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# Laboratory Experiments on 5G Cellular Technologies – A Case Study on the Synergy of Research and Experiential Learning

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## Abstract

Teaching and research complement each other. This is an advice often given to young professors, to encourage them to find synergy between research and teaching, i.e., to let research aid teaching, and vice-versa. When a professor develops new laboratory experiments for undergraduate courses in wireless communications, he/she may find it difficult to replicate research experiments, because they require expensive equipment, usually available in “research, non-teaching” laboratories. In this paper, we present a wireless laboratory that is used for both research and teaching. We show how the research on fifth generation (5G) cellular networks - including millimeter wave transmission, ultra-wideband wireless communications, and multiple-input-single-output (MISO) antennas – helped develop laboratory experiments for undergraduate engineering students. The experiments not only teach students about 5G technologies, but also how to use real-time spectrum analyzers, vector signal generators, arbitrary waveform generators, and signal analyzers, which will help their engineering and/or research careers.

## 1. Introduction

What is experiential learning? Although it often refers to courses with laboratory experiments, it is an effective type of learning which interconnects theory and innovation. The book “Make it Stick” [1] explains that when we present students with new problems and they need to apply the theory they learned in the classroom to solve these problems, usually through hands-on activities, students store what they learned in their long-term memory. By learning well something and seeing how it is applied, engineering students will apply what they learned to solve new problems, to create prototypes, to innovate.

As an example of experiential learning, consider an undergraduate course on Wireless Transmission System which teaches about the physical layer of wireless systems,

and uses theory from physics and math courses. It will have weekly laboratory experiments on topics such as:

- free space loss,
- multipath propagation,
- analog and digital modulation,
- multiplexing systems,
- wireless network systems, such as cellular and Wi-Fi.

Its laboratory requires spectrum analyzers, oscilloscopes, signal generators, and possibly microwave optics educational kits. Such equipment is expensive. Advances in software defined radio (SDR) [2] allow instructors to use less expensive equipment to develop new educational laboratories. For example, some of our teaching laboratories at Texas A&M University use USB dongles (e.g., DVB-T RTL USB [3]) that act as an SDR receiver, operating between 50 and 2200 MHz.

However, there are two practical challenges that professors face to keep the experiential learning relevant in their courses. One is to keep their wireless course – lecture and laboratory - up-to-date with current wireless technologies. The other is the cost of laboratory equipment, because higher frequency ranges mean higher costs. For example, fifth-generation (5G) cellular systems will use millimeter wave signals, between 30 and 300 GHz [4]. Laboratory experiments to teach about 5G technologies would enhance a wireless course, but how to support educational laboratory experiments at such high frequency range?

This paper presents a case study of a laboratory at the Communications and Networking Department (Comnet), at Aalto University, in Finland, that has a common laboratory setup for teaching and research. Through collaboration between Texas A&M University and Aalto University, a group of American students took a Wireless Transmission Course at Aalto University in the Summer of 2017 (Fig. 1). There they performed experiments on a multi-purpose laboratory that is used for teaching communications courses and 5G research. Next, we describe the setup of a

specific laboratory bench in that lab and how it is used to teach three different concepts of 5G systems: millimeter wave transmission, ultra-wideband (UWB), and multi-channel generation.



Fig. 1 A Texas A&M student at the wireless laboratory at Aalto University, doing an experiment with a 60 GHz antenna used for research on 5G cellular systems.

### 3. Wireless Laboratory at Aalto University

The wireless laboratory at Aalto University is a multi-purpose lab that serves several undergraduate courses while being used by graduate research assistants and professors.

#### 3.1 – Courses

Table 1 lists the courses that use the wireless laboratory at Aalto University.

Table 1 – Courses taught at the Wireless Lab at Aalto University

Course	Title
ELEC-E7410	Communication transmission lines
ELEC-E7250	Laboratory course in communications engineering
ELEC-C7320	Software radio course
COM-EV	Wireless Transmission Systems (Summer Course for Texas A&M)
S-72.2311	Laboratory course in communications engineering I

The first course (Communication and Transmission Lines) has three laboratory experiment, including coaxial and twisted pair cable measurements using time domain reflectometry, optical component measurements, and shielding of coaxial cables.

The Laboratory Course on Communications Engineering allow students to experiment with different types of radio link measurements, from interference measurements in Digital Video Broadcasting – Terrestrial (DVB-T systems) to investigation of Wireless Local Area Network (WLAN) throughput), among others.

The second Laboratory Course on Communications Engineering I, listed in Table I, is an older laboratory course, now part of E7250, but under this course new labs are being developed (i.e., alternative labs), such as the 5G laboratory experiments that will be described in Section 4.

We adopted a combination of the aforementioned laboratory experiments in our study abroad course at Aalto University. The radio link lab, in particular, was a good example of hands-on experiment to understand microwave point-to-point links at 58 GHz. In that experiment, students used the reflection of a nearby building, and controlled the transmitted/received power by adjusting the blinds at the laboratory window (Fig. 2). They took measurements of received power, bit error rate (BER), and receiver gain, as in the sample shown in Table 2.

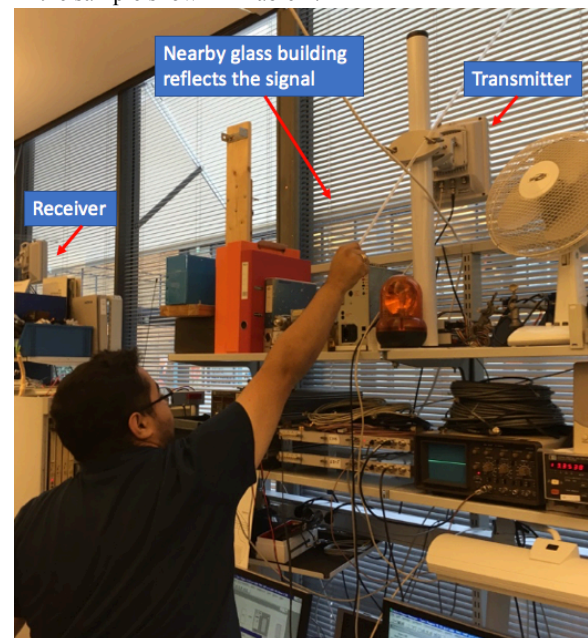


Fig. 2 A simple and memorable experiential learning example: an experiment with a microwave point-to-point link at 58 GHz, in which students adjust the angle of aluminum blinds and measure bit error rate (BER).

Table 2 – Sample results of the radio link experiment and blinds experiment presented in a post-laboratory report.

Blind Settings	Received Power (dBm)	Receiver Gain (V)	BER
Both Fully Open	-45	2.9755	0
Fully Open, Slightly Closed	-48	3.1672	0
Fully Open, Half Closed	-51	3.2879	0
Fully Open, Slightly Open	-55	3.2879	0
Fully Open, Fully Closed	-71	4.5440	$5.4 \times 10^{-5}$
Fully Closed, Half Closed	-72	4.6045	$3.8 \times 10^{-4}$
Fully Closed, Fully Closed	0 (Disconnected)	5.0542	$1.2 \times 10^{-1}$

For each course, all laboratory work contains three parts: (i) preliminary exercises, (ii) lab measurements (done in two-person groups, with supervision of a teaching assistant), (iii) post-laboratory exercises/report.

### 3.2 – Research

To illustrate 5G research at Aalto, in 2015 Aalto University received a grant called TAKE-5 to create a testbed for a 5G network [5]. Other Finnish universities participate in this testbed, as well as companies such as Ericsson, Huawei, and Nokia. It is a project that is part of a larger initiative by the Finnish government called 5G Test Network Finland (SGTNF).

At the physical layer, Aalto University has researchers working on millimeter-waves transmission systems, such as a millimeter-wave channel sounder and millimeter-wave antennas, as presented in [6]. Some of the researchers involved in these projects are using the same equipment as undergraduate students in the wireless laboratory at Aalto.

## 4. Laboratory Experiments on 5G

As for the 5G laboratory experiment developed in 2016 as part of the old Communications Engineering course, there is one laboratory bench at the wireless lab at Aalto University that is dedicated to 5G. Fig. 5, at the end of this paper, shows a “big picture” of the laboratory bench setup and how the instruments are connected. Devices under test (DUT) can be connected as well. Several laboratory experiments use this setup: devices can be connected and disconnected, and configurations can be changed from one experiment to another. As a result, this setup is modular and multi-purpose.

Note that smaller devices such as analog low-frequency generators, filters, amplifiers, attenuators were not added to the picture. Also, because students and researchers can control the devices locally or remotely, parts of a local network are added to the picture.

The antennas in the picture are connected or just added closely to the instruments. If an experiment uses non-licensed frequencies or frequencies owned by the university, students connect coaxial cables and antennas only during the experiments. For licensed frequencies, researchers use an RF-chamber and radio channel simulator that can be added to this laboratory setup.

It is possible to use software-defined radio (SDR) generators and receivers in the laboratory, as shown on the right side of Fig. 5. At the moment, this is only being used for research. By using this option, researchers have possibilities to use this set for testing components that they have developed for the new technologies.

The laboratory setup in Fig. 5 supports the following experiments:

- millimeter wave transmission,
- ultra wideband (UWB),
- multi-channel generation.

which are described next.

### 4.1 Millimeter wave transmission

This lab covers the following theoretical themes:

1. Standard IEEE 802.11 ad;
2. Signal Mixing;
3. Intermediate Frequency (IF);
4. Shannon’s Channel Capacity Theorem.

Before doing the laboratory experiments, students receive reference material and papers that address each topic above. This is an important part of lab work, because this course can work even without lectures.

Using the equipment at the bottom of Fig. 5, this experiment includes four tasks: 60 GHz carrier generation; signal mixture; Intermediate Frequency; millimeter wave transmission of ultra-wideband (UWB) signal.

### 4.2 UWB

The theory covered in the Ultra-Wideband (UWB) lab includes topics such as ultra-wideband; sample rate of a laboratory instrument; marker, trigger and flag signals. For all these topics, a literature package is given to students to help them prepare for the laboratory experiment.



Using the setup shown in the middle of Fig. 5, this experiment consists of three tasks: frequency response of a filter with 800 MHz range; ultra-wideband signal generation; and signal capture.

On the UWB signal generation task, students learn how to generate a multi-carrier signal and a swept-frequency cosine signal with bandwidth of 6 GHz, load it to the UWB signal generator equipment, transmit it, and send it to the serial data analyzer and spectrum Analyzer and process the received signal. In most tasks, students measure the received signal and fill in tables such as Table 3.

Table 3 – Measurements of UWB signal.

Signal Bandwidth, GHz	Received Signal Level, dBm
1	
2	
3	
4	
5	
6	
7	

#### 4.3 Multi-channel generation

The reference material that students receive before the lab cover theoretical topics such as:

1. Fourier transforms;
2. I/Q representation of a signal;
3. Frequency response of a filter;
4. Nonlinear distortion;
5. Intermodulation distortion;
6. Clock signal;
7. Eye diagram.

Using the equipment as in the setup at the top of Fig. 5, this experiment includes several tasks: frequency response of a filter; intermodulation distortion measurements; multichannel synchronized transmission; clock signal and eye diagram.

In particular, the experiment on multichannel synchronized transmission (shown in the setup in Fig. 3), allows students to experiment with multiple-input-single-output (MISO) systems, where four antennas are used to transmit and one antenna is used to receive the signal.

This laboratory setup was used in our study abroad course on Wireless Transmission Systems. Fig. 4 shows our students changing position of transmitter during path loss measurement. The receiver with antennas is inside laboratory.

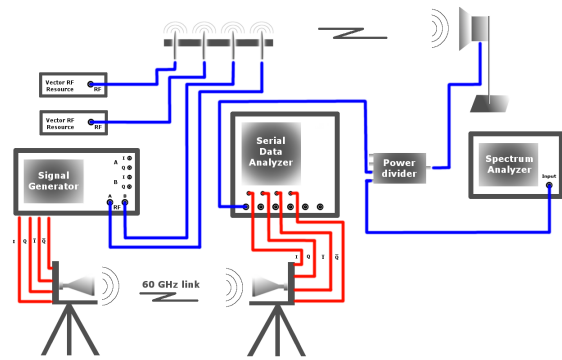


Fig. 3 Setup for MISO experiment.

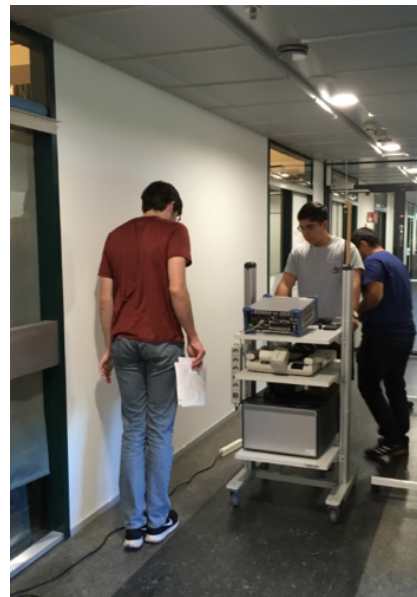


Fig. 4 Students taking measurements of MISO signal.

## 5. Summary

Collaboration between universities helps professors share best practices and ideas on how to promote experiential learning. The wireless laboratory at Aalto University represents an example on how to promote synergy of teaching and research, by providing its students with state-of-the art laboratory equipment that cover the latest advances in wireless communications. By learning how to use and take measurements with the equipment here described, students are well prepared for engineering and/or research jobs.

One motivation for this synergy is that these laboratory experiments require expensive equipment. Many instruments are very difficult to replace or repair. Moreover, RF and millimeter wave frequency use precision wires, antennas, and connectors. Therefore, students who

work in the laboratory are always supervised by an instructor and are required to read all the reference material before performing the experiments.

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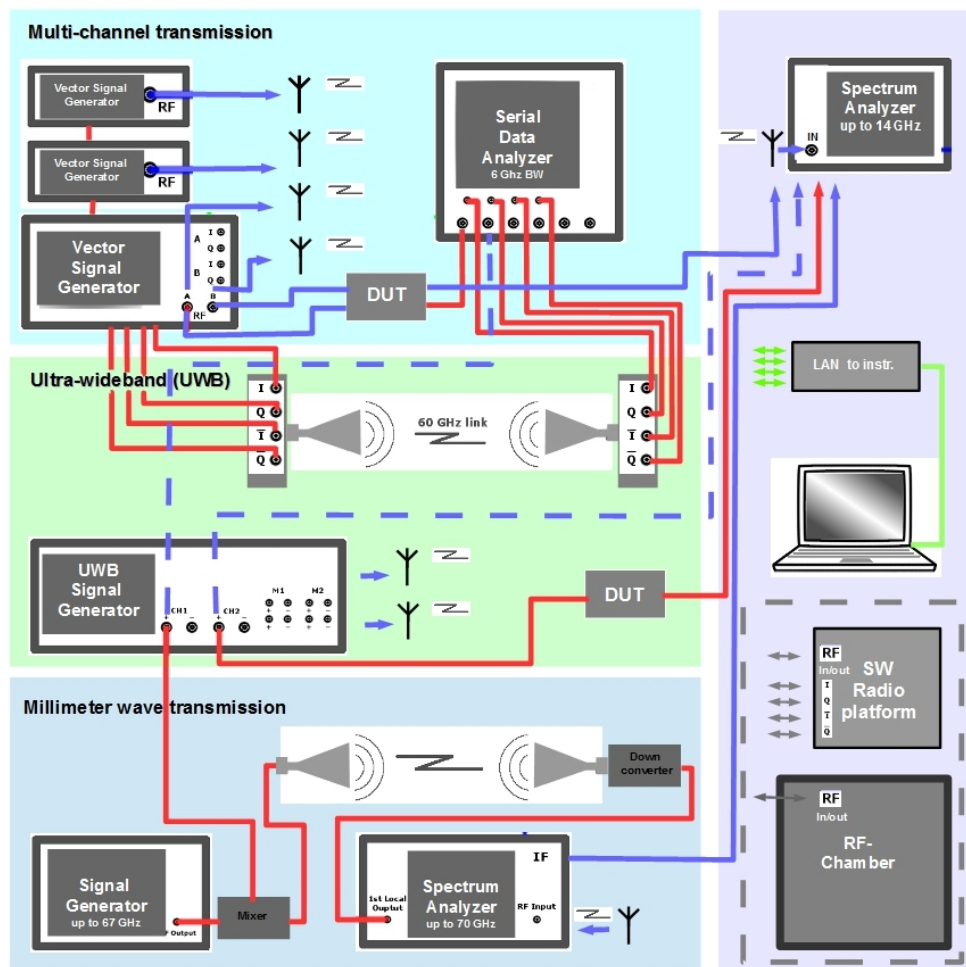


Fig. 5 General setup of laboratory bench for 5G.