

The role of Matlab and Simulink in teaching communications

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ABSTRACT

This paper describes the use of the Matlab and Simulink[®] environment in the process of teaching and learning digital communications. Communications, unlike networking, requires knowledge from many more disciplines, furthermore they all require some mathematical background. The number of component blocks in communication systems can be large unlike TCP/IP networking which sits below socket-based applications and over ready-designed link layer technologies. This makes understanding of networking relatively straightforward, this is not to say its configuration or operation is at all simple. In communications some blocks operate in the analog domain, whilst others in the digital domain and often blocks are optional or interchangeable. Simulation and modeling tools can help in the communications domain, their use also has well known advantages in the teaching and learning process. In this paper we give a *technical* description of the main concepts within communications using simulation and modeling tools based on Matlab and Simulink. We show how it eases the tasks of both student and teacher and illustrate the usefulness with some examples used in the faculty of engineering at the university of Porto, Portugal.

1. INTRODUCTION

There are a number of reasons for the inclusion of Matlab and Simulink into a communications course. One of the main problems in teaching wireless courses is the required scope and depth of the mathematics needed. Matlab and Simulink can help to illustrate the mathematical principles via numerical simulations or readily constructed solutions, complementing the theory taught in class. Another reason is to study the many parts of a communication system *separately*. Due to the numerous sequential blocks in a system, often mirrored from sender to receiver it is possible to study the operation or performance of one slice in isolation. A typical structure is shown in figure 1, the system with

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some abstraction, can be studied between any two blocks in the top and bottom halves of the figure. Matlab and Simulink have ready made blocks for the lower level components not explicitly chosen. From a pedagogical perspective,

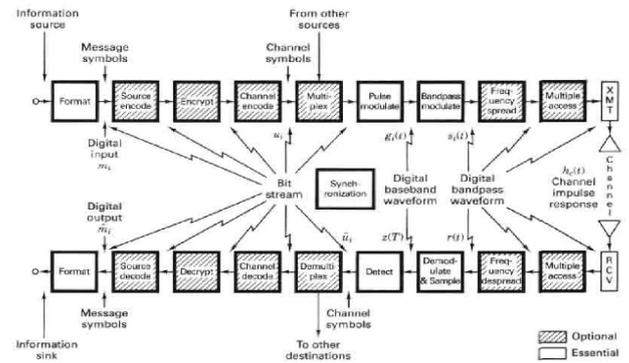


Figure 1: Block diagram of typical digital communication system [Sklar]

Matlab and Simulink use aids the lecturer by providing examples in class quickly and easily. With a small amount of knowledge sample scripts and blocks can be easily readied for demonstrations. More in-depth scenarios can be used in practical/laboratory sessions. Both Matlab and Simulink consist of a large number of ready made components to construct both analog and digital systems. Furthermore there are tools which aid in the performance and understanding of the systems under study, we will see some of these in section 4.5. From a practical point of view, particularly in wireless communication, analytical solutions may be intractable or be very tedious to derive and hence simulation approaches need to be used. We will not delve deeper into the theory vs. simulation, however Matlab and Simulink can provide (the only) solutions to difficult theoretical problems.

2. TYPICAL COURSE STRUCTURE

In this section we give a brief (and general) overview of the topics typically taught in a communications course. In order to make the concepts a little clearer, we need to explain the concepts of bandpass, baseband and modulation. A bandpass signal is obtained by modulating a baseband analog or digital signal onto a carrier. A baseband waveform has a spectral magnitude that is nonzero for frequencies in the vicinity of the origin ($f = 0$) and zero elsewhere. A bandpass waveform has a spectral magnitude that is nonzero for

frequencies in some band concentrated around a frequency $f = \pm f_c$ where $f_c \gg 0$, f_c is called the carrier frequency. Modulation is the process of modifying the source information onto a bandpass signal with a carrier frequency f_c by the introduction of amplitude or phase changes (sometimes both). The bandpass signal is called the modulated signal and the baseband source signal is called the modulating signal. Usually the teaching of communications at the undergraduate level is split over two semesters for electrical engineering students. Below is a selection of units/modules that typically compromise all but the most esoteric of communications courses.

1. **Signals and systems.** Sometimes known as signals and spectra. The traditional approach of teaching digital communications uses both time (temporal) and frequency (spectral) representations of the signals, with emphasis on the frequency domain. Students are often exposed to the transmission of signals through Linear Time Invariant (LTI) systems. Additional required material including random processes, autocorrelation, spectra of signals (PSD) and convolution are usually introduced in the first phase of communications courses.
2. **Baseband transmission.** Baseband modulation and demodulation over non-noisy and additive white Gaussian noise (AWGN) channels. The simpler cases of binary modulations are usually considered first. The channel may be presented as a filter and its effect on the signal in terms of distortion analyzed. Bandlimited channels may be included. More detailed courses may include intersymbol interference, the Nyquist distortionless criterion and an introduction to channel equalization.
3. **Analog modulation.** The aim is to transmit an analog signal over a transmission channel. The amplitude, frequency or phase of a baseband signal can be modulated according to a carrier which is chosen to propagate *best* over a given medium, e.g. the atmosphere in AM radio transmission. Different variants on amplitude modulation exist whilst frequency or phase somewhat less so.
4. **Analog to digital conversion.** Typically includes sampling and quantization, with lossy Pulse Coded Modulation (PCM) techniques and lossless ones such as Huffman coding. In the lossy quantization a number of quantizers might be taught such as differential, adaptive and non-linear forms.
5. **Digital modulation.** In digital modulation, an analog carrier signal is modulated by a digital bitstream. Digital modulation methods can be considered as digital to analog conversion, and the corresponding demodulation or detection as analog to digital conversion. The changes in the carrier signal are chosen from a finite number of M alternative symbols. The simplest case is for $M = 2$ which results in binary modulation. The most fundamental digital modulation techniques are based on so called "keying". In the case of phase shift keying, a finite number of phases are used the simplest being BPSK for $M = 2$.

6. **Passband transmission.** Passband digital communication typically includes the geometric representation of signals, correlation receivers and communications performance in terms of error rates and bandwidth.

7. **Line coding (optional)** Digital baseband modulation is known as line coding, basic ones include return to zero (RZ), non-return to zero (NRZ).

In a second semester, the following topics may be covered. Typically topics within wireless communications are considered as part of a second course.

1. **Link budget analysis (optional).** Sometimes known as communications link analysis. It deals with the attenuation of the signal, free space and sources of noise. Some courses introduce the E_b/N_0 metric which is the bit energy per noise spectral density (PSD). Topics such as noise temperature and line losses are included, for engineers of systems this is an important unit.
2. **Channel capacity (optional).** Determining the capacity of a channel, either ideal or noisy is fundamental in communication theory. Concepts developed by Shannon are taught via information theory and illustrated through examples. Also the earlier taught concepts of probability are revisited, conditional probabilities and entropy.
3. **Channel coding.** In digital communications, a channel code is a term referring to a forward error correction (FEC) code and bit interleaving. The concept of avoiding ARQ strategies via sending redundant data (the code) or interleaving the data over time and/or frequency is known as channel coding. Noise and interference is the source of impairments leading to losses when considering random channels.
4. **Spread spectrum systems.** The underlying technique in 802.11 and CDMA systems. Typically taught in a second course on communications. Spread spectrum techniques permit multiple access, through terminals using the same frequency band, by using different spreading codes.
5. **OFDM.** A number of orthogonal subcarriers are used to carry data. The data is divided into parallel data streams, one for each subcarrier. Each subcarrier is modulated with a conventional modulation scheme at low symbol rates to maintain data rates similar to conventional schemes. OFDM provides good mitigation of fading effects due to multipath effects. Normally features wholly or in part, in 2nd semester courses.
6. **Fading channels (optional).** Depending on the obstructions between sender and receiver antennae, varying signal attenuations may occur, statistical studies of the properties of such channels are part of a fading channel unit. Time varying systems may be introduced in the case of user mobility as well as the mitigation of fading effects such as OFDM.

- MIMO (optional).** Multiple Input, Multiple Output systems, where spatial diversity is achieved through using more than one antenna. Many of the principles of the earlier discussions can be generalized to the case of multiple send and receiver antennae, relies heavily on linear algebra and information theory.

3. MATLAB AND SIMULINK'S FEATURES

Many networking engineers are familiar with Matlab as a tool for linear algebra, however the toolboxes are not always known. One of the reasons is cost, as each must be purchased separately. The toolboxes extend Matlab's abilities into application specific domains. For example The communications toolbox has many functions for the design of the physical layer of communications links such as: source and channel coding, interleaving, modulation, channel models, and equalization. The conjunction of Matlab's ease of use, speed and familiarity with the numerous toolboxes make it an attractive option for teaching. There are 66 examples and 24 demonstrations within Matlab's standard communication distribution. Simulink in many respects mirrors the

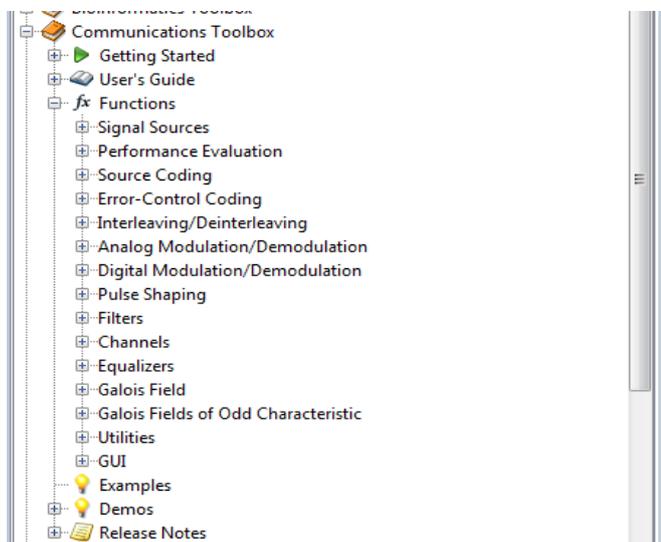


Figure 2: Matlab's communication toolbox.

functionality of Matlab. All of the functionality in the toolboxes are available in Simulink. Their roles however are quite different, one being a scripting language with a focus on data types and processing routines, whilst Simulink is a design tool. Within Simulink there are 44 examples and 50 demonstrations, The thought process behind Simulink is very much as operational blocks. Input and output is typically viewed graphically, via presentation "scopes" with heavy processing performed in Matlab. Simulink's included libraries are customizable blocks.

3.1 As a modeling tool

Matlab and Simulink provide (potentially) many levels of abstraction. This is without resorting to programming many lines of computer code and hence keeps programs short and illustrative. Referring back to figure 1 and depending on the level needed, a communication system can be constructed with minimal effort. That said, the level of abstraction of a

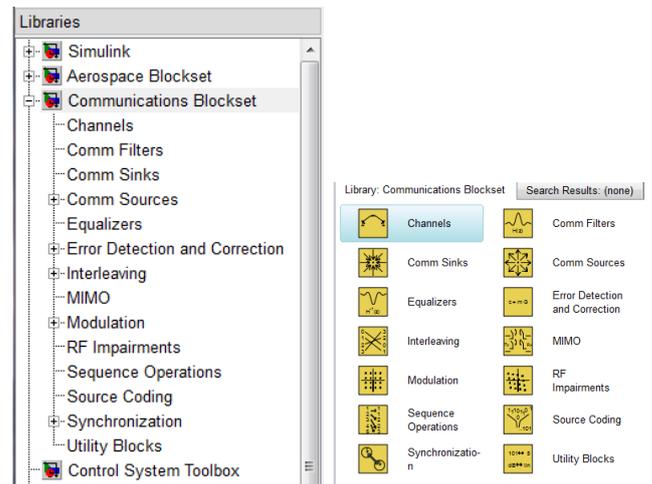


Figure 3: Simulink blocksets

single block may vary considerably, for example the number of samples in a rectangular pulse (`rectpulse`) to the wireless channels types (`Rayleigh/Rician`). Modeling in Simulink is somewhat easier than in Matlab. This is due to its graphical nature and the block orientated design is more intuitive for the user. In many cases a combination of Simulink and Matlab are needed as Simulink is a time domain tool. Simulink can save variables to the Matlab workspace, however it is more common to execute a Matlab script that in turn runs a Simulink block.

3.2 As a learning tool

Many students find the hands on experience of writing, executing and testing scripts very valuable in learning communications. It solidifies taught ideas or can provide a new insight that some students did not obtain due to the mathematical explanation. Alternative ways of seeing the same scenario is always recommended in good pedagogy. This is something students have found instructive in class, usually prompting more questions after a short demonstration. At the university of Porto, an example is typically give at the end of a lecture, whilst the laboratories explore the concepts further. Students are given pdf guides on the topic as well as question and answer sheets to be completed during the session and comprise part of the final grade. The same lecturer is present in the laboratory sessions to guide and answer any questions.

3.3 As a fast experimental tool

Matlab uses an interpreter, thereby on avoids the edit → compile → link → development cycle with compiled computer languages. However it is still possible to compile Simulink blocks into so called "accelerate" mode using existing libraries with Microsoft's Visual C++ suite. This gives the best of both worlds, fast development in a learning environment, and fast execution in computationally heavier situations where native code outperforms line by line interpreted results. Matlab can link with parallelized libraries using multi-CPU and multi-core machines. Fast development actively encourages experimenting with problems and assists in the "what-ifs" commonplace in communications.

4. EXAMPLES

We now present some examples using Matlab and Simulink to show how communications principles can be taught.

4.1 Signal representation

The power spectral density (PSD) is a function of a frequency variable associated of a stationary stochastic process with dimensions of power per Hz. The spectral density is a measure of the frequency content of a stochastic process. It is used in communication systems to identify periodicities in the signal. An example is shown in figure 4. To show the frequency response of time domain data it is necessary to switch to Matlab, as Simulink only works with time domain data. Power spectra related to signals are very commonplace in fixed and wireless communications.

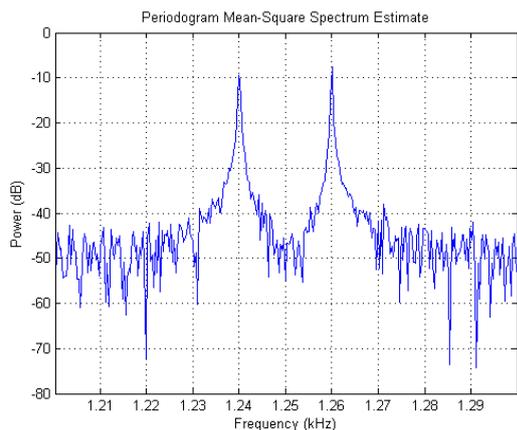


Figure 4: Power spectral density.

4.2 Analog modulation

In analog amplitude modulation (AM) the amplitude of the carrier signal is varied in accordance with the instantaneous amplitude of the modulating signal. Modulation is the process of encoding the source information, the modulating signal, into a bandpass signal the modulated signal. Shown below is an amplitude modulation signal example:

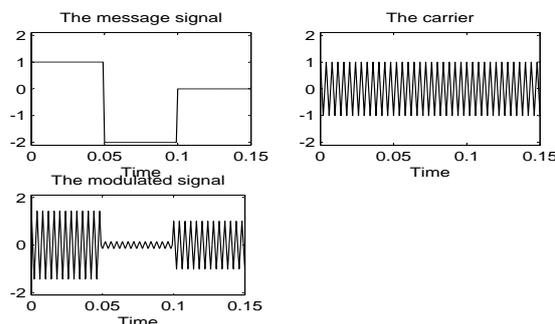


Figure 5: Analog modulation

4.3 Digital modulation

In Simulink it is straightforward to show the principles of digital modulation, in this case digital quadrature amplitude modulation. We use the M-QAM modulator baseband block to modulate random data, once the symbols have passed through a noisy channel, the model produces a scatter diagram of the data. The diagram shows the underlying signal constellation and importantly how the noise distorts the modulated signal from the constellation. The blockset used to create the scope is shown too.

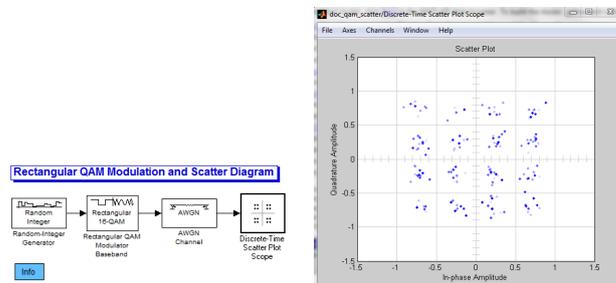


Figure 6: Digital demodulation in the presence of noise.

4.4 Quantization

Media files can also be used as an input to a simulation to provide a perceptible assessment of the performance of a digital communication system. For example, μ -law companding (nonlinear compression and expansion) of a speech signal for pulse code modulation (PCM) is often found in many texts. An analysis of the bit error rate in pulse code modulation (PCM) over a AWGN can also be presented with the audible performance. An example is shown in figure 7. The original

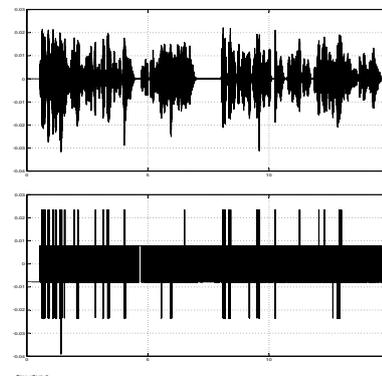


Figure 7: The effects of noise on transmitting an audio file over a channel. Upper the original samples, Lower the received samples.

and received samples are replayed for the student to listen to. In the laboratory parameters of the channel are changed with a statistical analysis required.

4.5 Performance tools

which help the design process such as bit error analysis, eye diagrams, trajectory and scatter plots make the learning process more accessible for the student.

BERTool. The discrete time eye scope displays multiple traces of a modulated signal to reveal the modulation characteristics such as pulse shaping, as well as channel distortions of the signal. BERTool has a graphical user interface (GUI) that enables one to analyze BER performance of communications systems as shown in 8.

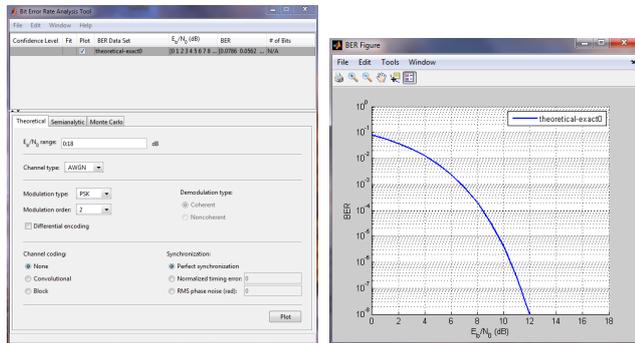


Figure 8: BERTool configuration and related plot

Eye scope. An eye diagram is a tool for studying the effects of intersymbol interference and other channel impairments in digital transmission. The procedure to construct an eye diagram is to plot the received signal against time on a fixed-interval axis. This is repeated at the end of the fixed time interval, the result is many overlapping plots, figure 9 shows 100 such plots.

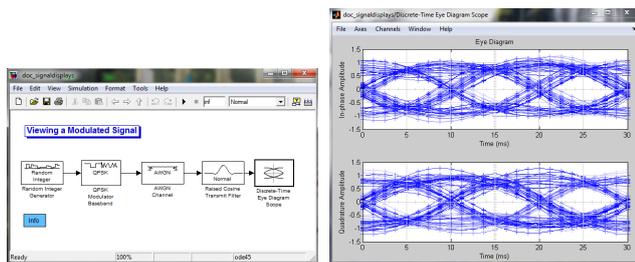


Figure 9: Simulink blockset and eye plot.

Trajectory/scatter scopes The discrete time scatter plot scope displays plots of a modulated signal to reveal the modulation characteristics, such as pulse shaping or channel distortions of the signal. As with the eye scope it is possible to view current scatter plot and previous ones. One difference between the trajectory and scatter scopes is the trajectory which connects the points.

5. FROM A TEACHING STANDPOINT

From a teacher’s perspective the use of Matlab and Simulink has a number of advantages:

- Give a different perspective of the problem
- Give the students a (half-constructed) base to work from
- Show the student the benefit of “what ifs” in design

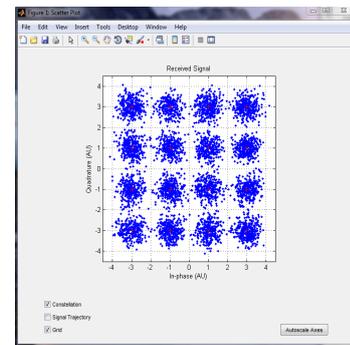


Figure 10: Scatter plot (with noise)

- Allow the students to make measurements and statistical studies of systems
- Convert the theoretical results to blocks, adding an engineering touch
- Ask the students to build complex blocks from simpler ones, underpinning important principles (not using the more complex ones immediately)
- Encourage interaction and collaboration with each other
- Fast speed of learning
- Show a complete system at the end of a course, to bring the ideas together
- Use the animation aspects, to show plots on top of each other (e.g. scatter)
- Show graphically the operation at hand

6. STUDENTS PERSPECTIVE

Scope of subjects needed: One of the main difficulties in learning communications in depth is the number, scope and depth of the disciplines needed. The learning process is exacerbated when simulation is used, which brings in topics from computer science as well. A short list of topics includes; communication theory, digital signal processing, probability theory, estimation theory, computer science, stochastic process theory, number theory, numerical analysis and linear system theory [TSRK03].

Difficulties: More specifically, when learning communications, the complex baseband representation can cause some difficulties. Additionally the role of noise causes some problems in understanding the effects. Simulation can help in these areas.

Experimentation: The students obtain a feel for communication system through demonstrations from the teacher in class. After providing the background and theory, demonstrations enhance the understanding. In laboratory sessions, the students explore the ‘what ifs’ by changing the parameters in the scripts or in Simulink blocks. The block orientated, time orientated design of Simulink provides enormous time savings. A conservative estimate compared to build oneself tools are a twenty to fifty times faster. This is partly due to the graphical, design-friendly interface, but

also due to the immediate error checking, unlike a compiled native code simulator. Large libraries of existing *working* code helps the students, where they can modify existing code or modify working blocks.

7. FACULTY OF ENGINEERING COURSES

At the faculty of engineering in Oporto, the fundamentals of communications is split across two semesters. The first covers the basics of transmission, in particular the basics of signals and spectra, analog and digital modulation, quantization and sampling, baseband digital communication and passband digital communication. The course is run as lectures with short demonstrations at the end of most lectures. The laboratory sessions build on what has been taught and shown in the lecture. The second semester covers synchronization in digital modulations, including carrier phase recovery and recovering symbol timing. Spread spectrum techniques, including Direct Sequence Spread Spectrum (DSSS) and spread spectrum frequency hopping (SSFH). Some coverage of Intersymbol interference (ISI), CDMA multiple access, and spreading sequences such as Walsh, Barker and pseudo-random. Fading channels and MIMO are left to communication courses in Oporto.

8. DISCUSSION AND CONCLUSIONS

Extra motivation Critics of slide only material site that little insight or motivation for the student is provided [Sil10]. This is exacerbated by other courses the student may be studying at the same time presenting plentiful examples and applications. Unfortunately communications per se does not offer much in the application context, partly due to the layered structure and partly due to the banal nature of the transfer of bits. More interest therefore is needed for the motivation of students. In the example of quantization, using audio files may help demonstrate the usefulness of alternative presentations, by playing varying levels of distortion due to channel conditions.

Disadvantages We have not discussed the disadvantages of introducing Matlab and Simulink into teaching curricula. One is the examination of the material, although laboratory classes can be graded, it is not easy to examine the students knowledge gained from laboratory sessions. If the class preparation is not performed with balance, it is possible that students loose important problem solving skills in communications. This problem is true in many laboratory-examination courses. It is important to point out that we are not advocating the reduction or replacement of underlying mathematical principles, solely *supplementing* existing methods.

Individual perspective Although we have taken a teacher-student perspective many of the ideas are applicable in an individual setting process. This is important as if individuals can teach themselves communications in a more leisurely manner, they can use Matlab and Simulink as a platform for testing and verifying their ideas. Also for the would-be engineer the scope perspective would be very similar to what a engineer would see in real practical situations.

Further resources In terms of code there are plentiful sources for Matlab and Simulink:

- Book supplements (see below)
- Mathworks extensive help files, examples and demos
- Mathworks user communities (Matlab central)
- Complete working demonstrations

In terms of reference books which focus on teaching communications via Matlab and Simulink there are the following [PS98, Sil09, TSRK03]. They differ in style and approach, [Sil09] concentrates on baseband and bandpass modulation/demodulation and sampling/quantization. [PS98] gives a review of signals and linear systems, random processes, analog modulation, A-D conversion, baseband transmission, as well transmission through bandlimited channels. Digital transmission via carrier modulation and channel capacity and coding are covered. Spread spectrum are included as well as a tutorial on Simulink. In the case of wireless communications, the channel itself can be studied followed from a Matlab and Simulink perspective [FnEn08]. Topics include shadowing effects, coverage and interference and multipath. Also MIMO and OFDM can be studied via a dedicated book [CKY10], which covers propagation and fading channels initially in the SISO case, MIMO channels come next, with OFDM and the important topics of synchronization and channel estimation. Channel capacity is revisited in the MIMO case. Finally the multiuser case is studied. Both these texts can be used in more advanced courses, probably at the post-graduate level due to the mathematical theory needed as well as the simulation approaches.

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