of a conducting wire (e.g., coil-recycled copper cable) wound in the form of a helix mounted on a reflector. A methacrylate cylinder or a plastic dowel is of help to wrap the wire around. Concerning the Yagi antenna copper rods for the reflector and passive dipoles and a recycled PVC boom are used. To help the students in the balun (balanced-unbalanced) fabrication and soldering process a 2x1-cm through-hole printed circuit board (PCB) is used.

Outdoor antenna pattern and gain measurements (M5, Table 2) are carried out by means of the set-up shown in Figure 6.

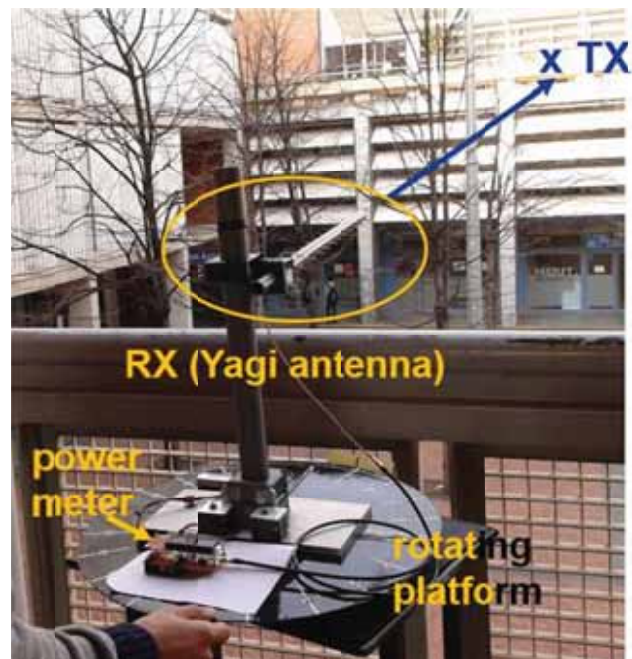
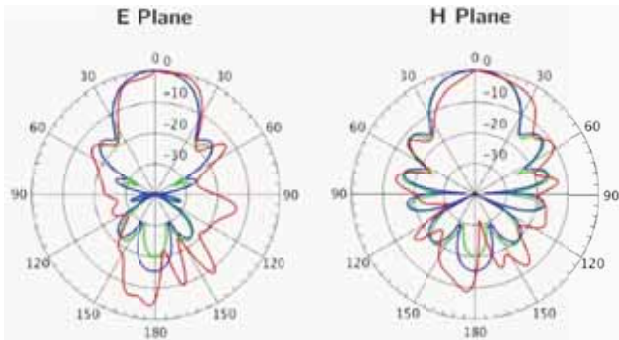


Figure 6. Outdoor antenna measurement set-up ("Plaça Telecom" square, North Campus, Telecom-BCN School)

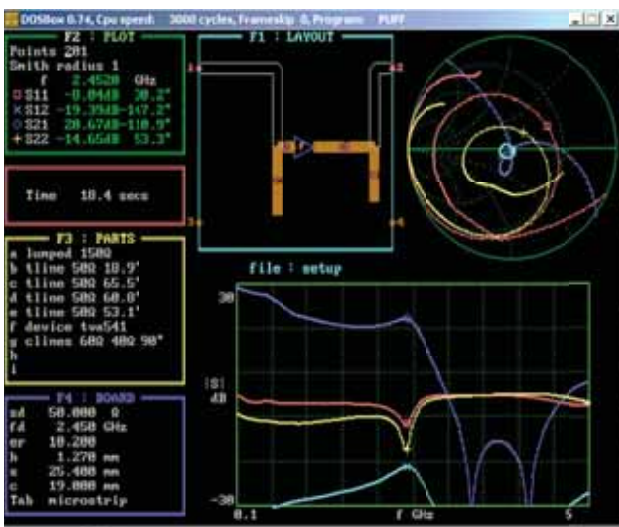
In transmission (TX) the base station is composed of one CC2500 transceiver (Figure 3a, b) and a four-patch antenna array of known gain, which is given by the faculties. In reception (RX) the antenna under test is positioned on a supporting bar on a rotating platform made of plastic-coated rigid cardboard. In RX, another of such transceivers

is configured in Received Signal Strength Indicator (RSSI) mode to measure the received power. The platform has an angular resolution of approximately 9 deg, which is enough for the antenna types considered. E- and H-plane pattern measurements (Figure 7) require to turn both TX and RX antennas 90 deg.



**Figure 7. Yagi antenna E- and H-plane radiation patterns (refer to Figure 6). (Blue/green) Theoretical pattern (NEC/Matlab™) [10]. (Red) Measured pattern. (Source: M. Oller, J.A. Ballester and C. Segarra, FDR, spring 2016)**

### 3.3 Amplifier block



**Figure 8. Amplifier matching simulation with PUFF software [11]**

Figure 8 shows PUFF2.1 simulation results (M6, Table 2) under the criterion of maximum-gain design. As a previous step to the simulation process the students measure the operating point of the BFG424F transistor (typ. 3V, 10 mA) so as to incorporate the appropriate common-emitter S-parameters into PUFF. Adhesive stubs (to be fabricated by the students, Figure 3c) can be modelled as 6 pF series capacitors because the glue acts as an

insulator between the PCB microstrip line and the metallic part of the adhesive stub.

### 3.4. Outdoor measurement campaign and link-budget validation

This section essentially addresses M8 in Table 2.

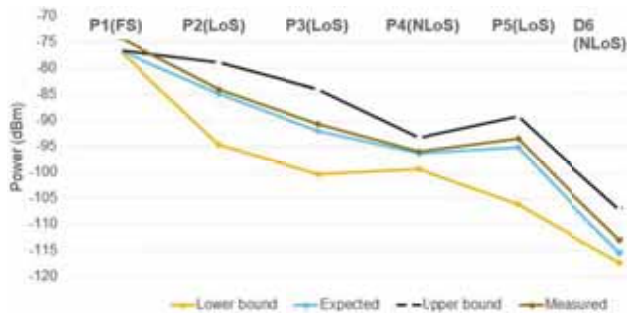
In order to carry out outdoor measurements with the WiFi link designed so far, a base station (BS) composed of a CC2500 transceiver and a monopole antenna in transmission is installed on the roof of D3 bldg. The mobile stations (MS) are each one of the students' lab team antennas connected to pertinent CC2500 transceivers configured in power –meter mode. Figure 9 depicts received power levels by one of the MS and related error rate as the MS moves along a row of buildings in the Campus. As expected, received signal levels become lower and lower as the MS moves apart from the BS. Reception cuts out in Non-Line-of-Sight (NLoS) situations arising when the MS is between building alleys or very far. Thus, red font labels represent the average number of wrong bytes per transmitted message (10-byte message).



**Figure 9. WiFi link performance map. (Green dots) Received signal strength [dBm] (Yagi antenna lab team). (Red dots) Points without reception (Yagi). (Blue points P1-P6) “Patch antenna” team measurement points. (Adapted from M. Oller, J.A. Ballester and C. Segarra, FDR, spring 2016)**

Finally, Figure 10 shows categorization of measurement points P1-P6 (Figure 9) into the different propagation situations under study (free space (FS), LoS, NLoS, refer to Sect. 2).

This categorization is achieved by using the propagation-model simulator previously developed by the students (M1 in Table 2) and which is refined now upon validation milestone M8.



**Figure 10. WiFi link: Validation of the categorization of the different reception situations at points P1-P6 (refer to Figure 9) according to ITU1411-1/7 model. (Back line) Theoretical received-power upper bound. (Yellow) Theoretical lower bound. (Blue) Theoretical expected level. (Brown) Measured level (patch-antenna lab team). (Adapted from J. Calderón, F. Guinot, D. Palacios, N. Solà, FDR, spring 2018)**

#### 4. Conclusions

All in all, the basic engineering project is to instil on BSc telecom students at the UPC Telecom-BCN School the critical thinking spirit while having hands-on lab.

After eight successive editions (2011-today) CDIO design-implement subjects are demonstrating to be an effective way to foster this challenge on a rampant technological environment as well as a suitable way to explain simple complex reality.

#### 5. Acknowledgements

CommSensLab (merging into a single body Remote Sensing, Antennas, Microwaves and Superconductivity) is a “María de Maeztu” Unit of Excellence funded by the Agencia Estatal de Investigación, Spain. This work has been funded by María de Maeztu MDM-2016-0600, and the Spanish Ministry of Economy and Competitiveness - European Regional Development Funds under TEC2015-63832-P project. Generalitat de Catalunya (Grup de Recerca Consolidat 2017-SGR-272) is also acknowledged.

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