Teaching the Basic Concepts of Communications Systems Using Interactive Graphics and Calculations

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Abstract

An open source, open content, and open access (free) electronic textbook, an ebook, introducing the concepts of communications system is described. The ebook is written in the Wolfram language, Mathematica. The purpose of this interactive presentation of communications systems is to bring the material alive through the use of student driven interactive graphics and dynamic performance metric calculations. In-line interactive questions are included to provide the students with rapid feedback regarding their understanding of the material. The ebook was used as the required text in EECS 562 Introduction to Communication Systems at the University of Kansas in the Spring of 2021.

Keywords

Communications systems, electronic textbook, ebook.

Introduction

It is common for electrical engineering curriculum to include an introduction to communications systems course, either required or as an elective. There are many books in the market to teach an introduction to communications systems course, e.g., [1], [2], [3], [4], [5], [6], [7], [8], [9], [10] and [11]. These texts provide comprehensive coverage of communications systems; mostly presenting analog and then digital modulation. An ebook will be presented which follows a different way to teach communications systems; an approach that uses a student driven interactive presentation of the fundamentals of communications systems. This ebook also takes a different pedagogical approach to teaching the subject.

Following a growing trend, this ebook is open source, open content, and open access, i.e., eventually it will become Open Educational Resources (OER) material. Open textbooks are becoming ubiquitous. OER material is intended to provide free access to openly licensed information to support teaching and research. There are several search web sites dedicated to help instructors find open textbooks in their field, e.g., the Open Textbook Library https://open.umn.edu/opentextbooks/ [12] and Openly Available Sources Integrated Search (OASIS) https://oasis.geneseo.edu/ [13], and OER Commons https://www.oercommons.org, [13].

This ebook is written in the Wolfram language, Mathematica [14]. Students access the material by downloading one file from the class web site and the free Wolfram Player from https://www.wolfram.com/player/. The ebook is then read by opening the one file using the Wolfram Player. The Wolfram Player allows the students to dynamically engage with the interactive material. The Wolfram Player runs on common operating systems, Windows 10, Mac, and Linux as well as iOS for iPads. This ebook also took advantage of several Mathematica notebooks from the Wolfram Demonstration Project [15]. MATLAB is commonly used for signal processing and communications system simulation [16]. Mathematica provided a direct method to integrate interactive graphics with text and equations as well as organize the material into openable/closable chapters/sections/subsections and therefore was selected for this effort. The current version of the ebook can be downloaded from Introduction to Communication Systems [17].

In the context of this effort interactive means that the static plots, typically found in traditional text books, are brought to life using student driven interactive graphics. For example, simultaneously showing a raised cosine pulse and its spectrum as the student gets to change the roll-off factor. This approach also enables dynamic performance metric calculations, e.g., showing the threshold effect (in frequency modulation) of the output signal-to-noise ratio as the student changes the modulation index. The interactive graphics allow the student to engage with and visualize the concepts that provide the basis for electronic communications. To reinforce the concepts, in-line interactive questions are included; the student provides an answer and gets immediate feedback; if their answer is wrong then they can try again. The ebook also contains many worked problems; these guide the students toward solutions of some of the in-line interactive questions.

Not only can the student directly interact with the material, a unique pedagogical approach is used to present communication systems concepts. After a review of signals and systems the presentation directly goes to building baseband waveforms from a stream of information bits, where analog-to-digital conversion is discussed as just another way to generate information bits. This approach reflects our current world, where information is often already in the form of bits, e.g., documents, e-mail, and texts. After the transformation of bits into digital baseband waveforms, double-sideband suppressed carrier (DSB-SC) modulation is presented. Concepts from DSB-SC are all that are needed to introduce quadrature modulation followed by discussions of digital modulation techniques, specifically, Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK), M-ary Quadrature Amplitude Modulation (M-QAM), M-ary Phase Shift Keying (MPSK), Time Division Multiple Access (TDMA) and the basics Orthogonal Frequency Division Multiplexing (OFDM). The ebook gives the students the essentials needed to understand 5G and WiFi technologies early in the semester; relating the material to devices they use every day. The remaining topics build upon each other culminating with an introduction to the implementation of OFDM, with examples from WiFi and OFDM as used in 4G/5G communications systems. Here, the students see how the concepts presented throughout the semester tie together, from M-ary baseband symbols, pulse shaping, dynamic resource allocation enabled by the combination of TDMA/OFDM, the bit error rate vs signal-to-noise ratio (E_b/N_0) for different orders of M-QAM, receiver noise figure, path loss and antenna gain lead to current systems using adaptive modulation techniques. The ebook contains 16 chapters, each followed by a set of homework questions. Throughout the ebook systems trade-offs and design alternatives are stressed. The material in this ebook has been covered in one semester.

However, some detailed theoretical developments are included and a comprehensive coverage of all aspects of communications systems, e.g., the wide variety of modulation schemes, are not considered. There are several text books that provide such a treatment, for example, [1], [2], [3], [4], [5], [6], [7], [8], [9], [10] and [11]. Those texts cover a wider array of communication systems and techniques as well as a more in-depth development of the underlying theory, often provide material for more than one semester.

The approach taken here also has advantages for instructors. With a license for the latest version of Mathematica instructors can lecture directly from the ebook. The material has been specifically formatted so that the source Wolfram notebook (.nb file) can be directly used during lectures taking advantage of Mathematica's "Classic Slide Show" functionality. The "Classic Slide Show" functionality enables the instructor to show the text and interactive plots in a viewable (slide-like) format. The "Classic Slide Show" functionality was used while teaching EECS 562 Introduction to Communication Systems at the University of Kansas in the spring of 2021. A solutions manual has been developed for the end of chapter questions. Solutions for the homework for each chapter have been written as separate Mathematica notebooks. These have in-line solutions. Instructors can easily change the numbers in some of the problems and then the homework notebooks recalculates the solutions; providing a path for changing the problems each semester. There a simple method for instructors to remove the solutions, make a pdf and distribute the homework to the students.

The table of contents of the ebook is discussed next. Examples of the interactivity are then presented followed by samples of the in-line questions, ending with a discussion of how the ebook supported remote learning in the spring of 2021.

New Order of Topic Presentation

After a review of signals and systems many communications systems text books first present analog modulation, e.g., double sideband suppressed carrier, double sideband large carrier-commercial AM, vestigial sideband modulation (VSB), single side band, frequency and phase modulation. Often the superheterodyne receiver is discussed along with analog modulation, usually AM. Later in these textbooks digital modulation is discussed, e.g., BPSK, MPSK, amplitude shift keying (ASK), frequency shift keying (FSK), QPSK, and MPSK, M-QAM often followed by other types of digital modulation, e.g., differential phase shift keying and minimum shift keying. Coverage of OFDM is not often in depth [18]. While this order of presentation was suitable when analog modems were common and used FSK and when analog TV used VSB for video and FM for audio, today’s technology, i.e., cable modems, WiFi, 4G and 5G cell systems, is dominated (at an introductory level) by ODFM, TDMA, and dynamic M-QAM. A goal for this ebook is to, as soon as possible, in the semester motivate students by introducing them to communications systems concepts for devices they own and use every day. The ordering of the material was also driven by another goal; to stress the systems trade-offs and design alternatives, e.g., engineering trade-offs among radio frequency (RF) bandwidth requirements, receiver complexity/cost, transmitter power requirements, antenna size, carrier frequency, and the distance between transmitters and receivers. To achieve this goal a chapter introducing the elements involved in constructing link budgets and using them to conduct engineering design trade-off studies is included following the discussion of analogy modulation and the superhetrodyne receiver. This sets the stage for developing the concept of processing gain in the context of the noise performance of analog modulation techniques. The students can then include the processing gain in their link budgets and learn about the trade-offs among key system parameters, e.g., transmitter power and the required RF bandwidth to meet customer specified signal-to-noise ratio. Performance of digital communications system, with a focus on the bit error rate (BER) as a function of the E_b/N_0 is presented next. For BPSK and MPSK the link budget concepts are applied to again highlight trade-offs among key system parameters. The students are now prepared to tie together all the concepts they have studied so far to develop and understanding of the implementation issues associated with WiFi, 4G and 5G cell systems. The ebook concludes with a chapter introducing error control coding, cumulating in defining the coding gain which again can then be factored into link budgets. Below is the table of contents.

Examples of Student Driven Interactive Graphics and Dynamic Performance Metric Calculations

The purpose of this section is to provide a flavor of the student driven interactive graphics and dynamic performance metric calculations included in the ebook. These interactive graphics will be presented dynamically during the conference. The first example, Figure 1, shows how the

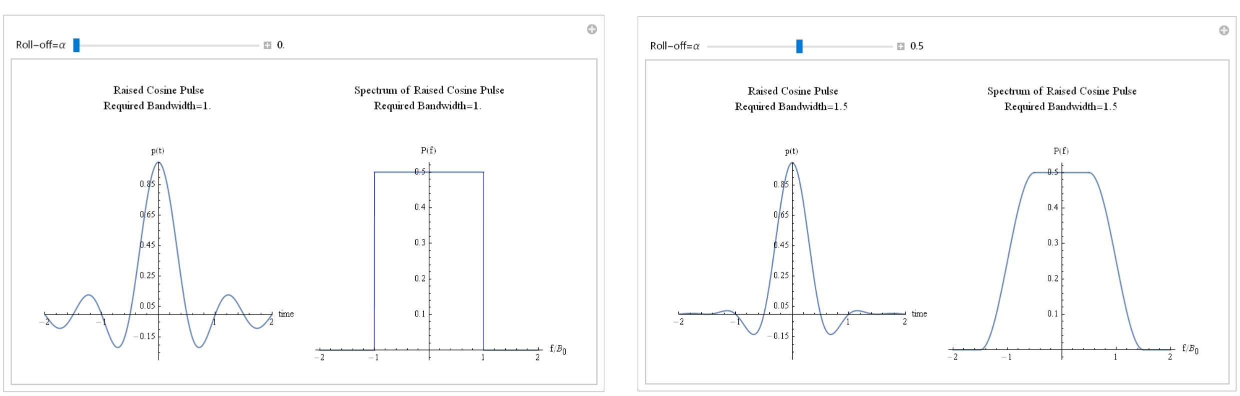

Figure 1 Interactive Time/Frequency Raised Cosine Graph

student can visualize the impact of changing the roll-off factor (by using the slide bar) of a raised cosine pulse in time and frequency.

The mathematics of intersymbol interference (ISI) are not conducive to understanding the concept; Figure 2 shows an interactive graphic that the student can use to explicitly see the impact of ISI as the bandwidth and roll-off factor changes; this interactive is particularly useful for explaining the benefit of using the additional bandwidth required by raised cosine pulses.

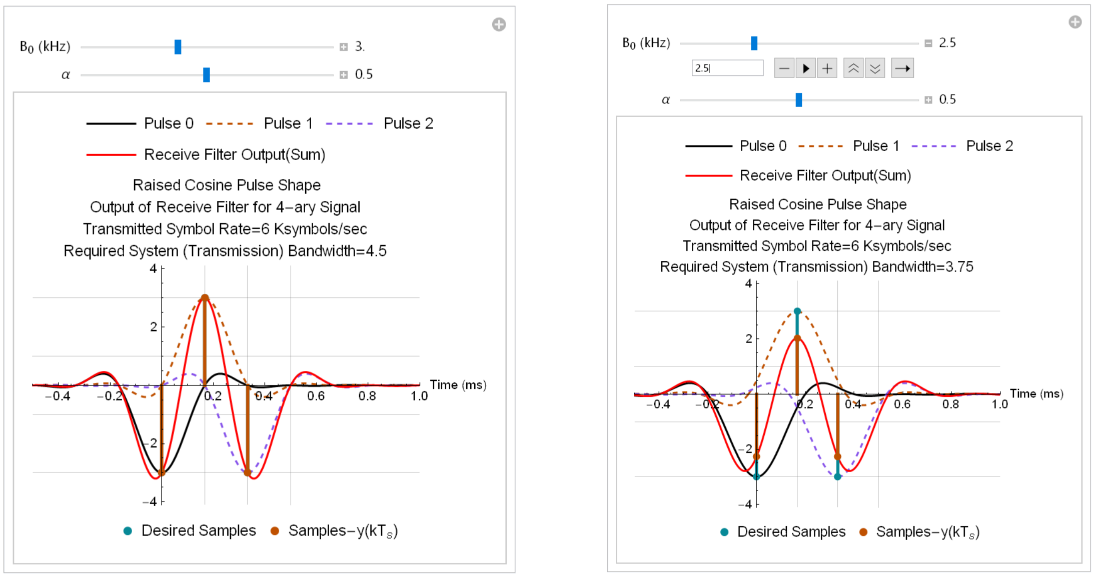

Figure 2 Interactive Demonstration of ISI

Keeping with visualizing ISI, eye diagrams are used to qualitatively examine timing errors and noise margin. An interactive eye diagram is shown in Figure 3; here the impact of ISI, noise and jitter can be visualized.

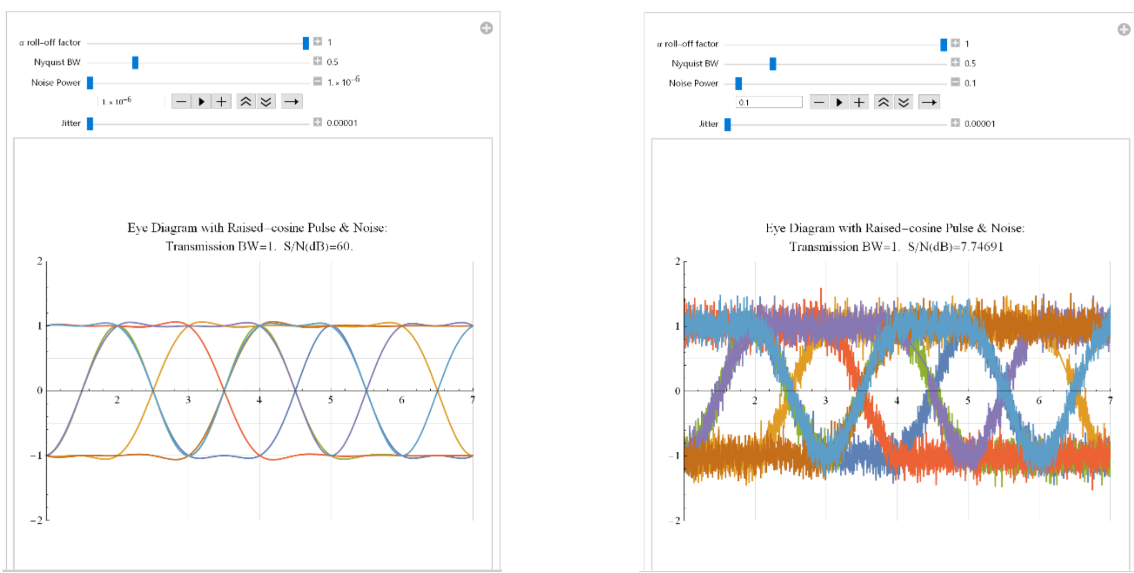

Figure 3 Interactive Eye Diagram

Interactive graphics also help the students see the validity of approximations used in theoretical developments. In Figure 4 the approximation used in the development of the processing gain for FM modulation is shown.

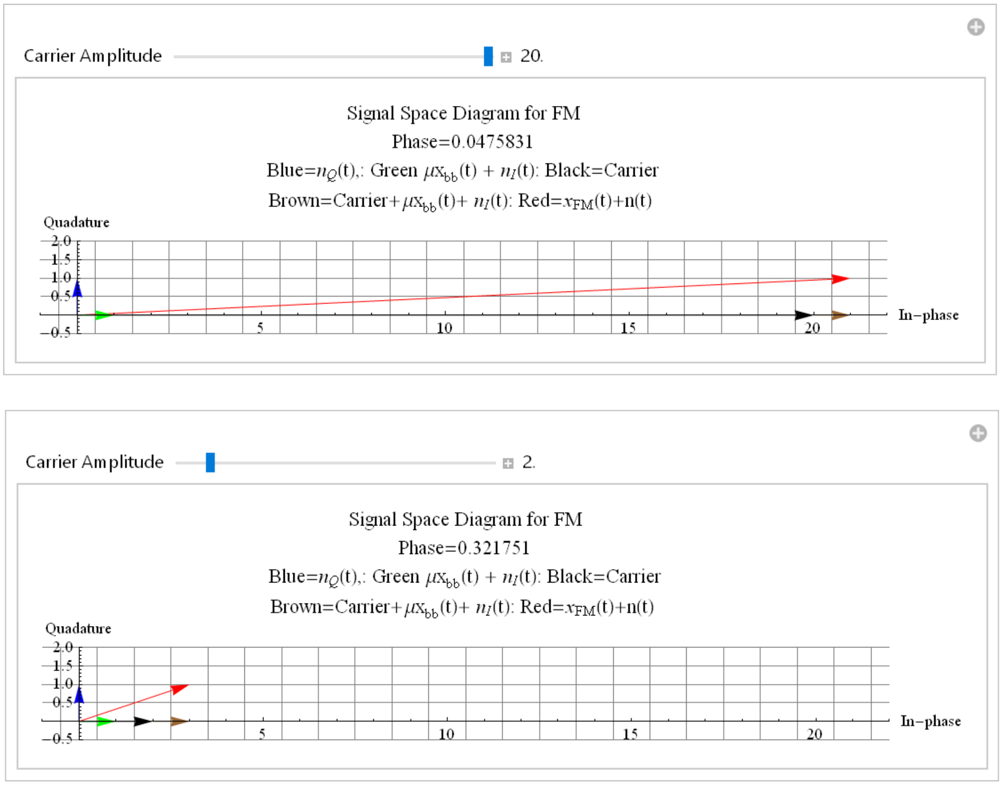

Figure 4 Visualization of an approximation used in FM Demodulation Analysis

The students can also directly see performance trade-offs as a function of systems parameters. The noise performance of FM is given in Figure 5, an interactive plot of the post-detection S/N vs the pre-detection as the FM modulation index is changed by the student. The interactive graphic clearly shows the students the threshold effect and its dependence upon the modulation index.

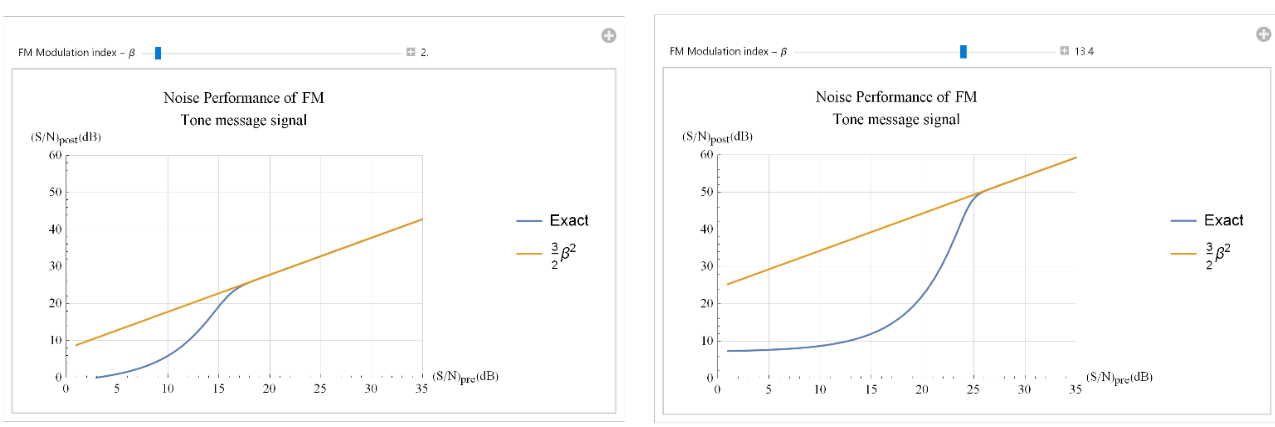

Figure 5 Noise Performance of FM

System trade-offs can be illustrated graphically. Figure 6 shows the received signal power as a function of distance where the system parameters are interactively varied. Figure 6 brings out the effect of the path loss exponent. To enable the students to see the system trade-offs involving antenna gain, the gain of a parabolic reflector antenna was used as a proxy to represent a relationship between normalized antenna size (diameter/wavelength) and antenna gain. In the interactive elements, the calculations are not at all valid if calculated antenna gain is less that 0dB. For a given carrier frequency the students can set the diameter to get a gain of 0dB to model an isotropic antenna.

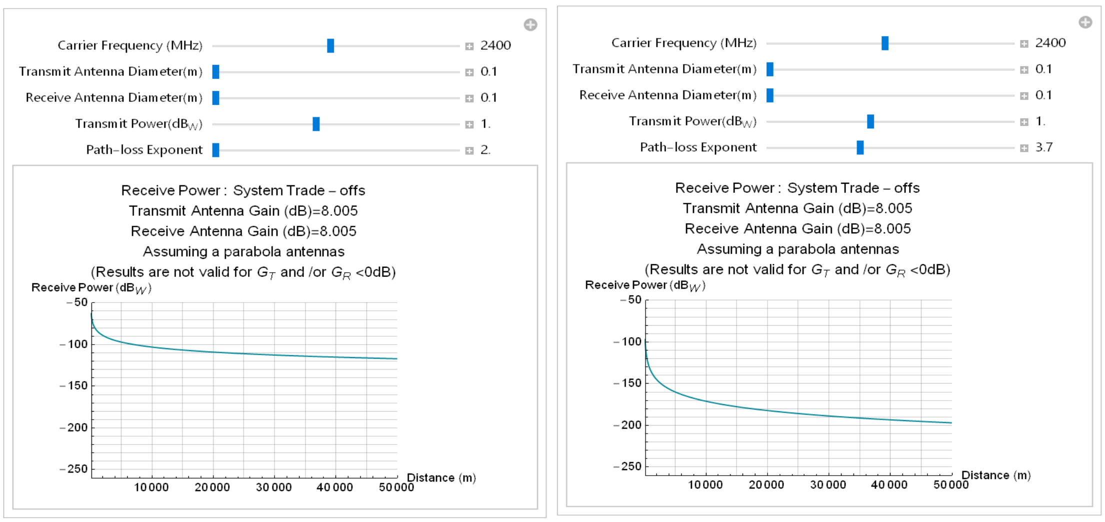

Figure 6 Receive Power vs Distance Trade-off Study

Link budgets are commonly calculated using a spreadsheet. An imbedded interactive table in the ebook provides spreadsheet functionality. A link budget with parameters modeling the

Link Budget
(Results are not valid for G_T and/or G_R <0dB)

f_c(MHz)	7500
λ(m)	0.04
P_T(dB$_W$)	1
Diameter Tx (m)	0.3
Transmit Antenna Gain: G_T(dB)	27.4442
Distance (m)	360 000 000 000
Propagation Exponent	2
Path Loss (dB)	281.069
Diameter Rec (m)	70
Receive Antenna Gain: G_R(dB)	74.8038
P_R(dB$_W$)	−177.821
Noise Figure(dB)	0.29
Equivalent Noise Temp	20.0259
Antenna Temp	100
Bandwidth (MHz)	0.0005
Noise Power(dB$_W$)	−180.819
Margin(dB)	0
(Signal-to-Noise)$_{pre}$(dB)	2.99769

Figure 7 Link Budget with System Parameters Modeling the Perseverance Mars Rover Communications System

Perseverance Mars rover communications system is given in Figure 7 (parameters in black system are user input and red indicates calculated values).

To help the students visualize the detection process for digital RF modulation techniques interactive graphs are included to show the samples of output of the in-phase (I) and quadrature (Q) integrate-and-dump filters. The students can then change to noise variance to see how the spread of the points in the I/Q graphs changes or change the signal amplitude to see how the

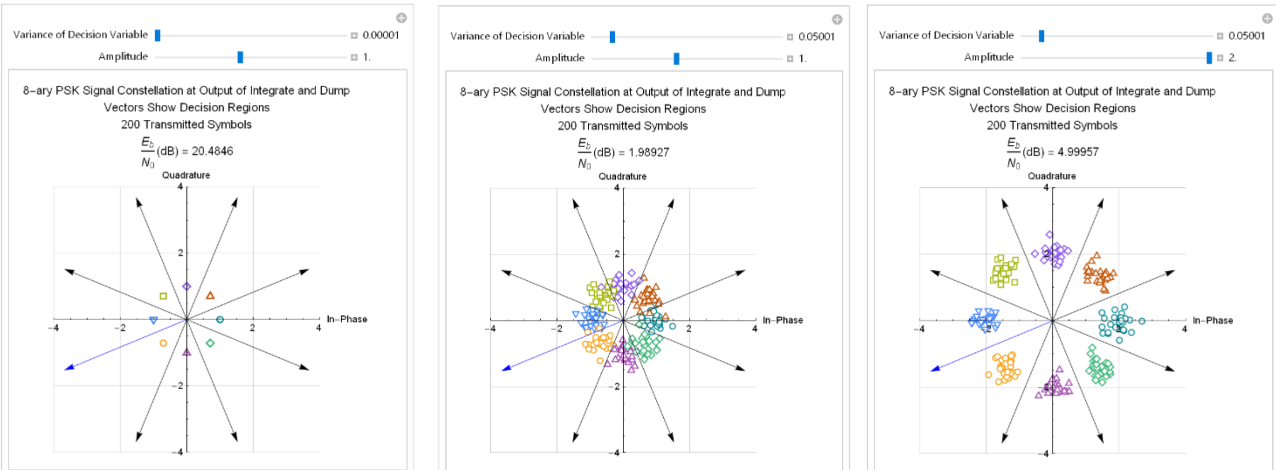

Figure 8 Visualization of Symbol Detection in 8-PSK

signaling point spread out as the signal power is increased; this process enables them to visualize the minimum distance detection algorithm as shown in Figure 8.

The examples discussed above are a few samples of the interactive graphics and dynamic performance metric calculations included in the ebook. The next section presents some examples of the in-line interactive questions include in the ebook.

In-line Interactive Questions

Throughout the ebook the students have an opportunity to answer in-line questions, if the answer is right the ebook will return CORRECT. The students can continue to submit answers until the provide the correct solution. The ebook does not keep track of any student responses; the interactive questions are included to provide rapid feedback regarding their understanding of the material. Broadly, the questions are either True/False or require a numerical solution. The True/False questions often address system performance trends and trade-offs. Figure 9 contains several examples of in-line questions.

Remote Learning

This ebook supported the remote teaching of the fundamental concepts of communications systems in the spring of 2021. The EECS 562 Introduction to Communication Systems at the University of Kansas is a four-hour class including a laboratory. For many years the existing laboratory used the TIMS (Telecommunication Instructional Modelling System) system from Emona see: https://www.emona-tims.com/emona-product/advanced-lab-teaching/. In the spring of 2021 the class had students attending the lectures and laboratory in-person as well as some individuals who could only attend both remotely.

The in-line questions, examples and homework as well as using the "Classic Slide Show" functionality used during lectures was aimed at improving the Zoom experience for the remote learners. Remote access to laboratory experiments using real hardware was enabled by using the Emona net*TIMS FreeWire system see [19] https://www.emona-tims.com/emona-product/nettims-freewire/. The Emona net*TIMS FreeWire hardware system physically located on campus (in the EECS 562 Laboratory) provides users with real-time control and measurement of real hardware elements of a communications system over the internet. Users access the Emona net*TIMS FreeWire hardware over the Internet using common web browsers. Users configure elements of a communications system, e.g., oscillators, multiplers, noise sources, and filters, creating an end-to-end communications system, e.g., a BPSK transmitter receiver using the same methods as the in-person students. The students physically in the laboratory plug the module together using patch cables, the remote learners connect the modules using a point and click. The Emona net*TIMS FreeWire system includes oscilloscope and spectrum analyzer functionality to

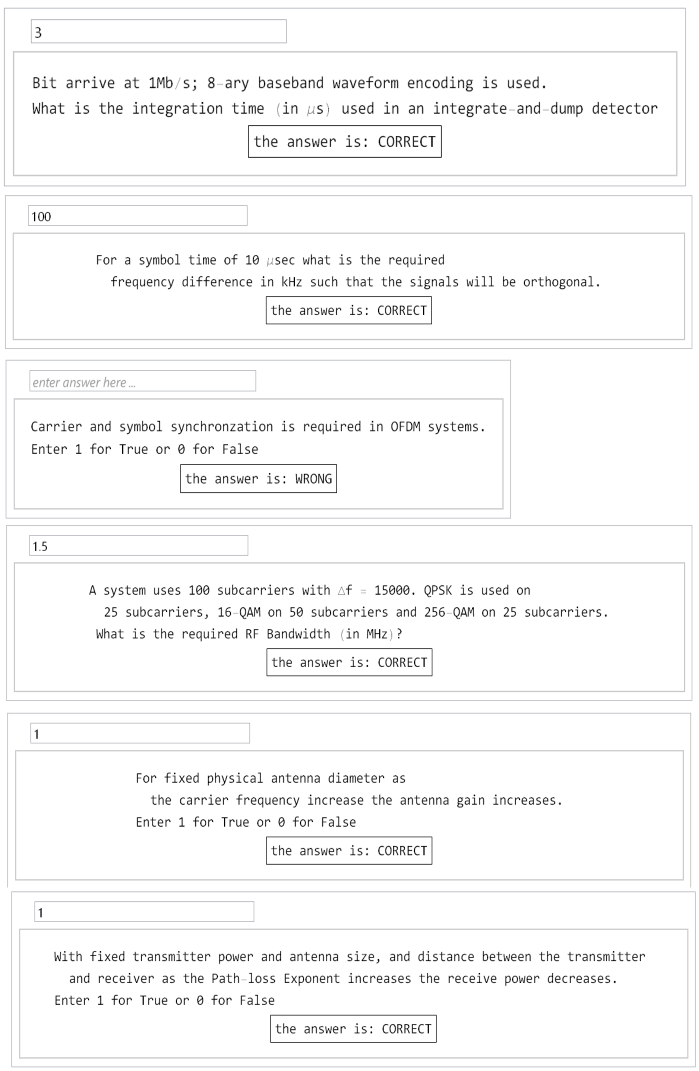

Figure 9 Examples of In-line Interactive Questions

measure system performance. Six new laboratory experiments were written for the net*TIMS FreeWire to ensure that the remote learners had a laboratory experience comparable to the in-person students. These experiments are included as an appendix in the ebook.

Conclusions

Active engagement of students in the learning of the basic concepts of communications systems is facilitated by the free open source, open content, and open access electronic textbook described above. The ebook also used a different approach to teaching the subject; introducing digital modulation, especially OFDM as quickly as possible. Highlighting communication system design trade-offs are also a focus of the ebook. This ebook combined with the Emona net*TIMS FreeWire experiments provided an avenue for offering lectures and a laboratory experience to a combination of in-person and on-line learners.

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