Teaching Analog and Digital communication concepts in one course

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Abstract

During the quarter to semester conversion at Ohio Northern University, the electrical engineering course curriculum committee decided to introduce analog and digital communication concepts in one four credit semester based course, with three hours of lecture and three hours of lab per week for fifteen weeks. The two concepts were taught before in two separate four credit quarter based courses, with three hours lecture and three hours lab per week for twenty weeks. Hence, a total of fifteen lecture hours and five lab periods were lost due to the semester conversion. Nevertheless, the instructor was still able to cover the necessary material in one course for the first time in the last academic year. Also, the numerical values of the students' feedback were above the college average. This paper summarizes the challenges and advantages of introducing analog and digital modulation techniques in one concise semester base course.

Introduction

An introductory course on communication systems should usually include analog and digital modulation techniques. The class should explain the difference between baseband and passband communication systems, cover the different methods for modulating and demodulating signals, analyze the performance of different modulation techniques in noisy and distortion channels, and focus on the tradeoffs between power and bandwidth in different communication systems. Such a class is usually required for electrical engineering majors and can be taken as technical electives for computer engineering majors. Additionally, the class is offered at the junior or senior level and it sometimes can be accepted for credits towards a graduate degree.

After the conversion from the quarter to semester system at Ohio Northern University, the electrical engineering curriculum committee decided to group the previous analog and digital communication classes into a communication systems class that covers both topics. The class is four credits with three 50 minutes lectures and one lab period of 180 minutes per week. This gave the author an opportunity to design the class from scratch and schedule the lab experiments, accordingly.

The road for designing a course successfully is based on requiring the right prerequisites, selecting the textbook and picking the topics to be covered in the class. A strong background in Fourier series and transform and their respective properties, which is usually covered in a signals and systems class, is essential for a student to understand the concepts covered in the class. Students taking this class should also have a good background in statistics. For the subject of communication, very few text books cover both analog and digital modulation techniques. One example of such text books that was used in this class is "*Modern digital and analog communication systems*", by Lathi [1]. Although digital modulation techniques are prevalent nowadays, a good balance between the analog and digital modulation techniques is necessary for enhancing the students' knowledge. In fact, introducing analog communication techniques first, as discussed in the course description section, helps students better understand digital communication techniques.

A lab component would enrich the students experience and help in the understanding of the material. In a previous work [2 and 3], the author summarized an effort to address this need through the integration of a complete set of experiments with this communication class. The experiments were scheduled to integrate with the lecture material on a weekly basis, as shown in the next section. These experiments were all implemented using a telecommunication instructional modeling system known as tims[4].

Finally using new education techniques such as collaborative education and independent study [5 and 6] helps students better enjoy the class environment. For example, in this class students were encouraged to discuss approaches and ideas for homework problem with each other to inspire collaborative education. Also, a case study was assigned to students at the final week. The purpose of this case study was to encourage students to learn more materials via independent study and share the information with the rest of class.

This paper gives a detailed description of the course including the classroom topics and lab components covered each week. It also compares the course to the two separate courses that used to cover the same material during the quarter system. Since the course has already been offered once under semester system, it was possible to collect assessment data based on students' end of term feedback. The course assessment is also summarized in this paper. A conclusion section, at the end of the paper, states the main challenges and advantages of introducing analog and digital modulation techniques in one concise semester course.

Course Description

The class starts with an introductory lecture that explains how all communication systems can be divided into three main blocks: transmitter, channel and receiver. The lecture also reviews the concepts covered in Signals and Systems, which is a prerequisite to any communication class and required for electrical and computer engineering students. The review concentrates on Fourier transform and its properties and the classifications of signals between analog vs. digital, random vs. deterministic, and energy vs. power.

In the next lecture, the discussion shifts to classifications of different communication channels. First, the channel is modeled with a transfer function. If the magnitude spectrum of this transfer function is constant and its phase spectrum is linear, the channel is considered ideal. Next, if the transfer function of the channel is time invariant, the channel can be transformed to an ideal channel using a simple equalizer at the receiver side. Finally, challenging concepts such as nonlinear, fading / time varying and multipath channels are introduced. A case example on the effect of nonlinear channels on frequency division multiplexing is given at the end of the lecture.

The third lecture focuses on autocorrelation and how it is used to analyze signals. The Fourier transform of autocorrelation is the Power Spectrum Density (PSD), which indicates the distribution of power over the spectrum. By the end of the first week, students have the necessary tools to analyze both signals and channels.

The second week starts by a lecture that discusses the difference between baseband and passband communication techniques. It explains why passband is necessary for any wireless communication system. Next, Double Side Band Suppressed Carrier (DSB_SC) is introduced as a means of transferring the signal from baseband to passband. This modulation technique can only be modulated coherently using a locally generated carrier, which must be in-phase with the modulated signal. The lecture ends with a case example that shows the effect of phase differences between the locally generated carrier and the modulated signal on the demodulated message signal at the receiver side.

The following lecture discusses the electronics behind the modulator/demodulator used to generate DSB_SC. In particular, it focuses on how to build the multipliers necessary to shift the spectrum of the message signal between the baseband and passband. In addition, the lecture explains two types of frequency mixers (sub-hetrodyne and superhetrodyne) that can be used to change the carrier frequency of the passband signal without going back to the baseband. After this lecture, students meet in the lab to build the DSB_SC modulator/demodulator from basic electronics modules and analyze the message, modulated and demodulated signals in both the time and frequency domain using an oscilloscope and a spectrum analyzer.

The final lecture of this week discusses the Double Side Band with a Carrier (DSB_C) modulation technique. This technique is mainly used because it is so easy to demodulate the signal at the receiver side using envelope detectors or rectifiers. However, it suffers from bad power efficiency since the power associated with the added carrier is simply wasted. The designer should be careful in selecting an index of modulation, which is defined as the ratio between the peak amplitude of the message signal and the amplitude of the added carrier, so that the message signal can still be detected in the envelope while the power efficiency is not too low. A modulation index of unity, if possible, is usually the best trade-off.

Both DSB_SC and DSB_C use double the bandwidth necessary to transmit a signal at the passband. Single Side Band (SSB) modulation techniques, which are introduced in the first lecture of the third week, can solve this problem. However, they are usually hard to implement because they either require an ideal bandpass filter or an ideal phase shifter, so called Hilbert transform.

Instead of transmitting on a SSB, Quadrature Amplitude Modulation (QAM) transmits two message signals within the DSB using two orthogonal carriers; that is, with a phase shift of $\pi/2$. Because this technique can only be detected coherently, it can easily suffer from cross talk or co-channel interference between the two transmitted messages. This technique is discussed in the second lecture of the third week. After this lecture, students meet in the lab to build DSB_C, SSB and QAM communication systems and analyze them in the time and frequency domain.

In the last lecture of this week, Vestigal Side Band (VSB) modulation technique is introduced as a good trade-off between SSB and DSB. This technique needs a bandwidth which is slightly higher than the SSB but can be implemented using realizable filters. By the end of this week, students have a good idea about all the different amplitude modulation techniques.

Week four covers advanced topics in amplitude modulation such as carrier acquisition at the receiver side and super heterodyne AM receivers. Because in coherent receivers it is very hard to generate a carrier at the receiver side which is in-phase with the received modulated signals, Phase Locked Loop (PLL) or Costas loop can be used to acquire the carrier from the received signal and use it in the demodulation process. Tuning to different radio stations can be done by using a tunable Band Pass Filter (BPF) at the radio frequency range, changing the carrier frequency of the selected station into an intermediate frequency using a super-hetrodyne mixer, and demodulating the message at the intermediate frequency to get the message signal. These three steps are done in a super heterodyne AM receiver, which is covered at the end of week four as a case example of a complete practical system. During this week, students also use the lab to build PLLs and analyze them.

Amplitude modulation techniques suffer in fading channels because the information resides in the amplitude of the carrier. As an example, it is very hard to receive AM stations below bridges or inside tunnels. Angle modulation techniques such as Frequency or Phase Modulation (FM and PM) are not affected as much in fading channels because the message signal modulates frequency or phase of the carrier instead of its amplitude. Hence, if the amplitude of the modulated signal is attenuated in a fading channel, the message signal will still be detected at the receiver. In addition, angle modulation techniques give communication engineers a good trade-off between bandwidth and power. For example, the communication link between a geostationary satellite and a receiver at the earth level is usually very power limited but not bandwidth limited. Since the link is point-to-point, using directive antennas an engineer can use a very large bandwidth without interfering with other signals in the space. Angle modulation techniques are a perfect fit in such cases because engineers can increase the bandwidth and reduce the power of the transmitted signal. These concepts are discussed in an introductory lecture at the beginning of week five as a bridge-way between amplitude modulation and angle modulation techniques.

For the rest of week five, students understand the difference between PM and FM, apply Carson's rule to estimate the bandwidth of angle modulation techniques, verify Carson's rule in the class and the Lab using a single tone message signal and know the difference between Narrow Band (NB) and Wide Band (WB) angle modulation techniques. Modulation index is redefined as the ratio between the bandwidth of the frequency deviation of the carrier and the bandwidth of the message signal and used to differentiate NB from WB.

Both NB and WB FM can be generated using a Voltage Controlled Oscillator (VCO). However, for large frequency deviations the VCO can easily become nonlinear. To solve this problem, WB FM is usually generated indirectly using NB modulators and frequency multipliers. This technique for generating WB FM is called Armstrong indirect FM transmitter. Demodulation, on the other hand, can be achieved using a number of different techniques such as a differentiator plus an envelope detector, frequency counter or PLL. These concepts are covered both in the class and the lab during week six. By the end of this week, students have a good idea about all the different analog modulation techniques and their features.

Week seven starts with a quick review on the concepts studied in Statistics for Engineers, which is the second prerequisite of this class. These concepts include an introduction to probability theory, random variables, Gaussian normal distribution as an example of probability density functions, and statistical averages. After being corrupted with noise while traveling through the channel, modulated signals at the receiver side can be modeled as wide sense stationary random processes. That is, random signals with constant means and an autocorrelation function that varies only with time shifts. Fourier transform is used to derive the PSD of this corrupted signal from its autocorrelation. This PSD is divided into two parts. The first part is related to the signal and the second part is related to the noise. Integrating these two parts, the power Signal to Noise Ratio (SNR) can be found.

After this necessary background, the rest of week seven focuses on the behavior of different analog modulation techniques in the presence of noise. First, students understand how most noise in the real world can be modeled as Gaussian. Next, different type of noise are differentiated based on their PSDs between white and colored. The PSD of any noise type is then divided into an in-band and out-of-band noise. By the end of the week, students will be able to relate the SNR of the demodulated signal at the output of any analog receiver to the SNR of the corrupted modulated signal at its input. Using this knowledge, they will be able to compare the performance of the different modulation techniques in the presence of noise. This week marks the end of the first module of the class, which focuses on analog modulation techniques. The lab period is used to provide the students with a summary of all the concepts learned in this module.

Week eight covers Analog-to-Digital Converters (ADC) as a bridge-way between analog and digital modulation techniques. It starts with a review of the sampling theory, which is usually covered in Signals and Systems. Then, anti-aliasing filters are introduced as a mean to bind the bandwidth of the message signal before starting the sampling process. Using Nyquist criterion, the message signal should be sampled at a rate of at least twice its bounded bandwidth. After sampling, quantization can transform the different analog samples from the message into digital.
The following lecture discusses how the number of levels used in the quantization stage and their distribution has a direct effect on both the quality of the digitized signal, which is defined by the Signal to Quantization Noise Ratio (SQNR), and its bit rate. Because message signals can vary a lot in their amplitudes, it makes more engineering sense to distribute the quantization levels in a non-uniform manner. This non uniform distribution can be achieved using companding techniques such as μ-law and A-law, which compress the message signal before the ADC and expand it after the Digital-to-Analog Converter (DAC). After companding, the SQNR will be independent of amplitude message variation.

In the final lecture of this week, differential pulse code modulation is described. Oversampling the message signal can make the variation between the different samples small enough so that future samples can be predicted from the previous samples. The error of this prediction can then be calculated using the true value of the sample. The quanitzer is then used to digitize the error signal instead of the message signal. To reconstruct the message signal, the DAC will simply accumulate the error signal. Sigma-delta ADCs use this technique to achieve high SQNR with a simple two-level quantizer. The lab of this week is divided into two parts. In the first part, students utilize sampling theory to Time Division Multiplex (TDM) two message signals. In the second part, the professor implements a first order Sigma-delta ADC to demonstrate the theory discussed in the class.

Weeks nine and ten focus on baseband digital modulation techniques that can only be transmitted through cables. In the first lecture, students will learn how to differentiate different baseband signals based on their line code and pulse shape. Although baseband digital signals can be considered random, their corresponding autocorrelation is again function of time shift only and hence their PSD can be easily derived. The PSD is affected by the line code and pulse shape used to implement the baseband digital signal. Line codes such as on-off, polar and bipolar and pulse shapes such as return to zero, non-return to zero and split phase are discussed thoroughly in class, implemented in the Lab and analyzed both in the time and frequency domain.

In the second lecture, students will know how to define the relation between the bit rate of the baseband digital signal and the essential bandwidth required transmitting this signal through a channel. Within a cable a signal is rarely corrupted with noise. However, because the bandwidth of the cable is limited, baseband digital signals can be distorted enough at the receiver side to cause Inter-symbol-Interference (ISI). This effect limits the bit rate of the transmitted signal. In the third lecture, special pulse shapes are introduced as a method to reduce the effect of ISI. These pulse shapes include raised cosine, duobinary and modified duobinary.

The eye diagram is introduced in lecture four and used in the lab to show the amount of distortion a baseband digital signal can suffer after passing through a cable. The opening and closing of the eye can give a good indication on the performance of the receiver. Next two types of channel equalization are discussed in lecture five. After this lecture, students will be able to build either a zero-forcing or a MSE equalizer and use it in conjunction with raised cosine filters to increase the bit rate of the transmitted signal without causing ISI. Finally, M-ary Pulse Amplitude Modulation (PAM) is given in lecture six and used in the lab to utilize channel bandwidth more efficiently. Through the use of PAM, bits can be grouped together as symbols and each symbol is represented using different amplitude. Because the symbol rate is much smaller than the bit rate, higher bit rates can be transmitted within a band-limited channel.

Weeks eleven and twelve focuses on passband digital modulation techniques. Baseband digital signals cannot be transmitted wirelessly unless they are modulated. Binary passband modulation techniques include Amplitude Shift Keying (ASK), Phase Shift Keying (PSK) and Frequency Shift Keying (FSK). These techniques are considered a special case of analog modulation techniques because the message signal is confined to digital. Hence, students can easily understand how to modulate and demodulate a passband digital signal using these various techniques in one week. This point emphasizes the importance of introducing the analog modulation techniques first. Unlike ASK and FSK, PSK cannot be demodulated non-coherently because the information resides in the phase of the modulated signal. On the other hand, Differential Phase Shift Keying (DPSK), which is introduced later in week eleven, can be demodulated non-coherently. Assuming that the phase of the carrier does not vary with in the duration of two bits, the carrier phase can be acquired from the previous bit and used to demodulate the current bit of a DPSK signal. During this week, students will implement the various binary passband digital modulation techniques in the lab and analyze them.

M-ary passband digital modulation techniques such as MASK, MPSK, MFSK and Quadrature Amplitude Modulation (QAM) are introduced in week twelve. MASK, MPSK and QAM are a good mean to trade Bandwidth with Power in band-limited channels that are not heavily corrupted with noise. Although these techniques are all used for the same purpose, they differ in the method used to represent each symbol. MASK uses different amplitudes for different symbols, MPSK uses different phases for different symbols and QAM is a hybrid technique that uses both different amplitude and phase to represent different symbols. The allocation of the different symbols in the three different techniques is based on a constellation diagram so that neighboring symbols do not differ by more than one bit. MFSK, on the other hand, is used to trade Power with Bandwidth in power-limited channels such as satellite communication and channels that are heavily corrupted with noise. All these M-ary techniques are implemented in the Lab during week twelve.

Unlike analog receivers, digital receivers have a decision making stage to find the value of the received symbol. The decision is based on the correlation or matching between the received pulse and the different shapes of symbols. The receiver can commit an error if the received pulse is corrupted enough with noise, suffer from ISI, or distorted. The probability of committing error is the figure-of-merit in digital communication. Week thirteen starts with an introductory lecture that discusses the probability of error that is considered acceptable for different applications. Due to safety issues, CAN protocol, which is used for communication between different electronics within a car, require extremely low probability of error. The rest of week thirteen derive the probability of error for on-off, orthogonal and polar signaling for coherent and non-coherent detection. BASK is an example of on-off signaling, BFSK is an example of orthogonal signaling and BPSK is an example of polar signaling. During this week students use the lab to analyze the performance of binary receivers for signals that are corrupted with noise.

Week fourteen discusses receivers for M-ary modulation techniques. It starts by introducing vector space analysis and basses functions. Next, students understand how a decision can be made based on the projection of the received waveform on the different basses functions. Finally, the probability of errors of MASK, QAM, MPSK, and orthogonal MFSK are derived for coherent and non-coherent detection. After this week, the second and final module of the class is covered. During this week, the lab period is used as a review session to summarize different digital modulation techniques.

Week fifteen is reserved for a case study on advanced digital modulation techniques. Such techniques may include but are not limited to Minimum Shift Keying (MSK), Gaussian Frequency Shift Keying (GFSK), spread spectrum techniques such as Code Division Multiple Access (CDMA) and Orthogonal Frequency Division Multiplexing (OFDM). Students research these different advanced techniques and discuss them in the class.

Comparison with the quarter based courses

Under the quarter system, the contents of this class were covered in two separate classes with 30 lecture hours and 30 lab hours in each class. Hence, a total of 15 lecture hours and 15 lab hours were lost in the semester transition. Based on this, the author was forced to exclude some material which includes:

- An introductory week at the beginning of the analog communication class.
- One week of review in the analog communication class that covers Fourier transform and series in details.
- One week of review of the statistical concepts before describing the behavior of analog communication systems in the presence of noise.
- One week of students' presentations at the end of the analog communication class.
- An introductory week at the beginning of the digital communication class.
- One week of students' presentations at the end of the digital communication class.

The two introductory weeks were combined and covered in a concise way during week 1 of the new semester based course. Excluding the two weeks of review, forced the students to review these concepts on their own. Under the new course formats, students are given a long homework at the end of week 1 that covers all the different review concepts. The instructor also encourages students, who are having trouble remembering these concepts, to visit him during the office hours. Instead of reserving two complete weeks of lectures for students' presentations, students were assigned a case study that compares CDMA to OFDM. The case study was discussed in the last week of class. Also, a number of labs were combined together to be covered in less number of lab periods.

On the other hand, integrating the two classes together helped students understand the interconnection between analog and digital communication techniques. For example, they understood that digital signals are nothing but a special case of analog signals. They also find that while the figures of merits in the analog and digital communication techniques are different, they are actually related through the ratio of the signal power to the noise power.

Course Assessment

As mentioned before, the communication systems class has already been offered once in its current format under semester system. At the end of the class students were asked the following questions in their end of term feedback:

1. This course enhanced my problem solving abilities.
2. The homework helped my understanding of the material
3. The textbook was valuable in my learning experience.
4. The workload for this course in relation to other courses of equal credit was as expected.
5. The laboratory assignments facilitated my learning experience.
6. The laboratory assignments and course material reinforced one another.
7. The laboratory equipment was modern and useful.

Students answered each question with either strongly disagree (SD), or disagree (D), or undecided (U), or agree (A), or strongly agree (SA). The answers were rated between one for SD and five for SA. A total of 16 students took the survey in 2012.

As shown in table 1, the means of the seven questions were between 4 and 4.8. Questions that are related to the lab achieved the highest means, which means that students strongly agreed with the fact that the lab material matches with the material covered in the class and reinforce it.

Students also acknowledged the good choice of textbook and selection of homework problems. Most importantly students approved that the course load is comparable with other courses of same number of credits and enhanced their problem solving abilities. For the sake of comparison, Table 2 summarizes the survey results of 2011. During this academic year Ohio Northern University was still under quarter system and the material was covered in two separate classes. The first class covers analog communication techniques and the second class covers digital communication techniques. A total of 17 students took the survey in the first class and a total of 20 students took the survey in the second class. Comparing Table 1 to Table 2, it is clear that there was no decline in the means of the different questions. In fact, most of the means were slightly improved. Hence, students prefer the new format of the class.

In addition students wrote the following comments:

1. "Unlike some courses, it is imperative that students take the prerequisites."
2. "The book was pretty good about having examples and decent summaries to supplement the class but it was just very theory heavy."
3. "Transition to semesters seemed to go fairly well."
4. "Pacing of content/workload seemed fine."

Comment 1 is expectable because the class needs a lot of background information. Comment 2 acknowledges the good choice of the book, but describes it as theoretically heavy. While it is important to always show the application aspects of the course material, it is the author's opinion that a theoretically heavy textbook should be a good reference to the students in their professional life. Finally while comments 3 and 4 are balanced, they somehow support the seamless semester transition and the fine pacing of the class content.

Table 1. Results of the 2012 survey

	SA	A	U	D	SD	M
Q1	4	9	2	1	0	4
Q2	7	7	2	0	0	4.3
Q3	6	4	6	0	0	4
Q4	3	12	0	1	0	4.1
Q5	13	2	1	0	0	4.8
Q6	13	3	0	0	0	4.8
Q7	10	6	0	0	0	4.6

Table 2. Results of the 2011 survey

Analog	SA	A	U	D	SD	M
Q1	4	10	1	1	1	3.9
Q2	4	10	0	1	2	3.8
Q3	3	10	2	0	0	4.1
Q4	2	14	0	1	0	4
Q5	9	7	0	1	0	4.4
Q6	11	6	0	0	0	4.6
Q7	5	11	1	0	0	4.2

Digital	SA	A	U	D	SD	M
Q1	7	9	0	4	0	4
Q2	9	7	2	2	0	4.2
Q3	6	8	4	1	1	3.9
Q4	5	13	0	2	0	4.1
Q5	11	7	1	1	0	4.4
Q6	13	6	1	0	0	4.6
Q7	10	8	0	1	1	4.3

Conclusion

This paper gives a complete description for an introductory course on communication systems that covers both analog and digital modulation techniques. The course is four credits with three hours of lectures and three hours of lab per week and runs for fifteen weeks to cover a complete semester period. While designing the course syllabus, a decision was made to divide the class into two separate modules and cover the analog module first. The challenge in implementing this syllabus is to cover the behavior of the modulation techniques in the presence of noise separately for the two different modules, which may cause some redundancy in the material. This redundancy, though, made the class more organized. Also, it was logical to analyze the behavior of digital receivers in the presence of noise directly after introducing them because those receivers are usually optimized based on the properties of noise in the channel.

Although the instructor was forced to exclude some review material from the course while transitioning from quarter to semester format, the exclusion of the review material didn't affect the performance of the students. Also, compared to the previous years, the mean of most of the survey questions in the students' feedback were improved, which showed that students prefer the new format of the class.

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