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# **AC 2011-2298: ANALOG AND DIGITAL COMMUNICATIONS LABORATORY EXPERIMENTS USING EMONA TMS**

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# **Analog and Digital Communications Laboratory Experiments Using Emona TIMS**

## **Abstract**

In 2007 the electrical engineering program at MSOE revised a required principles of communications course, which had been a lecture-only course, to include a weekly two-hour laboratory. Laboratory experiments were developed using the Emona TIMS communications modules, covering analog and digital communications concepts such as double sideband – suppressed carrier (DSB-SC); amplitude modulation (AM); frequency modulation (FM); sampling, quantization, and pulse-code modulation (PCM); amplitude, frequency, and phase shift keying (ASK, FSK, PSK); and bit error rate for a baseband digital signal in the presence of noise. Another experiment recently added involves direct sequence spread spectrum (DSSS) and code-division multiple access (CDMA). This paper presents an overview of the experiments that have been developed, focusing on features of the experiments that are not in the TIMS manuals. The paper also discusses how these experiments have helped the students visualize communication-system concepts.

## **Background**

Since Fall 2007, the EE program at MSOE has included a weekly laboratory in the required principles of communications course (EE-4021), which is taught over a ten-week quarter. The course consists of three one-hour lecture periods and a weekly two-hour laboratory period, all taught by a full-time faculty member, since MSOE does not employ teaching assistants. Five experiments were developed for the initial offering: an introduction to the TIMS system with DSB-SC; AM; FM; sampling, quantization, and PCM; and bit-error rate for a baseband digital signal in noise. Fall 2008 saw an additional introductory lab with spectral measurements and an experiment on ASK and FSK. Digital modulation methods BPSK and QPSK were added as an additional experiment in Fall 2009, and DSSS and CDMA were introduced as the most recently developed experiment in Fall 2010. The course aggressively covers a long list of communications topics, and this is achievable in the ten-week term because entering students are expected to have strong backgrounds in signals and systems, and probability and statistics.

Many of the above-described experiments have been adapted from the TIMS-provided manuals. Modifications to TIMS-provided experiments were made to further clarify experimentation or to add or delete parts of the experiment. These modifications were aimed at improving the learning objectives for the course. For example, the experiments in the TIMS manuals do not assume that the oscilloscope being used has spectrum-analyzer capabilities. All of the modified experiments take advantage of this capability to allow the student to visualize the important frequency-domain characteristics of various signals. MSOE is fortunate to have five laboratory rooms that each has at least ten stations with such an oscilloscope, allowing students to regularly experiment with frequency-domain measurements.

There have been other studies that in some cases focus on the use of Emona TIMS equipment for communications laboratories [3], while in other cases [4, 5] use other laboratory configurations. Reference 4 refers to the large expense associated with commercial, modular systems such as the

Emona TIMS equipment. At MSOE the communications laboratory has gradually evolved from having no modular communications equipment to one TIMS unit, then four units, then seven units, and at this time nine TIMS units. Our current laboratory configuration having nine TIMS units supports laboratory sections that each has up to 18 students, with two students working together at each station. The total cost has been high, but it has been spread over several years. The current laboratory configuration supports many experiments that in some cases integrate TIMS modules with other breadboarded systems and/or other signal generation and measurement equipment. This has allowed MSOE to offer communications courses with laboratory exercises that are easily and quickly assembled with the TIMS modular equipment, and that have versatility permitting easily configured system modifications and integration of other (non-TIMS) subsystems. For example, a simple envelope detector built on a breadboard separate from the TIMS equipment allows easy experimentation with different RC time-constant values.

### **Overview of experiments and modifications to TIMS-provided experiments**

An introduction to the laboratory and review of spectral measurements are the focus of the first experiment (Experiment 0) in EE-4021. This introductory experiment does not use the TIMS equipment. It covers laboratory safety, presents report documentation expectations, and reviews frequency-domain spectrum measurements performed using the FFT-based function available in typical digital oscilloscopes. The students generate a specified periodic function using the Agilent 33120A Arbitrary Waveform Generator (AWG) and measure the rms values of spectral components using the Agilent 54622D digital oscilloscope. These results are then compared to theoretical results that can be predicted using methods from the prerequisite signals and systems course.

The TIMS system is introduced to the students in the second experiment (Experiment 1). The objectives of this experiment are to create a double sideband – suppressed carrier (DSB-SC) signal and a pseudorandom binary sequence (PRBS) signal using the TIMS modules and to observe the spectra of the DSB-SC and PRBS signals on the oscilloscope, comparing results to the theory presented in lecture. This experiment provides students with an exposure to TIMS modules that operate with analog signals, producing a DSB-SC signal, and TIMS modules that produce digital signals, in particular the PRBS signal. This Experiment 1 used at MSOE is very similar to laboratory exercises in the TIMS manuals. This experiment, early in the term, gives the student the capability to generate pseudorandom data signals, which are often used when testing communication links. With the MSOE modifications, this experiment also reinforces the concepts of digital data signal spectrum and bandwidth, which are introduced in the lecture.

Amplitude modulation (AM) is the topic explored in Experiment 2. Several AM concepts are visualized in this experiment, including measuring peak-to-peak and trough-to-trough voltages for AM signals with different modulation indices, viewing the time- and frequency-domain functions of the AM signals on the oscilloscope, viewing these functions for different types of information signals such as sine and triangle waves, using the XY mode of the oscilloscope to view the modulation trapezoid, and building a simple envelope detector to demodulate the AM signal. For this experiment the TIMS-provided experiment was modified to include message signals other than sinusoidal messages, and to include AM signal generation via built-in features of a typical arbitrary waveform generator (that is, the Agilent 33120A). Students experiment

with both the AWG-based AM modulator, which is easily set up, and the TIMS-based AM modulator, which involves functional blocks that directly correspond to the AM signal equation. For simplicity and ease of comparison to fundamental theory from lecture, the TIMS-provided experiment was also modified to use a simple three-component envelope detector (diode, resistor, capacitor), as a demodulator, instead of one constructed with a precision rectifier functional block and a low-pass filter module. Modifications to the TIMS-provided AM experiment also emphasize frequency-spectrum measurements that demonstrate that the spectrum of the message signal is replicated in both upper and lower sidebands of the AM signal, for example when the information message is a triangle-wave signal.

Frequency modulation is the focus of Experiment 3. The students calibrate the VCO module to output an FM signal with a specified carrier frequency and sensitivity, and observe the nonlinear regions of the frequency-out versus voltage-in characteristics of the VCO. This is very similar to what is done in the TIMS-provided experiment. FM signals with two different modulation indices are observed on the oscilloscope; first in the time domain to estimate the frequency deviation, and then in the frequency domain to measure spectral components for comparison with theory. The TIMS-provided experiment was modified to include an easily configured time-domain oscilloscope measurement to determine negative and positive peak frequency deviations from maximum and minimum time periods as depicted on Figure 1. The TIMS-provided experiment was also modified to have the student design the modulator for a specified signal bandwidth, and use the spectrum-analyzer function built into the oscilloscope to measure the resulting FM signal bandwidth and compare it to the value specified for the design. That is, the student determines the required  $\beta$  value to result in the specified FM signal bandwidth, and configures the message signal level into the VCO to produce that desired  $\beta$  value. A typical measured FM spectrum for this part of the FM experiment is shown in the next section of this paper. A zero-crossing detector is built using the TIMS modules to demonstrate a type of FM demodulator, similar to the TIMS-provided experiment section with an FM demodulator.

Experiment 4 focuses on the concepts of sampling, quantization, and binary pulse code modulation (PCM). Students use the Dual Analog Switch module to sample a sinusoidal signal. The TIMS-provided experiment was modified to use the arbitrary waveform generator to create a pulse train with a 20% duty cycle, for sampling, instead of Twin Pulse Generator module. It was felt that there is some value in being able to set up a commonly used generator to produce such a pulse train, and performing such a set-up is done quite easily. The TIMS-provided experiment was also modified to have the students view the spectrum of the sampled signal, identify the alias components on the sampled-signal spectrum, and observe the effects on the recovered signal if the alias components are not all removed by low-pass filtering. In the experiment modified for MSOE, a Tunable Low-Pass Filter module is used instead of the fixed-cutoff-frequency filter built into the Headphone Amplifier module, and students are required to set the cutoff frequency of the filter module to an appropriate value for signal recovery. This Experiment 4 also uses the PCM Encoder module to quantize a signal, using both uniform and A-law companding, much like the TIMS-provided experiment. Students experimentally determine the “staircase” transfer characteristic of the quantizer in order to demonstrate the linearity of uniform quantization.

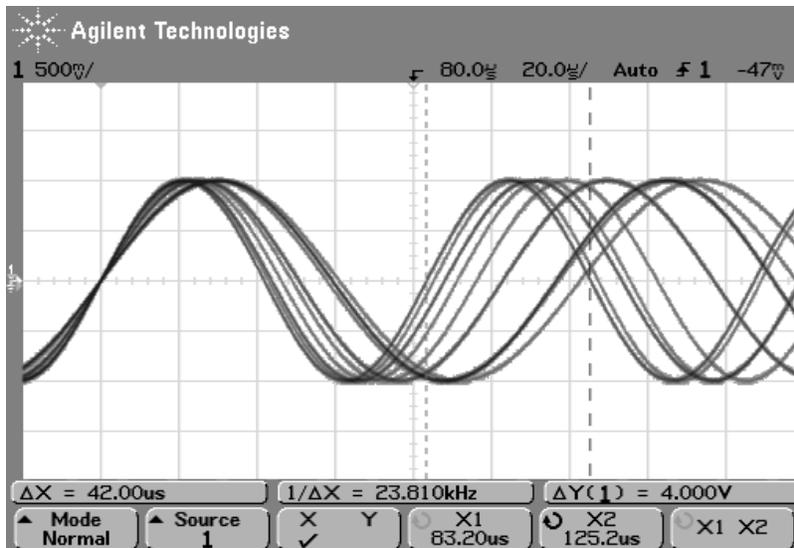


Figure 1. FM time waveform for measurement of maximum time period (125.2  $\mu\text{s}$ ) and minimum time period (83.20  $\mu\text{s}$ ), and calculation of peak frequencies (7987 Hz and 12,020 Hz) and peak frequency deviations from 10-kHz carrier equal to -2013 Hz and +2020 Hz.

Digital communications signals are the focuses of Experiments 5 and 6. In the former, students build and view amplitude-shift keyed (ASK) and frequency-shift keyed (FSK) signals in the time- and frequency-domains, using PRBS signals as the binary message signals. The TIMS-provided ASK experiment implies that a low-pass filter can be used on the digital data signal prior to the ASK modulation done by an analog switch. In order to realize the benefits of this low-pass filtering, the experiment adapted by MSOE has been modified to use a low-pass filter on the digital data signal prior to ASK modulation done by a multiplier instead of an analog switch. The TIMS-provided BPSK experiment was simplified to eliminate the phase shifter and line-code encoder, but still have a functional modulator that produces the expected BPSK waveform. Instead of using an M-level encoder to generate I and Q data signals from a bit stream, as is done in a TIMS-provided experiment, a QPSK modulator is constructed in Experiment 6 using two independent data streams from the Sequence Generator module, each multiplies either a sine or cosine carrier, and the two modulated carriers are added. The use of the spectrum-analyzer capabilities built into the oscilloscope again allows students to view signal spectra. Students easily verify that the bandwidth of the BPSK signal with message data at some specified rate is the same as the bandwidth of the QPSK signal with data at that rate being conveyed by each of the two quadrature components of the signal. In addition, students experimentally determine a constellation plot for the QPSK signal.

Bit error rate (BER) for a baseband digital signal in the presence of additive noise is experimentally determined by students in Experiment 7. Because of a large number of connections to be made between modules, the TIMS units are prewired so that the students can focus on calibrating the channel model to a specific signal-to-noise ratio, view eye patterns to determine the optimum sampling time, set up the BER measurement instrumentation, and finally measure the experimental BER for various signal-to-noise ratios. The TIMS-provided experiment was modified in several ways. First, a careful distinction is made between power

signal-to-noise ratio,  $S/N$ , and the energy signal-to-noise ratio,  $E_b/N_0$  commonly encountered for plots of bit error rate (BER). The theoretical plots are actually in terms of  $E_b/N_0$ , although the values of  $S/N$  and  $E_b/N_0$  are approximately equal for the signaling in this experiment. Secondly, the observation of eye diagrams with various levels of noise is done in this BER experiment rather than as a separate experiment. Another modification was to have the students observe the signal that has a pulse at each sampling time (called the Z-MOD signal) on the second channel of the oscilloscope while observing the eye diagram on the first channel. While observing this the student adjusts the decision point control on the Decision Maker module, and can attempt to place the decision point where the opening of the eye is widest. This is shown on the oscilloscope screen shot called Figure 2 below. This allows the student to visualize the sampling process for a single-sample-per-bit receiver, and helps in-class discussions of systems that automatically set and track the timing of the samples, or that use multiple samples per bit.

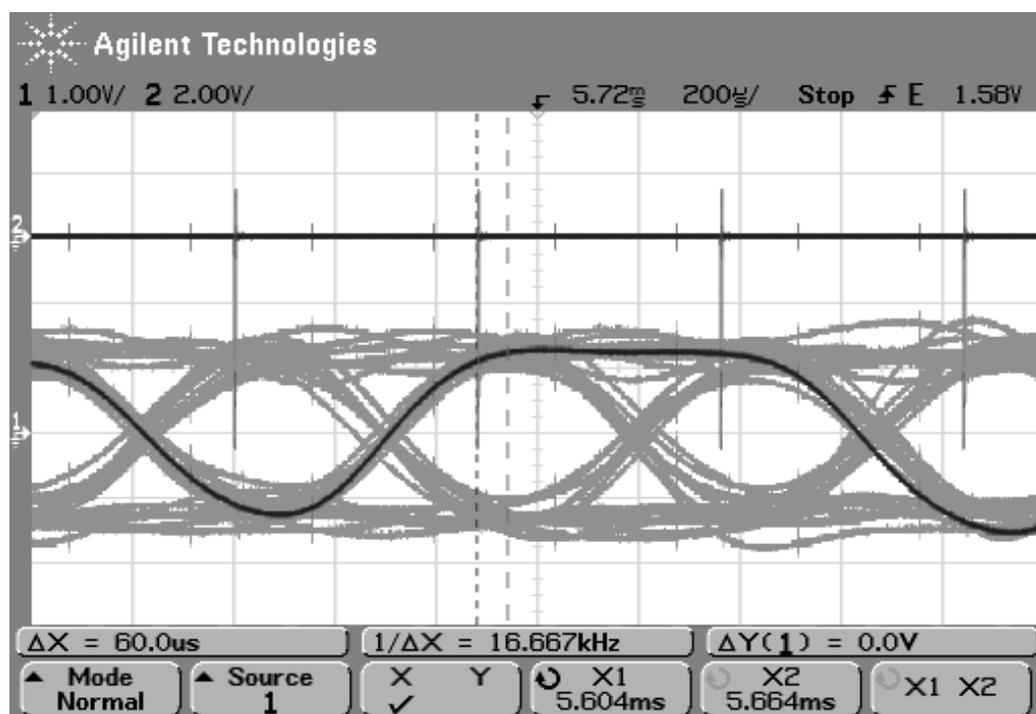


Figure 2. Eye diagram band-limited data signal with additive noise, and sample-time-marking signal (called Z-MOD signal) indicating sample times set approximately  $60 \mu\text{s}$  too early.

The most recently developed experiment introduces students to direct-sequence spread spectrum (DSSS) and code-division multiple access (CDMA) signals. Students generate a DSSS signal as the product of a PRBS message signal and a sinusoidal carrier, first producing a narrowband BPSK signal, and then multiplying by a pseudonoise (PN) chip sequence, producing the desired DSSS signal. The students then view the spectra of the narrowband BPSK and DSSS signals, showing the advantage of DSSS in “hiding” a digital signal in additive channel noise. The availability of the spectrum-analyzer capability within the oscilloscope has allowed the experiment adapted by MSOE to have students compare the spectra of the narrowband BPSK signal (before band-spreading), both with and without white noise, to the wideband CDMA signal with and without noise.

## Helping students visualize communication-system concepts

The laboratory experiments are set up so that students are able to visualize a number of different communications signals. Analog signals such as DSB-SC, AM, and FM are generated using sinusoidal and other periodic message signals. Digitally modulated signals such as ASK, FSK, BPSK, QPSK, and DSSS signals are created using pseudorandom bit sequences. Students take screenshots of waveforms and spectra for inclusion in a laboratory notebook. Analytical questions are asked so that students can compare what they see to the theory they learn in lecture.

One example of visualizing signals involves the spectrum of a tone-modulated FM signal. A voltage controlled oscillator (VCO) is calibrated so that the FM signal produced has a sensitivity of 1kHz/V. As a prelaboratory exercise, the students are asked to determine the necessary input voltage to produce an FM signal with a bandwidth of 5 kHz and plot its magnitude spectrum. Students then take measurements of spectral components to compare to the theoretical values predicted in the prelaboratory exercise. Figure 3 shows the spectrum of a typical FM signal that would be measured by a student in this experiment. The students become familiar with practical bandwidth definitions, such as the 20-dB bandwidth, and the spectrum shown on Figure 3 has a measured 20-dB bandwidth of 5.96 kHz. Table 1 compares theoretical to experimental values of the frequency components shown on Figure 3.

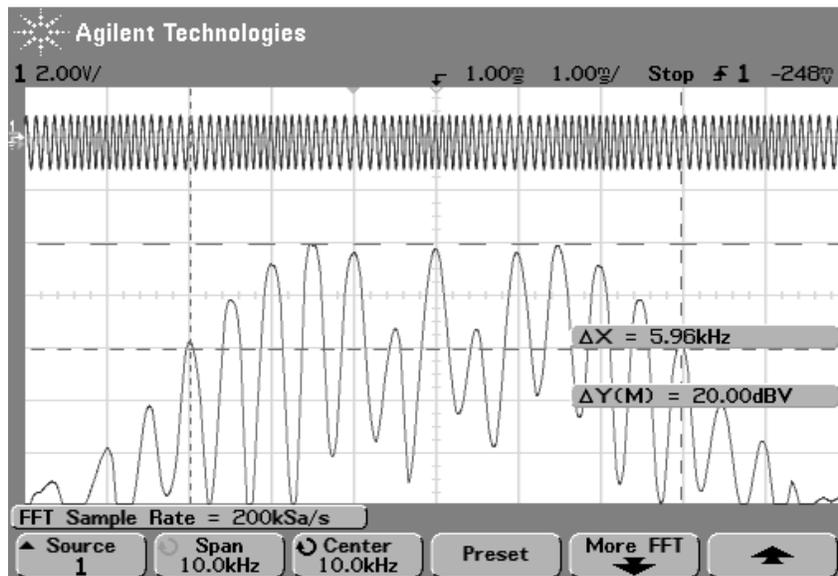


Figure 3. Time waveform and spectrum of 2-volt peak-to-peak FM signal having 10-kHz carrier, 500-Hz message, peak frequency deviation set to 2 kHz, and showing resulting measured 20-dB bandwidth (including all components within 20 dB of the largest) of 5.96 kHz.

Table 1. Theoretical and measured spectral component levels for 2V peak-to-peak FM signal having 10-kHz carrier, 500-Hz message, peak frequency deviation set to 2 kHz.

Frequency (kHz)	10.0	9.5/10.5	9.0/11.0	8.5/11.5	8.0/12.0	7.5/12.5
Theoretical rms Level (dBV)	-11.0	-26.6	-11.8	-10.3	-14.0	-20.6
Measured rms Level (dBV)	-11.2	-26.8	-11.5	-10.3	-13.7	-20.3
Difference (dB)	-0.2	-0.2	+0.3	0	+0.3	+0.3

As was mentioned in the previous section, the most recently developed experiment introduces students to direct-sequence spread spectrum (DSSS) and code-division multiple access (CDMA) signals. Students generate a DSSS signal as the product of a PRBS message signal and a sinusoidal carrier, first producing a narrowband BPSK signal, and then multiplying by a pseudonoise (PN) chip sequence, producing the desired DSSS signal. The students then view the spectra of the narrowband BPSK and DSSS signals, showing the advantage of DSSS in “hiding” a modulated signal in additive channel noise. The availability of the spectrum-analyzer capability within the oscilloscope has allowed the experiment adapted by MSOE to have students compare the spectra of the narrowband BPSK signal (before band-spreading), both with and without white noise, to the wideband CDMA signal with and without noise. As can be observed in Figures 4 through 7 below, the narrowband BPSK signal is observable above the noise, whereas the wideband DSSS signal is observable when there is no noise but is hidden by the noise when noise is present.

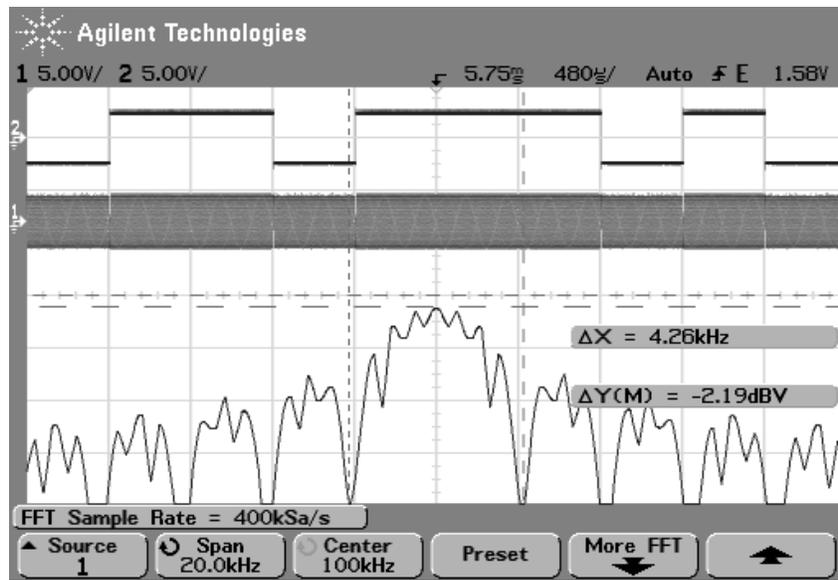


Figure 4. Narrowband BPSK signal having spectrum with null-to-null bandwidth of 4.26 kHz and peak level of -2.19 dBV (pseudorandom data on upper part of scope image, at 2.083k bps, narrowband BPSK signal waveform shown just below message waveform).

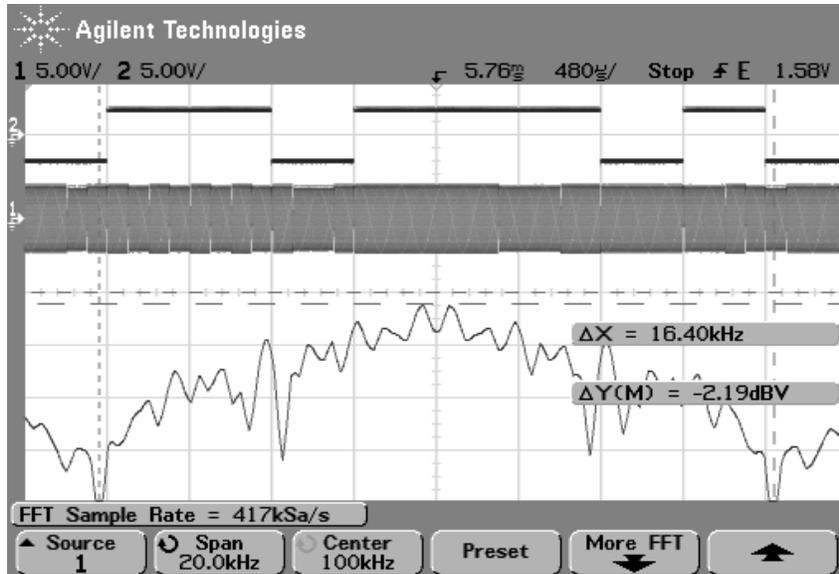


Figure 5. Wideband DSSS signal having spectrum with null-to-null bandwidth of 16.40 kHz and peak level of -2.19 dBV (pseudorandom data on upper part of scope image, at 2.083k bps, wideband DSSS signal waveform shown just below message waveform).

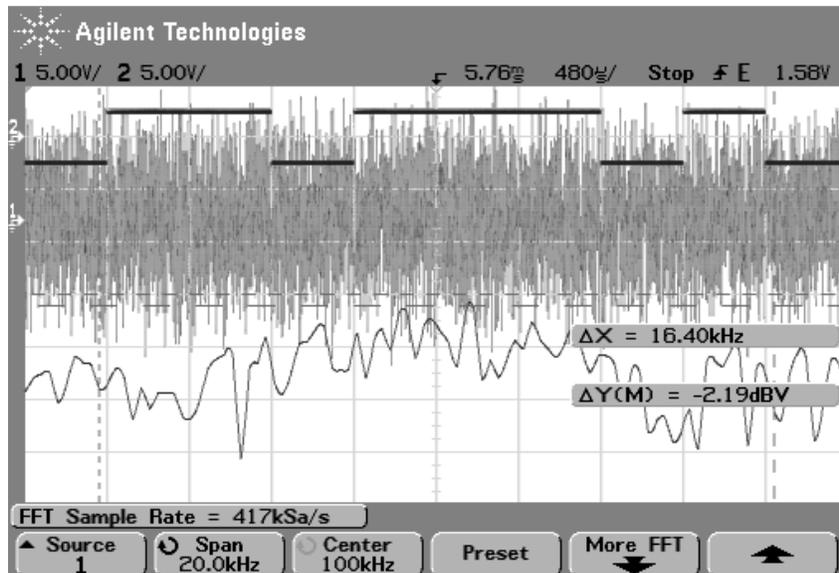


Figure 6. Wideband DSSS signal having spectrum with null-to-null bandwidth of 16.40 kHz (unobservable) and peak level of -2.19 dBV masked by additive noise that has twice the rms voltage of the DSSS signal (pseudorandom data on upper part of scope image, at 2.083k bps, wideband DSSS signal waveform with additive noise shown just below message waveform).

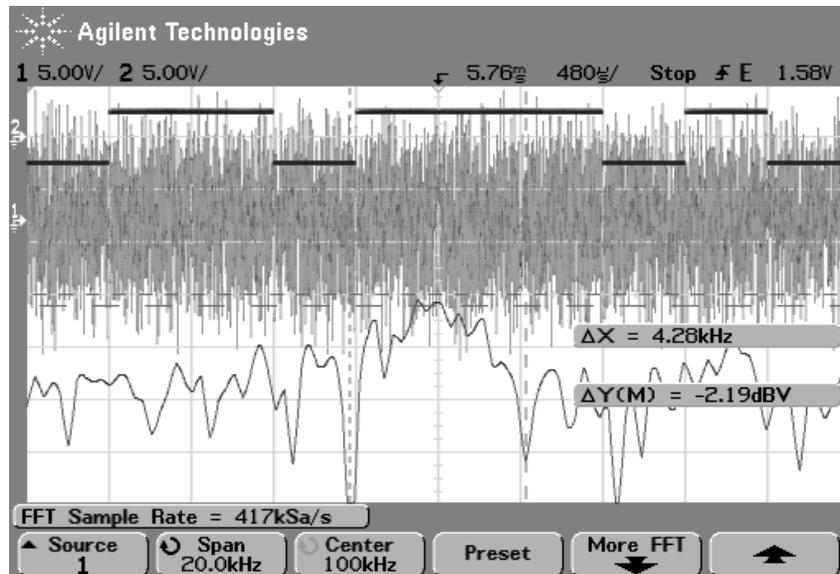


Figure 7. Narrowband BPSK signal having spectrum with null-to-null bandwidth of 4.28 kHz (observable) and peak level of -2.19 dBV minimally masked by additive noise that has twice the rms voltage of the DSSS signal (pseudorandom data on upper part of scope image, at 2.083k bps, narrowband BPSK signal waveform with additive noise shown just below message waveform).

### Student performance and feedback

Past students have remarked on the necessity of a laboratory component: on surveys received from students taking the course prior to the inclusion of the laboratory, in one of the course offerings 44 percent of the respondents wrote, under the item, “Things which could be improved,” comments requesting the addition of a laboratory, such as, “Should consider adding a Lab hour. Not enough practical Application.”

Students’ abilities to visualize communications signals in both the time- and frequency-domains have improved steadily since the introduction of the required laboratory session. Student laboratory grades and overall course grades have been compiled for each of the last four years, and the resulting data are displayed below in Figures 8 and 9. It should be noted that the larger number of students in 2007 was because the primary author led two sections of the course in 2007 and only one section for each of the other three years. The grades of students who dropped the course during the term are not included in the data below.

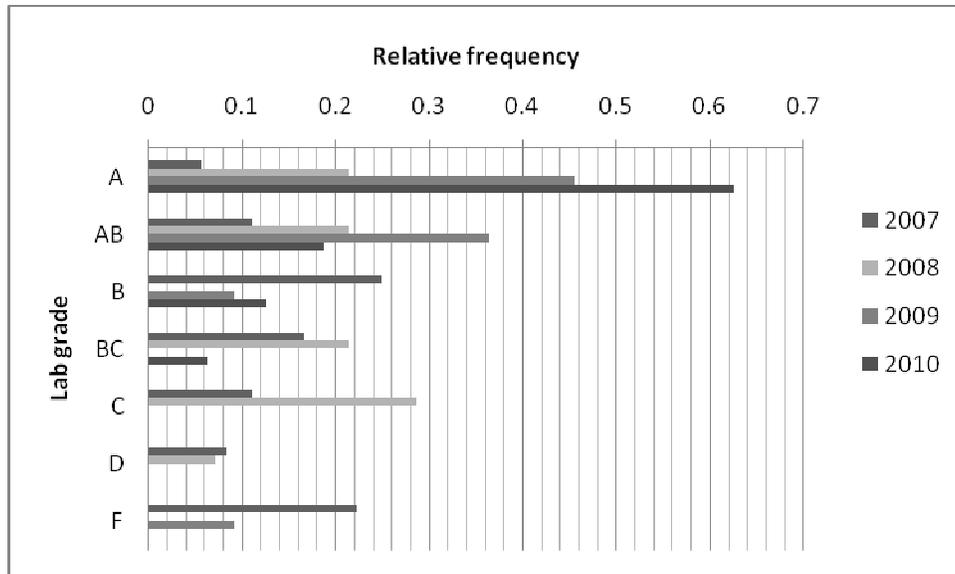


Figure 8. Lab grade distributions for 2007-2010.

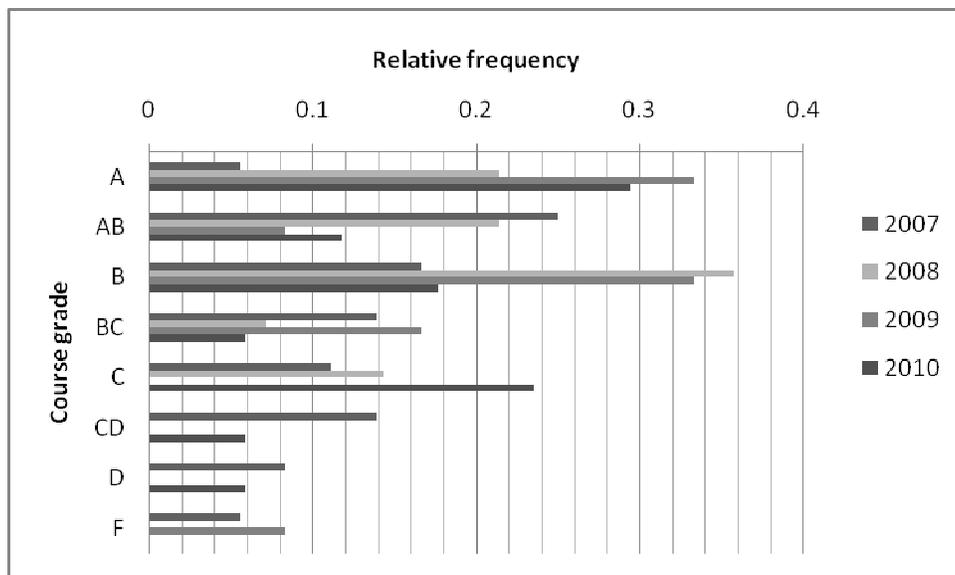


Figure 9. Course grade distributions for 2007-2010. 2007: n = 36, 2008: n = 14, 2009: n = 12, 2010: n = 17.

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