J. Eng. Technol. Sci., Vol. 54, No. 6, 2022, 220602

A Low-Cost Laboratory Practice for Fundamental Learning of Wireless Digital Communication

Titon Dutono[1,*] & Tri Budi Santoso[2]

[1]Departemen Teknik Elektro, Politeknik Elektronika Negeri Surabaya, Jalan Raya ITS, Keputih, Kec. Sukolilo, Surabaya 60111, Indonesia
[2]Departemen Teknologi Multimedia Kreatif, Politeknik Elektronika Negeri Surabaya, Jalan Raya ITS, Keputih, Kec. Sukolilo, Surabaya 60111, Indonesia
*E-mail: titon@pens.ac.id

Highlights:

- Students able to deal with real systems instead of only having theoretical and classical intensive classes.
- Time and frequency domain observation of radio propagation signal.
- The proposed practices are required hands-on intensive face-to-face interactions between the students and the lecturer/instructor.
- Evaluation by students of the data link layer practices was carried out and continued with assessment.

Abstract. Several studies have shown that the main challenge in teaching complex systems involving many theoretical backgrounds to senior students is their lack of confidence. In this paper, we present an approach to the teaching methodology of an undergraduate course in a telecommunication study program. The first goal of this methodology is to help students understand the theoretical concepts behind wireless digital communication systems through direct practice to give them more exposure to a real system through affordable practice activities in an experiential context, utilizing an HF radio and a single-board computer (SBC). The second goal is to challenge senior students to understand the data link layer by using white box testing of the syntax of the programming language embedded in the SBC. This approach is ideally carried out based on offline and hands-on class activities, however, the pandemic condition made it unavoidable to do it online using a demonstration model. Feedback from students was collected through written comments, post-testing, including a facility index analysis, and a questionnaire that was distributed using the available e-learning system. The post-test results showed that the average score was 72 out of a maximum of 100.

Keywords: *computer science; electrical engineering; hands-on; individual practice; senior students; telecommunication; undergraduate; white box testing.*

1 Introduction

The results of studies on learning in the field of electrical and computer engineering (ECE) in the freshman year clearly show that theoretical objects are

Received February 15th, 2022, Revised June 15th, 2022, Accepted for publication August 8th, 2022.
 ISSN: 2337-5779,
DOI: 10.5614/j.eng.technol.sci.2022.54.6.2

.

much easier to learn when students already have experience with the variables and elements involved. Also, if theoretical understanding is related to real-world experience, freshman students will be able to avoid boredom and lack of patience in waiting to learn engineering subjects in the sophomore year [1]. For this reason, it is necessary to increase exposure to the real engineering world in the form of laboratory practices that are designed to be more interesting so that the students feel compelled to learn more deeply.

We are now in the middle of Industrial Revolution 4.0 (IR 4.0). The proliferation of devices is one of the symptoms that can be felt in this era. Among these devices, the most prominent is a small computer called SBC (single-board computer), which is easily available in local electronic markets at very affordable prices, even though having more computing power than many of the formerly known supercomputers [2]). The most popular SBC is Raspberry-Pi, which is continuously being developed to achieve new functionality and better performance. The consequence of this is that when the industrial sector hires a fresh graduate, they almost always require prerequisite minimum skills, such as C programming coding for driving an SBC for a particular-task or even developing an application based on the platform of wearable devices.

A global trend in higher learning is shifting from ‘what is being taught’ to ‘what is being learned’ [3]. This means that study programs must prove that their graduates achieve specified learning outcomes. At the same time, higher education also requires reviewing and redesigning its education system to be more relevant towards industrial needs. The concrete action that must be taken is adding more exposure of students to real systems instead of only having theoretical classes and classical intensive classes. The problem is how to find challenging and attractive practices. The practices must include a real system (not a simulation), a complex system (not a simple one), and manifestations of subjects that have been studied. Simple practices will already have been conducted during the sophomore period, for instance, electric circuit practices and basic communication practices carried out based on the observation of signals using an oscilloscope, a spectrum analyzer, and other analog measurement devices. Simple practices can be boring for senior students. However, too complicated practices will make students lose their confidence.

The data link layer is the second layer of the classical OSI standard. We chose the data link layer as the general theme of the proposed practices because it is developed based on hardware and software to provide the means to detect and possibly correct errors that may occur in the physical layer. In wireless communication, the radio acts as the physical layer, while the computer acts as the data link layer. It could be said that the physical layer is the hardware platform, with the data link layer on top acting as the software to manage and perform data delivery while maintaining the integrity of the datagram.

In this paper, individual practices for senior-level undergraduate students to demonstrate real data link layer practices in an experiential context applied to a real system (not a simulation) are introduced. The practices focus on decomposition of the system as an approach to understanding complex systems.

2 Method of Choosing Practices for Senior-level Undergraduate Students

The name of the course and the attached practices is Radio Communication Course. It has three credits and is designed for senior-level undergraduate students. The principles and theoretical aspects of the course are discussed for 100 minutes in weekly in-class sessions, while the attached practices are carried out in different time slots of 150 minutes per week.

In this section, we present a discussion of the criteria for choosing the theme of advanced practices of a complex wireless digital communication system for students in the senior year [4,5,6]. Almost all subjects and knowledge supporting the platform have already been learned during the sophomore year, the junior year, and the on-going senior year. Therefore, it is necessary to develop compulsory student practices or hands-on projects for the senior year using the following criteria:

1. The practices are meant for an individual course instead of the usual group-based course, therefore the workstation should consist of affordable hardware and common measurement devices, such as a regular oscilloscope, an amateur HF radio, an AVO meter, and other simple equipment.
2. The digital communication system of which the working will be reviewed is a real system (not simulation-based). Even though it is not a simple system it must have a low bit rate in order so it can be observed step-by-step.
3. The practices or hands-on projects must involve all aspects that are capable of being dealt with by the students, such as radio waves, the modulation/demodulation process, the channel coding/decoding process as well as its performance.
4. The knowledge required to understand complex wireless digital communications systems has been studied by all participating students.
5. Challenging the students to aggressively implement this complex system because they have been already introduced to C coding and programming in the sophomore and junior years.
6. The C language is deliberately chosen because of its convincing advantages, such as closeness to the hardware as well as the fact that many examples of

.

implementations of telecommunications systems are written in C, which is widely available as open-source software.

2.1 Theme of the Practices

Based on the criteria mentioned above, we set up a package of student practices that deploys the Weak Signal Propagation Report (WSPR) software developed by Dr. Joe Taylor, Nobel laureate in astrophysics 1993, and a member of HAM radio with callsign K1JT [7]. WSPR represents a method of gauging HF propagation conditions utilizing quite a simple principle, although the used technology behind it requires theoretically intensive training. The details of the WSPR technical specifications can be found in [7,8].

A low bit rate digital signal sounds like a single tone. The digital messages it carries are hardly noticeable. Modulation uses frequency shift keying (FSK) with a very small shift, occupying an extremely narrow bandwidth (only 6 Hz). We consider this subject matter because it is in line with the spirit of frequency conservation as the basic philosophy of radio communication. Long-haul communication, low bit rates, and extremely narrow bandwidths are the basic considerations we adopted to choose as the theme for these practices.

A signal received from long-haul communication is exciting for the students because it could be coming from thousands of kilometers away. Low bit rate data transmission enables students to observe signal processing on a step-by-step basis, using an instantaneous print-out of the signal shape in the time and the frequency domain, respectively. The observation points are tapped from the Test Point (TP) software. Also, an extremely narrow bandwidth confronts the students with its implications, i.e., the depth of the underlying theory required to keep the integrity of the data of the transmitted messages.

WSPR consists of a transmitting and a receiving part. Transmitting a radio wave requires a frequency usage license. Every country has its specific law to properly regulate the frequency spectrum usage, but based on the ITU Recommendation, all countries have the same rules regarding the usage of portions of the frequency spectrum. Academics, in the name of research or teaching activities, often unintentionally, or even intentionally, neglect the law concerning frequency spectrum usage. To specifically avoid such potential violations, we propose to install only the receiving part.

The presence of noise, jitter, Doppler shift, and frequency drift during data transmission through a noisy channel are matters that must be mitigated or compensated to provide successful decoding of the digital signal during the receiving process. Therefore, the real challenges come when implementing the receiving process, which requires a theoretically intensive method.

Even though WSPR is run voluntarily by members of Amateur Radio all over the world, nowadays it tends to be more intensively used, not only for probing a specific propagation path but also for wider use, such as solar activity observation [11,12]. This means that at any time, the presence of WSPR signals in the HF bands is quite high due to being used as signal source in this practice.

2.2 Device Preparation

2.2.1 Hardware Set-Up

In this article, conventional usage of a Raspberry Pi board for teaching purposes is applied by exploiting its inherent processing power and its embedded I/O peripherals, such as monitor, keyboard, mouse, cables, connectors, and an HDMI-to-VGA converter (only for disabling the HDMI standard display to avoid erratic pointing to the audio device) is proposed. The SBC Raspberry Pi 2 Model B is used as the processor in the proposed practices. The technical specification is available online. The only additional device is an external USB sound card with a C-Media chipset to supply audio input at a 16 bits/sample resolution as well as an additional audio output when needed, even though audio output is not necessary for the practices. The hardware configuration can be seen in Figure 1.

2.2.2 Software Set-Up

The Raspberry Pi platform is initially installed with the Ubuntu MATE Linux distribution. Several Linux distributions support Raspberry Pi boards, even though there are no particular or academic reasons for choosing Ubuntu MATE as the platform for these practices, in fact, several unofficially reports state that the Ubuntu MATE distribution is used more widely compared to other distributions.

The next step is to download and install the required library upon the compilation of open-source WSPR source code [8], such as ALSA Audio API, FFTW3, and GNUPLOT. These libraries are freeware and easily installed by using the apt-get command line tool.

Like any piece of hardware, an additional USB audio card only needs a device driver as an interface to make the hardware visible and available to the operating system. Nowadays, the Advanced Linux Sound Architecture (ALSA) interface is supported by the Linux kernel. Therefore, writing the source code in the C language, we used the ALSA API (Application Program Interface) when required

.

to open communication to the audio card for acquisition of the audio signal that comes from the HF radio.

The receiving part of WSPR consist of three separates parts, i.e., audio signal acquisition, signal processing, and data processing. After the audio signal is captured by the audio signal acquisition part, the signal is processed in both the time and the frequency domain, so that the discrete Fourier transform (DFT) is frequently used during the processes. The application program interface (API) FFTW was adopted for computing the DFT because of its stability, efficiency as well as its wide use. A manual and a comprehensive explanation about the use of FFTW are available online.

The signal processing part needs real-time observation of every step of processing by printing the intermediate values. Gnuplot is a portable command-line driven graphic utility for Linux and other platforms. However, under the C language we can pass values from the local process to Gnuplot by using a pipe interface to generate a real-time display of values that are continually changing. A manual and instructions on how to use Gnuplot are available online.

2.2.3 The Practice Manual

The manual of the practices was written separately for the ten modules of the practices. Each module has its supporting theories. Its underlying mathematical model is written per module in a detailed manner. The manuals are installed on a website and are ready to be downloaded by students at any time.[1]

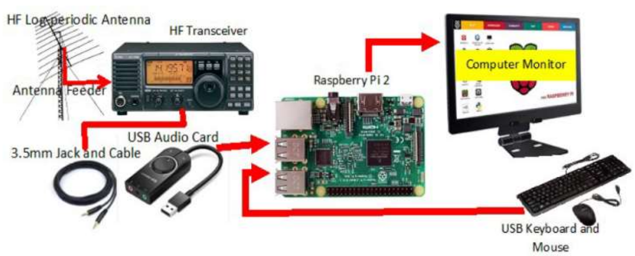

Figure 1 The workstation in the practices only consists of commonly available and affordable devices.

2.3 Pandemic Emergency Condition

The series of proposed practices are not designed for online teaching delivery. Instead, the practices require hands-on intensive face-to-face interaction between

[1] URL: http://titon.lecturer.pens.ac.id/

the students and the lecturer/instructor. However, the pandemic emergency condition required us to change the teaching delivery to truly online.

A demonstration model was set up to carry out the online-based teaching delivery system, as shown in Figure 2. The model requires an HDMI capture device (ELGATO HD60 S+), live streaming software called OBS (open broadcaster software), and video conferencing software called Zoom.

By using the setup shown in Figure 2, all the screen activity of the Raspberry Pi can be captured perfectly and delivered to the screen of all students who are attending the Zoom conference. The work-from-home lecturer then executes all the steps written in the practice manual on the platform of a Raspberry Pi-based workstation, while all attending work-from-home students listen and focus on the subject being delivered by the lecturer. Interaction between the students and the lecturer/instructor is expected to be intensively carried out during the demonstration model explanation.

2.4 White Box Testing for Recognizing Syntax Functionality

Telecommunication engineers use calculus and statistics to create abstract representations of the radiofrequency wave, modulation system, and propagation constraints and then solve various problems at this abstract level. Software engineers use discrete math to create a digital representation of software and then solve problems through a digital hardware implementation.

Creating an educational environment that has the outcome of student competence in unifynig both engineering jobs is a difficult challenge that higher engineering education faces in the IR 4.0 era. Indeed, executing these practices would encourage the students to be software engineers while they are studying in a telecommunication engineering study program.

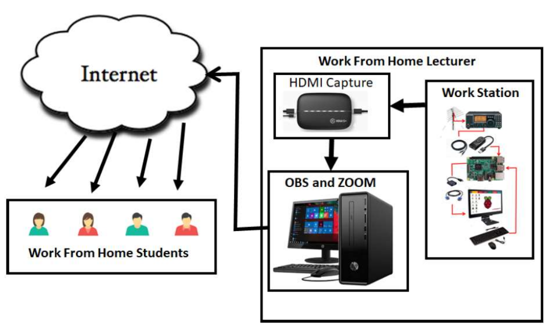

Figure 2 The required setup for the online teaching delivery system.

.

3 Description of Practices

The long journey of the WSPR signal receiving process is depicted by the block diagram shown in Figure 3. The results of processing can temporarily be observed via four test-points (TP-1 until TP-4), as shown in the figure, by printing the intermediate values.

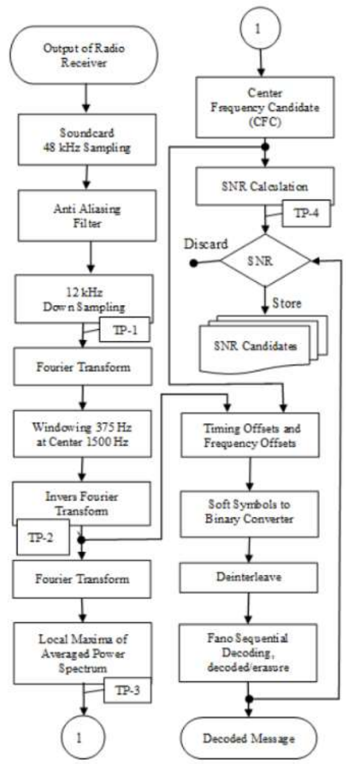

Figure 3 Block diagram of the long journey of the WSPR signal decoding.

3.1.1 Practice I - General Explanation of Signal Sources

The signal sources used in these practices are WSPR signals that may be transmitted from thousands of kilometers away. Practice I consist of a general explanation of how to use the available laptop based WSPR software package. The software should be set to receiving mode only. During the general explanation, the teacher or instructor uses a laptop or desktop that is connected to the HF transceiver, trying to receive the WSPR signal from the antenna by using the WSPR software. The important points of the explanation are the availability of a WSPR signal within the listed working frequencies as well as how to download the WAV file that is recorded by the software for signal source purposes.

3.1.2 Practice II - Signal Acquisition by Using a USB Sound Card

The topic of Practice II is time synchronization and signal acquisition by using a USB sound card. WSPR is a timing-sensitive digital communication system. Therefore, it requires time synchronization between the transmitter and the receiver, which can be based on Internet timestamps by calling the C Standard Library that contains time and date function declarations. Then, the fundamental concepts of signal acquisition by using a USB sound card in the ALSA library environment are introduced to the students through observation of the C program given in the module of the practice. The number of bits per sample, the format of the data, the buffer size, the structure of the sample, the sampling frequency, the structure of the sample frame, and the determination of the I/O device are the parameters to be initialized by passing them to the operating system via a syntax of the C program.

To avoid an erratic condition because of the variation of consumer-grade cards, the sound card is handled by default settings, including default frequency sampling at 48 kHz, while the WSPR program needs 12 kHz sampling. Therefore, it is necessary to downsample from 48 kHz to 12 kHz. The students must remember that before the decimation process from 48 kHz to 12 kHz, a 6 kHz lowpass filter should be inserted to avoid aliasing. The result of this section is a 114-second length AFSK signal with a sampling frequency of 12 kHz. The waveform will be observed by plotting a segment of the signal (say 256 samples) by using Gnuplot's pipe interface. The students can observe the plotting signal via TP-1 and intuitively they will determine that the result of the signal is normal or suspect of being impaired.

3.1.3 Practice III - Signal Conditioning

The WSPR signal has low power and occupies a very narrow bandwidth (only 6 Hz). The WSPR signal that must be extracted is buried in noise and under a great deal of power loss due to long-haul ionospheric propagation. Doppler shift, frequency drift, frequency calibration errors as well as timing shift are inherent constraints in wireless telecommunication system and require frequency and time offsets during the decoding processes.

Signal conditioning is processing of the signal to prepare it for the next stage of processing. The previous Practice-II provides a segment of the AFSK (audio frequency shift keying) signal that is centered at 1500 Hz with a sampling frequency of 12 kHz, a bandwidth of 2500 Hz (according to the channel

.

bandwidth of the HF receiver), and a length of 114 seconds. To increase the accuracy of the FSK demodulation process, it needs to zoom in on the signal through downsampling by 1/32 to 375 Hz.

The WSPR program uses the frequency domain to downsample the received AFSK signal. First, the 114-second long, 12-kHz sampled (i.e., 1,368,000 samples), digitized AFSK signal is transformed to the frequency domain by using the FFTW library function, becoming 2 × 1,474,560 points representing real and imaginary components in the frequency domain, with a frequency resolution of 0,008138 Hz per point. Thus, to get a signal with a bandwidth of 375 Hz, 46,080 points (i.e., 375/0.008138 points) are required. Then, 2 × 46,080 points are windowed, with the center at the 184,320th point (i.e., frequency 1500 Hz). After that, the windowed 2 × 46,080 points are inverse-transformed back to the time domain by using the FFTW library function, becoming 2 × 46,080 samples that represent in-phase and quadrature components in the time domain. Now, AFSK signals with a lower sampling frequency, i.e., 375 Hz, are available.

Like in the previous practice, the students should do white box testing to trace the above calculation of the program from scratch by tracking and recognizing on a line-by-line basis [15]. The students observe the waveforms by plotting a segment of the signal (say 256 samples) by using Gnuplot's pipe interface. The students can observe the plotting signal via TP-2 and will intuitively determine that the signal looks normal or suspect of being impaired.

3.1.4 Practice IV - Frequency Offset and Center Frequency Candidates.

The topic of Practice IV are the requirements of the frequency offsets to compensate for the intentional or unintentional frequency difference between the carrier frequencies generated by the local oscillators of the transmitter and the receiver on the opposite side, which causes a significant impairment for digital communication. Although they have studied the requirement of frequency offsets in a very detailed way, how to practically implement them is still a challenge for the students.

This practice introduces a method of frequency offsetting by means of offering several candidates for the center frequency in the range of ±150 Hz with the center at 150 Hz. To do this, the system carries out the following operations. First, the 2 × 46,080 samples of the AFSK signal are segmented into frames, where each frame may convey a symbol (frequency shift). Each frame is then windowed and analyzed by using the Short Time Fourier Analysis method by calling the FFTW library routine to perform a power spectrum analysis. The frame length for the purpose of this calculation is 512 samples and sliding is done by 128 samples. Therefore, 360 frames of the power spectrum are now available. The next step is the averaging of the power spectrum across all frames, followed by searching the local maxima to find the center frequency candidates (CFC).

Now, 512 points in the power spectrum across the whole AFSK signal are available to represent the bandwidth of 375 Hz with a resolution of 0.7324 Hz per point (i.e., 375 Hz/512). Then, smoothing by 7 points of the window is carried out to capture the local maxima in the range of 6 Hz (i.e., the WSPR bandwidth). At the same time, the presentation of the power spectrum is limited to 300 Hz (i.e., represented by 411 points) with the center at 150 Hz. The next step is searching for local maxima across the power spectrum to find the CFC, but its number must be limited to not more than 200, and it is only considered within the range of ±150 Hz. The students can observe the plotting of the CFCs via TP-3. A screenshot of these CFCs is shown in Figure 4, where the red circles show the CFCs within the range of ±150 Hz with the center at 150 Hz.

3.1.5 Practice V - SNR Estimation and Correlation Receiver

The previous practice showed how the system offers several candidates for the CFC, which will be used as a reference during the FSK demodulation process. Each CFC has its own signal to noise ratio (SNR) estimation, which is calculated based on the WSPR bandwidth as follows. Firstly, the average power spectrum is sorted in ascending order, which can be observed through TP-4. The noise level is estimated based on the assumption that the noise level spectrum frequency is the 30th percentile (i.e., frequency index 123 from the whole index 411). The SNR of all CFCs is then calculated by dividing each power level of the CFC with the estimated noise level. The students should trace this approach through a syntax, including how to represent the SNR based on the HF channel bandwidth. An explanation of this approach is written in the manual for the practice.

Furthermore, a correlator is used to convert each frame of the WSPR signal package to a symbol. To obtain the best performance, the correlator requires accurate timing and frequency. The presence of a pseudo-random sync pattern at the transmitter side makes the receiver demodulate the WSPR signal more accurately. Detection and recognition of the sync pattern establish the required time offsets, mainly to compensate for timing asynchrony between the transmitter and the receiver. It is known that the length of one package of the WSPR signal is 110.6 seconds. The time offsets are carried out by shifting the package of the WSPR signal forward and backward while searching the maxima of the total correlation coefficient, which is an accumulated correlation coefficient collected from all frames that have the most correlated signal toward pre-set local oscillators.

Each signal frame is demodulated using cross-correlation toward four pre-set frequencies of the locally generated signal to recognize one of the four-state symbol values. Furthermore, the pre-set frequency superimposed with the frequency offsets is required to track and compensate for the deviation due to the presence of Doppler shift as well as receiver local oscillator drift. The time-shifting and frequency deviation that correspond with the maximum total correlation coefficient are noted as coarse parameters that will be refined in the next processing. The important points that the students must consider in this practice, are the following:

1. The role of the sync pattern.
2. How to derive the equation of the Fast Sine/cos Generator used in the software.
3. How to carry out timing and frequency offsets.
4. The students must conduct white box testing to understand how the software carries out the above process in practice.

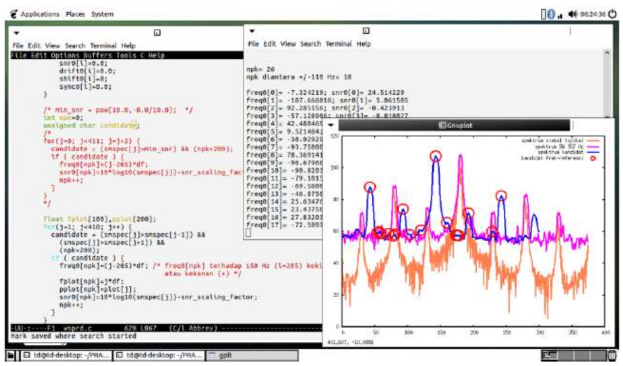

Figure 4 A screenshot of a window environment in Practice IV. The sub-window of the plotting center frequency candidates (CFC) shows the circles that represent CFCs within the range of ±150 Hz with the center at 150 Hz.

3.1.6 Practice VI and VII - Timing and Frequency Offsets Refinery and Symbols to Binary Conversion.

Coarse parameters for the timing and frequency offsets were found in the previous practice. The same correlation process as in the previous practice is carried out to refine these parameters by using the Vernier shifting step. The previous practice showed that the performance metrics towards the timing and frequency offsets are only a total correlation coefficient. However, in Practice VI, the performance metrics are both the total correlation coefficient as well as the status of the decoding process, successfully decoded or erased. The output of this process is a series of signal power samples, where each sample is quantized into values from 0 to 255.

Practice VII has the theme of the conversion of an analogue series to a series of binary values. This is carried out by using a statistical approach. The students should conduct white box testing to trace and observe the available source file to find out how to use the statistical approach to provide code for a device that works as designed. An explanation of this statistical approach is available in the manual of the practice.

It is well known that the convolution code is very reliable for correcting single-bit errors but is very susceptible to burst errors. Therefore, in practice, the use of convolutional code is always preceded by an interleave/deinterleave process that is intended to keep important bits in adjoining/neighboring positions away. The implementation of the interleave/deinterleave process uses a bit reverse algorithm, where bitwise processing can be carried out by C programming. There are many derivatives of bit reverse algorithms, but to optimize the speed, the algorithm must be selected by paying attention to the bit length of the data bit from the processor. The bit reverse algorithm used in the WSPR program was taken from [16].

3.1.7 Practice VIII - Generating Metric Tables for a Soft-Decision Convolutional Decoder

The performance of the convolution code using the soft-decision method will depend on the accuracy of the metric tables that have been prepared by simulation. It is assumed that the WSPR system operates the Binary Phase Shift Keying (BPSK) modulation scheme through the channel with additive Gaussian noise.

The assumption simulation parameters are a signal to noise ratio (SNR) of 6 dB and 8-bit quantized received signals, which means that the symbols are offset binary in the range of 0 to 255, with 128 corresponding to an erased symbol. $P(s|0)$, the probability of receiving s between 0 and 255, given 0 transmitted, and $P(s|1)$, the probability of receiving s between 0 and 255, given 1 transmitted, is then calculated using the log likelihood calculation platform. Zero is a special value since this sample includes all lower samples that are attached to this value. The same thing goes for 255, which is a special value for all upper samples. The plots of $P(s|0)$ and $P(s|1)$ are shown in Figure 5. Based on both conditional probabilities mentioned above, the metric tables are generated as codebooks to the log likelihood of a received signal s being a digit, either ‘0’ or ‘1’. This part shows to the students the bridge between simulation, when the conditional

.

probability is generated, and the real world, when the log likelihood is calculated during the decoding process.

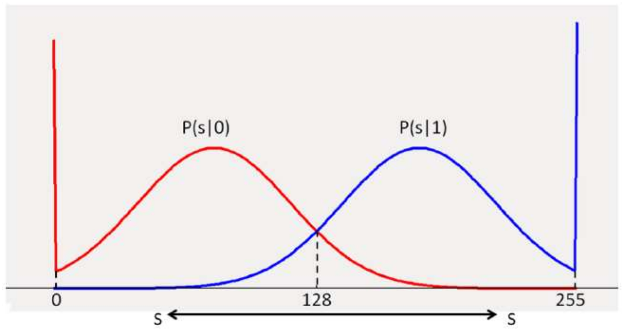

Figure 5 Plot of P(s|0), the probability of receiving *s* between 0 and 255, given 0 transmitted, and P(s|1), the probability of receiving *s* between 0 and 255, given 1 transmitted.

3.1.8 Practice IX— Fano Sequential Decoder for Convolution Forward Error Control Code

WSPR package data deploy parity bits called forward error correction (FEC) using a convolutional code scheme. The decoding process is carried out by sequential decoding (called the Fano algorithm) as the default. This part of the WSPR software was developed and contributed by P. Karn [17,18], and was recently integrated into the WSPR package when it became open source. The software itself is written quite elegantly by the contributor, so that by white box testing the students easily understand the objective of each syntax within the program. The behavior of the dynamic programming path of the Fano convolution decoder can be observed by printing the intermediate values during loops like the debugging process. The observations are carried out during practice activities.

Some important points while doing white box testing on the program that the students can read in the manual of the practice are:

1. How to generate metric tables for a soft-decision convolutional decoder.
2. How to derive the normal probability density function to become an approach that enables the computation to calculate the transition probability that a symbol occurs based on a given transmitted symbol.
3. How to implement a soft-decision convolutional decoder by using the Fano algorithm.
4. How to use the bitwise process in the C language during decoding, deinterleaving, and data unpackaging.

4 Result and Discussion

4.1 Evaluation of Practice Implementation

After accomplishing all the practices, evaluation of the data link layer practices was carried out. The first stage of the evaluation was assessment by students to evaluate the content of the practices and receive feedback from the students. This stage consisted of collecting comments regarding their impressions and opinions on the implementation of the practices, and questionnaires to express how confident they were after accomplishing the practices.

Table 1 Questionnaire for assessment by students.

Statements	Agreement				
	SD	D	N	A	SA
1. These practices helped me in understanding the principles of wireless communication.					
2. I feel more confident about implementing theory into a real system, especially in the field of wireless communication.					
3. These practices were an inseparable complement to the materials I have learned about wireless communication.					
4. My interest in telecommunication technology has increased.					
5. These practices directly combine theory and practice, especially in the field of wireless communication.					
6. I was familiar with all the syntax in the C language used in this practicum series.					
7. I can apply this system to an IoT system.					
8. The radio wave propagation theory I studied was sufficient to support the understanding of these practices.					
9. The signal processing theory I studied was sufficient to support the understanding of these practices.					
10. The coding theory I studied was sufficient to support the understanding of these practices.					

The second stage was a post test that consisted of 40 multiple-choice questions. The sequence of practices was tested in the last academic year with 55 students, consisting of 22 male and 23 female students. The reason why we need to make a distinction between male and female students is because the trend of female students' numbers in telecommunications engineering study programs in our college is increasing from year to year. Meanwhile, common opinion still says that the job of telecommunications engineer is a hardware-based and outdoor job that only suits male engineers. For this reason, we differentiated the result to

.

know the impact of the proposed practices on male and female students, respectively.

The questionnaire was given to the students at the same time as the post-test implementation by using the e-learning system available on our campus. The questions were 10 statements with which the students were asked to express their agreement in the range of SD – strongly disagree (score 0); D – disagree (score 2.5); N – neutral (score 5); A – agree (score 7.5); SA – strongly agree (score 10). This means a student got a score of 0 for a statement if he/she strongly disagreed with a statement. Vice versa, he/she got a score of 10 for a statement if he/she strongly agreed with a statement. Table 1 describes the 10 statements that had to be responded to by the students.

4.2 Post-test and Questionnaire Results Analysis

Figure 6 shows the histogram of the questionnaire-score and post-test score of the (a) male and (b) female students. As can be seen in Figure 6, the histograms of the questionnaire score and post-test score were found to be highly correlated, which shows the validity of the collected scores.

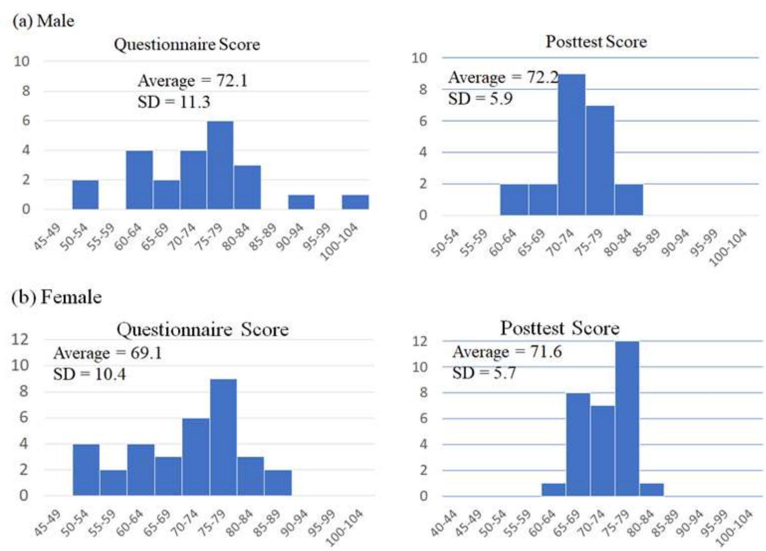

Figure 6 (a) Histogram of questionnaire scores and post-test scores of male students; (b) histogram of questionnaire scores and post-test scores of female students.

These figures also show that since the questionnaire consisted of qualitative questions, the standard deviation of the questionnaire scores (male = 11.3; female

= 10.4) was a tent that was wider than the standard deviation of the post-test scores (male = 5.9; female = 5.7) consisting of quantitative questions. Moreover, the average questionnaire score and post-test score of the male students (questionnaire score = 72.1; post-test score = 72.2) were higher than those of the female students.

Figure 7 depicts the facility index of each of the 40 questions given to the students during the post test. 2 questions had an extremely low index, i.e., questions 14 and 40, which had an index of only 1.8 % and 5.5%, respectively. The facility index is the average score of the students on the questions. This means that questions 14 and 40 were difficult or extremely difficult, or there was something wrong with the questions.

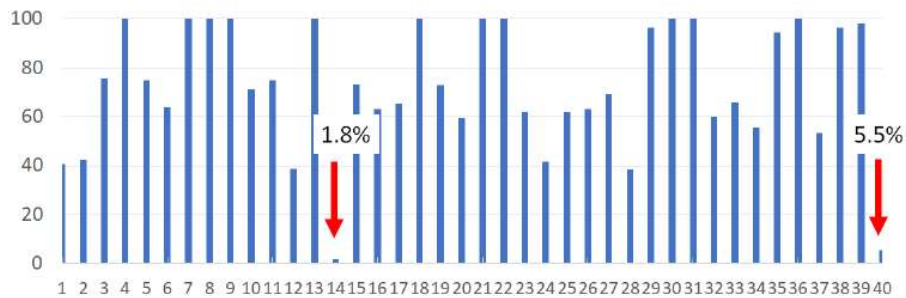

Figure 7 Facility index of each of the 40 questions.

We analyzed both questions as follows:

1. Question 14: "Digital communication systems that use a single-board computer (SBC) still require a USB soundcard for the following purposes" This question is related to the hardware that must be handled by the students during the implementation of the hands-on practices.
2. Question 40: "The sequential algorithm for convolutional decoding does not have a certain time in the completion of the decoding process. Some of the things below will affect the sequential decoding speed." This question is related to an observation step during the implementation of the hands-on practices.

The authors strongly believe these questions can be categorized as questions that should be easy for the students if they did the hands-on parts of the practices. These two questions are about the role and function of the devices used in these practices. It can be said that these two questions are experience-based questions, which means that students who have experience in handling the devices would be able to answer these two questions easily. But unfortunately, the pandemic

.

condition forced us to use a demonstration model, which can make students lose focus during implementation of the practices. This makes these easy questions tend to shift toward very difficult questions because the students did not have the opportunity to acquire important hands-on knowledge during the implementation of the practices.

All students wrote that they were very excited because they knew the signal was a real signal that could be coming from thousands of kilometers away. However, all of them complained that a demonstration model using an online system is not enough for understanding a complex system, so they needed more hands-on opportunities. Other comments from the students that could be used for the improvement of the practice deployment were:

1. They felt more challenged to dig deeper into the theory while remembering their programming skills and felt more confident in connecting theoretical knowledge they possessed with a real and complex telecommunications system.
2. For the first time they experienced the benefits of SBC for processing truly complex calculations.
3. Most of them only realized that propagation constraints such as Doppler shift as well as TX/RX performance on frequency drift and jitter timing are problems that exist in digital communication, and they felt this is the first time they saw a real mitigation process to obtain optimum digital telecommunications performance.
4. They hoped they would be given more opportunities to ask questions and confirm the content of practices, even outside of scheduled practice hours.

5 Conclusion

This sequence of practices was designed to be implemented in normal circumstances and within a hands-on approach, but the pandemic forced us to carry out these practices based on a demonstration model. The evaluation by the students, based on the post-test scores, revealed that the demonstration model approach was still sufficiently effective, with an average post-test score of 72, even though the students commented that the demonstration model was not enough to acquire the required knowledge. This was confirmed by the facility index analysis. The authors strongly believe that the reason was that the students had lost the opportunity to acquire important hands-on knowledge during the implementation of the practices. This means that when the circumstances are back to normal, in general, the post-tests scores can be expected to be higher. Moreover, the questionnaire responses by the students revealed that the average score of the male students was 3% higher than that of the female students. This is in line with the results of some studies, which stated that in general male students have more confidence compared to female students in the fields of science, technology, engineering, and mathematics [19].

The only challenge in implementing this practice model is that what is discussed is white box testing, where assistance is not only required to understand the theory and the algorithms of the communications process but at the same time, but also to master the overall program syntax. Currently, the authors must spend time to give assistance to students regarding detailed syntax programming levels. It still takes time to recruit assistants among laboratory members who can provide detailed assistance to students according to the above criteria. This paper discussed the implementation of an affordable experiental design to teach the concepts in a wireless digital communications system, which could be replicated by other engineering higher education institutions.

Acknowledgement

The authors would like to thank the Ministry of Research and the Higher Education, Republic of Indonesia for supporting this work with a PTUPT research grant for the fiscal year 2018. Thanks also go to the EEPIS-PENS e-learning administration team for their support during the setting up and implementation of the questionnaire and post-test.

References

[1] Carley, L.R., Khosla, P. & Unetich. R., *Teaching Introduction to Electrical and Computer Engineering in Context*, Proceeding of the IEEE, **88**(1), pp. 8-22, 2000.

[2] Schwab, K., *The Fourth Industrial Revolution*, The World Economic Forum, Geneva, Switzerland, 2016.

[3] Mills, J.E. & Treagust, D.F., *Engineering Education - Is Problem-Based Learning or Project-based Learning the Answer?* Australasian Journal of Engineering Education, **3**, pp. 2-16, 2003.

[4] Dawy, Z., Husseini, A., Yaacoub, E. & Al-Kanj, L., *A Wireless Communications Laboratory on Cellular Network Planning*, IEEE Transaction on Education, **53**(4), pp. 653-661, 2010.

[5] Kumar, S. & Payal, *Performance Investigation of MIMO Based CO-OFDM*, Journal of Engineering and Technological Science, **53**(5), 210508, 2021. DOI: 10.5614/j.eng.technol.sci.2021.53.5.8.

[6] Endra Joelianto, *On Minimal Second-Order IIR Bandpass Filters with Constrained Poles and Zeros*, Journal of Engineering and Technological Science, **53**(4), 210401, 2021. DOI: 10.5614/j.eng.technol.sci.2021.53.4.1.

[7] Taylor, J.H., *Weak Signal Propagation Reporter*, 2014, accessed from http://physics.princeton.edu/pulsar/K1JT/wspr.html, (27 January 2021).

.

[8] *WSPR Open-Source*, 2015, accessed from https://sourceforge.net/p/wsjt/wsjt/6122/tree/branches/wsjtx/lib/wsprd/, (27 January 2021).

[9] Camerona, T.G., Fioria, R.A.D., Warrington, E.M., Stocker, A.J., Thayaparan, T. & Danskina, D.W., *Characterization of High Latitude Radio Wave Propagation over Canada*, Elsevier, Journal of Atmospheric and Solar-Terrestrial Physics, **219**, 105666, August 2021.

[10] Blagoveshchensky, D.V., Maltseva, O.A., Anishin, M.M., Rogov, D.D. & Sergeeva, M.A., *Modeling of HF Propagation at High Latitudes on the Basis of IRI, Science Direct*, Advances in Space Research, **57**, pp. 821-834, 2016.

[11] Frissell, N.A., Miller, E.S., Kaeppler, S., Ceglia, R.F., Pascoe, D., Sinanis, N., Smith, P., Williams, R. & Shovkoplyas, A., *Ionospheric Sounding Using Real-Time Amateur Radio Reporting Networks*, AGU Space Weather, 2014. DOI: 10.1002/2014SW001132. (27 January 2021).

[12] Frissell, N.A., Vega, J.S., Markowitz, E., Gerrard, A.J., Engelke, W.D., Erickson, P.J., Miller, E.S., Luetzelschwab, R.C. & Bortnik, J., *High-Frequency Communications Response to Solar Activity in September 2017 as Observed by Amateur Radio Networks*, AGU Fall Meeting Abstracts, SA12A-08, 2018. DOI: 10.1029/2018SW002008.

[13] *GNU General Public License*, 2020. Accessed from http://www.gnu.org/education/education.html. (27 January 2021).

[14] Oinats, A.V., Nishitani, N., Ponomarenko, P., Berngardt, O.I. & Ratovsky, K.G., *Statistical Characteristics of Medium-Scale Traveling Ionospheric Disturbances Revealed from The Hokkaido East and Ekaterinburg HF Radar Data*, Earth Planets and Space, **68**, 8, 2016. DOI: DOI: 10.1186/s40623-016-0390-8.

[15] Ammann, P. & Offutt, J., *Introduction to Software Testing*, 2nd edition, Cambridge: University Press, pp. 57-58, 2017.

[16] Anderson, S.E., *Bit Twiddling Hacks*, 2005, accessed from http://graphics.stanford.edu/~seander/bithacks.html#ReverseByteWith32Bits. (January 15, 2018)

[17] Karn, P., *Toward New Link Layer Protocols, 1996*, accessed from https://www.semanticscholar.org/paper/Toward-New-Link-Layer-Protocols-Karn/02cf11ea008af92bec1d20318683251059a081ac. (January 15, 2018)

[18] Karn, P., *Convolutional Decoders for Amateur Packet Radio*, 2014, accessed from https://www.semanticscholar.org/paper/Convolutional-Decoders-for-Amateur-Packet-Radio, (January 15, 2018)

[19] Chachra, D., Franklin, W. & Kilgore, D., *Exploring Gender and Self-Confidence in Engineering Students: A Multi-Method Approach*, Proceedings of the 2009 American Society for Engineering Education Conference, 2009.