COMMUNICATIONS ENGINEERING

Fundamentals of Communications Systems

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Fundamentals of Communications Systems

About the Author

Michael P. Fitz has experience both as a teacher of electrical communications and as a designer of electrical communication systems. He has been a professor of electrical and computer engineering at the University of California Los Angeles (UCLA), the Ohio State University, and Purdue University. Professor Fitz won the D. D. Ewing Undergraduate Teaching Award at Purdue University in 1995. Prof. Fitz was a member of the editorial board of the IEEE Transactions on Communications. Dr. Fitz has worked as a digital communication system engineer for a variety of companies and currently is a senior communication systems engineer at Northrop Grumman. In these roles he has designed, built, and tested modems for land mobile and satellite communications applications. He received the 2001 IEEE Communications Society Leonard G. Abraham Prize Paper Award in the field of communications systems for his contributions to space-time modem technology.

This book is dedicated to

- *the memory of my parents. If my children become half the human beings that my siblings are, I will consider myself a success in life.*
- *Mary. She has given up much to let me pursue my follies. I hope I can now give back to her in an equal amount!*

Preface

My goal in teaching communications (and in authoring this text) is to provide students with

- an exposition of the theory required to build modern communication systems.
- an insight into the required trade-offs between spectral efficiency of transmission, fidelity of message reconstruction, and complexity of system implementation that are required for a modern communication system design.
- a demonstration of the utility and applicability of the theory in the homework problems and projects.
- a logical progression in thinking about communication theory.

Consequently, this textbook will be more mathematical than most and does not discuss examples of communication systems except as a way to illustrate how important communication theory concepts solve real engineering problems. My experience has been that my approach works well in an elective class where students are interested in communication careers or as a self-study guide to communications. My approach does not work as well when the class is a required course for all electrical engineering students as students are less likely to see the advantage of developing tools they will not be using in their career. Matlab is used extensively to illustrate the concepts of communication theory as it is a great visualization tool and probably the most prevalent system engineering tool used in practice today. To me the beauty of communication theory is the logical flow of ideas. I have tried to capture this progression in this text. Only you the reader will be able to decide how I have done in this quest.

Teaching from This Text

This book is written for the modern communications curriculum. The course objectives for an undergraduate communication course that can be taught from this text are (along with their ABET criteria)

- Students learn the bandpass representation for carrier modulated signals. (Criterion 3(a))

- Students engage in engineering design of communications system components. (Criteria 3(c),(k))
- Students learn to analyze the performance, spectral efficiency and complexity of the various options for transmitting analog and digital message signals. (Criteria 3(e),(k))
- Students learn to characterize noise in communication systems. (Criterion 3(a))

Prerequisites to this course are probability and random variables and a signal and systems course.

I have taught out of this book material in several ways. I have been lucky to teach at three universities (Purdue University, the Ohio State University, and the University of California Los Angeles) and each of these experiences has profoundly impacted my writing of this book. The material in this book has been used to teach three classes

- Undergraduate analog communications and noise (30 lecture hours)
- Undergraduate digital communications (30 lecture hours)
- Undergradute communications (40–45 lecture hours)

The course outline for the 30 lecture hours of analog communication is

1. Chapters 1 & 2 — 1 hour. This lecture was a review of a previous class.
2. Chapter 4 — 2 hours. These lectures build heavily on signal and system theory and specifically the frequency translation theorem of the Fourier transform.
3. Chapter 5 — 1 hour. This lecture introduces the concept of analog modulation and the performance metrics that engineers use in designing analog communication systems.
4. Chapter 6 — 5 hours. These lectures introduce amplitude modulation and demodulation algorithms. Since this course was an analog only course, I spend more time on the practical demodulation structures for DSB-AM and VSB-AM.
5. Chapter 7 — 5 hours. These lectures introduce angle modulation and demodulation algorithms. I like to emphasize that the understanding of the spectrum of angle modulations is best facilitated by the use of the Fourier series.
6. Chapter 8 — 2 hours. These lectures introduce multiplexing and the phase-locked loop. Multiplexing is an easy concept and yet students enjoy it because of the practical examples that can be developed.
7. Chapters 3 & 9 — 6 hours. These lectures introduce random variables and random processes. This, from the student's perspective, is the most difficult

part of the class as the concept of noise and random processes are mathematically abstract. Undergraduates are not used to abstract concepts being important in practice.

8. Chapter 10 — 3 hours. These lectures introduce bandpass random processes. This goes fairly well once Chapter 9 has been swallowed.
9. Chapter 11 — 3 hours. These lectures introduce fidelity analysis and the resulting SNR for each of the modulation types that have been introduced. The payoff for all the hard work to understand random processes.
10. Test — 1 hour.

The 30 hour digital only communication course followed the analog course so it could build on the material in the previous course. This course often contained some graduate students from outside the communications field that sat in on the course so some review was necessary. The course outline for 30 lecture hours of digital communications is

1. Chapter 1 & 4 — 2 hours. These lectures introduce communications and bandpass signals.
2. Chapter 9 & 10 — 2 hours. These lectures introduce noise and noise in communication systems.
3. Chapter 12 — 1 hour. This lecture introduces the concept of digital modulation and the performance metrics that engineers use in designing systems. This lecture also introduces Shannon's limits in digital communications.
4. Chapter 13 — 6 hours. These lectures emphasize the five-step design process inherent in digital communications. In the end these lectures show how far single-bit transmission is from Shannon's limit.
5. Chapter 14 — 4 hours. These lectures show how to extend the single bit concepts to M-ary modulation. These lectures show how to achieve different performance-spectral efficiency trade-offs and how to approach Shannon's limit.
6. Chapter 15 — 8 hours. These lectures introduce most of the modulation formats used in engineering practice by examing the complexity associated with demodulation.
7. Chapter 16 — 3 hours. These lectures introduce bandwidth efficient transmission and tools used to test digital communication systems.
8. Chapter 17 — 2 hours. These lectures introduce coded modulations as a way to reach Shannon's bounds.
9. Test — 1 hour.

The 40–45 hour analog and digital communication course I taught traditionally had a much more aggressive schedule. The course outline for 40 lecture hours of communications is

1. Chapters 1 & 2 — 1 hour. The signal and systems topics were a review of a previous class.
2. Chapter 4 — 2 hours. These lectures build heavily on Fourier transform theory and the frequency translation theorem of the Fourier transform.
3. Chapter 5 — 1 hour. This lecture introduces the concept of analog modulation and the performance metrics that engineers use in designing systems.
4. Chapter 6 — 4 hours. These lectures introduce amplitude modulation and demodulation algorithms. The focus of the presentation was limited to coherent demodulators and the envelope detector.
5. Chapter 7 — 4.5 hours. These lectures introduce angle modulation and demodulation algorithms. I like to emphasize that the understanding of the spectrum of angle modulations is best facilitated by the use of the Fourier series.
6. Chapter 8 — 0.5 hour. Only covered multiplexing.
7. Chapters 3 & 9 — 5 hours. This is the toughest part of the class as the concept of noise and random processes are mathematically abstract. Undergraduates are not used to abstract concepts being important in practice.
8. Chapter 10 — 2 hours. This goes fairly well once Chapter 9 has been swallowed.
9. Chapter 11 — 2 hours. The payoff for all the hard work to understand random processes.
10. Chapter 12 — 1 hour. This lecture introduces the concept of digital modulation and the performance metrics that engineers use in designing systems. This lecture also introduces Shannon's limits in digital communications.
11. Chapter 13 — 6 hours. These lectures emphasize the five-step design process inherent in digital communications. In the end these lectures show how far single-bit transmission is from Shannon's limit.
12. Chapter 14 — 4 hours. These lectures show how to extend the single bit concepts to M-ary modulation. These lectures show how to achieve different performance-spectral efficiency trade-offs and how to approach Shannon's limit.
13. Chapter 15 — 3 hours. These lectures introduce most of the modulation formats used in engineering practice by examing the complexity associated with demodulation.
14. Chapter 16 — 1 hours. These lectures introduce bandwidth efficient transmission and tools used to test digital communication systems.
15. Chapter 17 — 1 hours. These lectures introduce coded modulations as a way to reach Shannon's bounds.
16. Test — 1 hour.

The 45 hour course added more details in the digital portion of the course.

Style Issues

This book takes a stylistic approach that is different than the typical communication text. A few comments are worth making to motivate this style.

Property–Proof

One stylistic technique that I adopted in many of the sections, especially where tools for communication theory are developed, was the use of a property statement followed by a proof. There are two reasons why I choose this approach

1. The major result is highlighted clearly in the property statement. Students, in a first pass, can understand the flow of the development without getting bogged down in the details. I have found that this flow is consistent with student (and my) learning patterns.
2. Undergraduate students are increasingly not well trained in logical thinking in regard to engineering concepts. The proofs give them some flavor for the process of logical thinking in engineering systems.

General Concepts Followed by Practical Examples

My approach is to teach general concepts and then follow up with specific examples. To me the most important result from a class taught from this book is the learning of fundamental tools. I emphasize these tools by making them the focus of the book. Students entering the later stages of their engineering education want to see that the hard work they have put into an engineering education has practical benefits. The course taught from this book is really fun for the students as old tools (signals and systems and probability) and newly developed tools are needed to understand electronic communication.

Two Types of Homework Problems

This book contains two types of homework problems: (1) direct application problems and (2) extension problems. The application problems try to define a problem that is a straightforward application of the material developed in the text. The extension problem requires the student to think "outside the box" and extend the theory learned in class to cover other important topics or cover practical applications. *As a warning to students and professors*: Often times the direct application problems will appear ridiculously simple if you carefully read the text and the extension problems, as they are often realistic engineering problems, appear to be much too extensive for a homework problem. I have found that both types of problems are important for undergraduate education. Direct application problems allow you to practice the theory but are usually not indicative of the types of problems an engineer sees in practice. Alternatively students often desire realistic problems as they want a feel for "real" engineering but often get overwhelmed with the details needed in realistic problems. All direct application leads to a boring sterile course and all extension problems discourage all but the exceptionally smart and motivated. Having a book with both types of problems allows the student to both exercise and extend their learning in the proper balance.

Examples and Example Solutions

My learning style is one where a very succinct presentation of the issues works best. I originally wrote this book where the material was presented in a condensed version with little or no examples. I then followed each chapter with a set of example solutions to homework problems. During the many revisions of the book I came to realize that many students learn best with examples along with a presentation of the theory. I added a significant number of in-text examples to meet this learning need. I still like a succinct presentation so I did not move all example solutions to in chapter examples. Consequently, each chapter has a set of in-chapter examples and a set of worked solutions. This method was viewed as a compromise between a succinct presentation (my learning style and hopefully a few others) and lots of examples (many students' learning style).

Miniprojects

Both for myself and the students I have taught, learning is consumated in "doing." I include "Miniprojects" in the book to give the students a chance to implement the theory. The project solutions are appropriate for oral presentation and this gives the students experience that will be a valuable part of an engineering career. The format of the project is such that it is most easily done in Matlab as that is the most common computer tool used in communication engineering systems. To aid students who are not familiar with Matlab programming I have included the code for all the Matlab generated figures in the text on the book web page. This also allows students to see how the theory can be implemented in practice.

Writing of the Book

The big question that has to be answered in this preface is "Why should anyone write another communication theory book?" The short answer is "There is no good reason for the book and a rational person would not have written the book." The book resulted from a variety of random decisions and my general enjoyment of communication engineering. A further understanding of this book and my decision to write it can be obtained by understanding the stages I perceived in looking back on the writing this book. This documentation is done in some sense for those who will follow in my folly of attempting to write a book to give them a sense of the journey.

1. **Captured.** As a child, a high school student and a college student I was always drawn to math and science, to problem solving, and to challenges. Quickly my career path steered toward engineering, toward electrical engineering, and finally toward communication engineering. I took a job as a communication engineer while pursuing a graduate education. In the first

four years of working I used all of my graduate classes in solving communication problems and was a key engineer in a team that built and field tested a sophisticated wireless modem. I was hooked by communications engineering: It is a field that has a constant source of problems, a well-defined set of metrics to be used in problem solving, and a clear upperbound (due to Claude Shannon) to which each communication system could aspire.

2. **Arrogance.** I started my academic career, after being reasonably successful while working in industry, with the feeling that I knew a great deal. I was convinced that my way of looking at communications was the best and I started teaching as such. I found the textbooks available at the time to have inadequate coverage of the complex envelope representation of bandpass signals and bandpass noise and other modern topics. Hence my writing career started by preparing handouts for my classes on these topics. I quickly got up to 100 pages of material.
3. **Humbled but Learning.** It was not too long after starting to teach and direct graduate student research that I came to the realization that the field of communications was a mighty river and I had explored only a few fairly minor tributaries. I came to realize I did not know much and still needed to learn much. This realization began to be reflected in my teaching as well. I branched out and learned other fields and reflected my new understanding in my teaching methods and approaches. Much to my students' chagrin, I often used teaching as a method to explore the boundaries of my own learning. This resulted in many poorly constructed homework problems and lectures that were rough around the edges. As I am not very bright, when I synthesized material I always had to put it into my own notation to keep things clear in my own mind. After these bouts with new material that were very confusing for my students, I often felt guilty and wrote up notes to clarify my ramblings. Soon I was up to 200 pages of material on digital communications. As I would discover later these notes, while technically correct, were agonizingly brief for students and lacked sufficient examples to aid in learning.
4. **Cruise Control.** I soon got to the point where I had reasonable notes and homework and my family and professional committments had grown to the point where I needed not to focus so much on my teaching and let things run a bit in cruise control. During this time I added a lot of homework and test problems and continued to write up and edit material that was confusing to students. My research always seems filled with interesting side issues that make great homework problems. I started the practice of keeping a note book of issues that have come up during research and then tried to morph these issues into useful homework problems. Some problems were successes and some were not. In 2002, I was up to about 300 pages.
5. **Well I have 300 Pages...** At the point of 300 pages I felt like I turned a corner and had a book almost done and started shopping this book around to publishers. My feeling was that there was not much left to complete and once I signed a contract the book would appear in 6 months. This writing

would magically take place while my professional and family life flourished. I eagerly wrote more material and was up to 400 pages.

6. **...And Then Depression Set In.** When I looked at my project with the critical eye produced by signing a contract, it quickly became apparent that lots of pages do not necessarily equate to a book of any quality. At this time I also got my first reviews back on the book and quickly came to realize why all textbooks on communications look the same to me. If you took the union of the reviews you would end up with a book close to all the books on the market (that I obviously did not fully appreciate). During this time I struggled mightily at trying to smooth out the rough edges of the book and address reviewers' concerns, while trying to keep what I thought was my personal perspective on communications. This was a significant struggle for me, as I learned the difficult lesson that each person is unique in how they perceive the world and consequently in what they want in a textbook but I stubbornly soldiered through to completion.

In summary the book resulted not from a well thought out plan but from two disjointed themes: (1) my passionate enjoyment of communication engineering, (2) my constant naive thinking as a professional. The book is done and it is much different than I first imagined it. It is unique in its perspective but not necessarily markedly different than the other books out there. It is time to release my creation.

Heresies in the Book

The two things I learned in writing this book is that engineering professionals do not see the field the same and engineering professors do not like change. In trying to tell my version of the communication story I thought long and hard about how to make the most consistent and compelling story of communication engineering for my students. In spite of what I considered a carefully constructed pedagogy, I have been accused (among other things) of making up nomenclature and confusing the student needlessly. Since I now realize that I am guilty of several potential heresies to the field of communication education, I decided to state these heresies clearly in the preface so all (especially those that teach from this book) know my positions (and structure their classes appropriately).

1. **System Engineering Approach.** I have worked as a communication engineer in industry and academia. I do not have a detailed knowledge of circuit theory and yet from all outward appearances I have thrived in my profession by only being an expert in system modeling and analysis. This text will not give circuits to build communication systems as circuits will change over time but will discuss mathematical concepts as these are consistent over time. I am a firm believer that communications engineering is perhaps unique in how theory directly gets implemented in practice.

2. **Fidelity, Complexity, and Spectral Efficiency.** Everything in electronic communications engineering comes down to a trade-off between fidelity of message reconstruction, complexity/cost of the electronic systems used to implement this communication, and the spectral efficiency of the transmission. I have decided to adopt this approach in my teaching. This approach clearly deviates from past practice and has not proven to be universally popular.
3. **Stationary versus Wide-Sense Stationary.** An interesting characteristic in my education was that a big deal was made out of the difference between stationary and wide-sense stationary random processes – and most likely for all communication engineers of my generation. As I went through my life as a communication engineering professional I came to the realization that this additional level of abstraction was only needed because the concept of stationarity was arbitrarily introduced before the concept of Gaussianity. For my book, I introduce Gaussian processes first and then the idea of wide-sense stationarity is never needed. My view is clearly not appreciated by all[1] but my book has only stationary Gaussian processes and random variables. I felt the less new concepts in random processes that are introduced in teaching students how to analyze the fidelity of message reconstruction, the better the student learning experience would be.
4. **Information Theory Bounds.** My view is that digital communication is an exciting field to work in because there are some bounds to motivate what we do. Claude Shannon introduced a bound on the achievable fidelity and spectral efficiency in the 1940s [Sha48]. Communication engineers have been pursuing how to achieve these bounds in a reasonable complexity ever since. Many people feel strongly that Shannon's bounds cannot be introduced to undergraduates and I disagree with that notion! It is arguable that Claude Shannon has a bigger impact on modern life than does Albert Einstein yet name recognition among engineering and science students is not high for Claude Shannon. Hopefully introducing Shannon and his bounds to undergraduates can give him part of his due.
5. **Erfc(•) versus Q(•).** The tail probability of a Gaussian random variable comes up frequently in digital communications. The tail probability of a Gaussian random variable is not given by a simple expression but instead must be evaluated numerically. Past authors have used three different transcendental functions to specify tail probabilities: Erfc(•), Φ(•), and the Q(•). Historically, communication engineers have gravitated to the use of Q(•) as its definition matches more closely how the usage comes up in digital communications. I have chosen to buck this trend because of one simple fact: Matlab is the most common tool used in modern communications engineering and Matlab uses Erfc(•). Most people who read this text after having

[1]Some reviewers went so far as to suggest I needed to review my random processes background to get it right!

used other communication texts do not appreciate the usage of Erfc(•) but frankly this book is written for students first learning communications. This notation serves these students much better (even while it irritates reviewers) as it gives a more consistent view betweeen the text and the common communication tools.

6. **Signal Space Representations.** A major deficiency in my approach, according to some reviewers, is that I do not include signal space representations of digital signals. While I understand the advantages and insights offered by this approach I think signal space representations lead the students off course. Specifically, I do not know of a single communication system that uses the signal space concepts in designing a demodulator or a modulator other than to exploit orthogonality to send bits independently (see orthogonal modulations below). The best example of a high dimension signaling scheme is a direct sequence code division multiple access (DS-CDMA) system. To the best of my knowledge no DS-CDMA system does "chip" level filtering and then combining as would be suggested by a signal space approach but directly implements each spreading waveform or each spreading waveform matched filter. All demodulators I am familiar with are based on the concept of the matched filter. I feel taking the matched filter approach leads to a more consistent discussion, while many of my colleagues feel a signal space approach is necessary for their students to comprehend digital communications.
7. **Noncoherent and Differentially Coherent Detection in Digital Communications.** These subjects never enter this introductory treatment of communication theory as they are really secondary topics in modern communications theory. When I started my career there were three situations where tradition ruled that noncoherent or differentially coherent techniques were mandatory for high performance communications: (1) in the presence of jamming, (2) with short packets, and (3) in land mobile wireless communications. In the past 15 years I have worked on these types of systems in both an academic environment and as part of commercial engineering teams and not once were noncoherent or differentially coherent techiques used[2] in modern communication systems. I decided that rather than confuse the student with a brief section on these topics that I would just not present them in this book and let students pick up this material, if needed, in graduate school or with experience.
8. **Cyclostationarity and Spectrum of Digital Modulations.** This is a sensitive subject for many of my professional colleagues. I am strongly of the opinion that spectral efficiency is a key component of all digital communication discussions. Consequently, all digital transmissions must have an associated bandwidth. Interestingly nowhere in the previous teaching

[2]Except to support legacy systems.

texts was there a method to compute the spectral content of finite length transmissions even though this must be done in engineering practice. To be mathematically consistent with the standard practice for defining the power spectrum of random processes, I settled on the concept of an average energy spectrum. Here the average is over the random data sequences that are transmitted. For students to understand this concept they only need to understand the concept of expectation over a random experiment. This average energy spectrum is defined for any modulation format and for finite or infinite length transmissions. In contrast, many professors who teach communications are wed to the idea of computing the power spectrum of digital transmissions by

(a) Assuming an infinite length transmission
(b) Defining cyclostationarity
(c) Averaging over the period of the correlation function of a cyclostationary process to get a one parameter correlation function
(d) Taking the Fourier transform of this one parameter correlation function to get a power spectrum

This procedure has four drawbacks: (1) it introduces a completely new type of random process (to undergraduates who struggle with random processes more than anything else), (2) it introduces a time averaging for no apparent logical reason (this really confused me as a student and as a young engineer), (3) it only is precise for infinite length transmissions (no stationarity argument can be used on a finite length transmission), and (4) these operations are not consistent with the theory of operation of a spectrum analyzer that will be used in practice. Hopefully it is apparent why this traditional approach seems less logical than computing the average energy spectrum. In addition, the approach used in this book gives the same answers in the cases when cyclostationarity can be used (without the strange concept of cyclostationarity) and gives answers in cases where cyclostationarity cannot be used, and is consistent with spectral analyzer operations. Unfortunately, I have learned (perhaps too late in life) that when you are a heretic, logic does not help your case against true believers of the status quo.

9. **Orthogonal Modulations.** My professional career has led me on many interesting rides in terms of understanding of communication theory. Early in my career the communciation field was roiled by a debate of narrowband modulation versus wideband modulation sparked by Qualcomm's introduction of IS-95. At the time I felt wideband modulation was a special case of a general modulation theory. I remember at the time (roughly 1990) someone making the comment during a discussion that narrowband modulation was a special case of wideband modulation[3] and at the time I was dismissive of

[3] I believe this discussion was with Wayne Stark or Jim Lehnert.