Digital Communication Using GNU Radio

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Week-01

Lecture-01

Welcome to this course on Digital Communication Using GNU Radio. My name is Kumar Appiah and I belong to the Department of Electric Engineering, IIT Bombay. This is the introductory lecture on this course where we are going to look at aspects related to digital communication. We will look at several theoretical aspects and then implement them using simulations on the free and open source software called GNU Radio which will strengthen our understanding and also enable us to quickly prototype several practical systems. So this is the course introduction. We will briefly discuss who will benefit from this course and talk about the prerequisites.

We will then just delve a little bit on the course structure to see what aspects we are going to cover and how we will cover them. We will then talk about analog and digital waveforms and the differences just to revise and set a starting point for us and then I will recommend some references that you can look at as part of this course. This is an introductory course on digital communication. As you are aware, digital communication is powering the modern communication revolution.

I am sure that you are talking to several people on your phones and in fact, the very mode by which these lectures are being delivered to you is being made possible by the developments in the context of digital communication. The fact that we are able to get bits across reliably is something that is very very admirable and how that is being made is something that we are going to look at in this course. Our focus will be on the physical layer. So there is an ISO OSI 7 layer model for communication systems starting with physical layer right up to application layer between this network layer and several other aspects that you can look at. In that context, we are looking at the physical layer.

The job of the physical layer is to get bits across. You can see if you look at now the video or any other transmission that you have, they are all typically packetized and in different formats. For example, video can be in MP4, audio can be in WAV or MP3 or other formats can be text. So that is all application layer and then there is networking related aspects that put these into packets and send them across. But these packets themselves are being delivered in the form of bits across communication channel.

In this course, we will be focusing on the bits being sent and that is called the physical layer. One key differentiator in this course is that not only will we learn the aspects related to digital communication using some maths and theory, we will immediately implement all these things as simulations on the software called GNU radio. GNU radio is a free and open source software that is cross platform available for Mac, Windows, Linux and it's very powerful. It has a drag and drop interface where you can quickly wire together several simulations with great ease. In fact, it is very powerful.

It can even interface with hardware. So you can even build practical systems that transmit over the air and receive over the air as well using GNU radio. So our learning will be strengthened by hands-on learning with GNU radio where all the concepts that we will learn will be implemented on GNU radio as well. As a quick motivation, where do we see digital communication in our daily routine? So over here we can see several evolutions of phones over the past several years which we have seen. For example, you may remember these if you are very young, these were the old wireless phones that used to be there in the 90s and early 2000s.

This was the walkie talkie of even before. Nowadays we have this, but to call this a phone would be a little bit of an understatement. These are actually computers which will also allow you to talk. In fact, the phones that you hold in your hands are much more powerful than the chips that powered rockets maybe 40-50 years back. Now of course, talking to your family and friends is something that is very common and you have been doing that all the time, but these devices are very rich communication devices.

You are able to send text over them, send and receive text. These have now become our payment devices. You are able to interface them with your bank and then send and receive money. You are able to listen to music. Nowadays many people listen to podcasts and you are able to make video calls and all of these things are powered at the base level by digital communication in our daily life.

So in that sense, one of the basic recipes for successfully accomplishing these is the physical layer which is what we are going to study in the course called Digital Communication. In the background what is actually happening? So typically let's say that you want to make a call to your friend or a family member. You make a call, let's say over here, then the call essentially goes to the base station and to the base station the call goes, just so you know today, as bits. It doesn't go as a waveform, it goes as bits. Meaning of course bits are being sent in the form of a waveform, but your speech itself is not directly being sent in the same form.

It is being converted to a certain form of bits. These bits go over a cable backhaul along with several other signals to the base station to which your friend or family member is connected. There it is then directed back to the cell phone in the hands of your friend or family member and there those bits are converted back to your voice and this voice is played out so that your friend can listen to you speak. If it is far away, then there is multiple other backhauls which are possible. Would be a satellite backhaul, so you send this particular signal to a satellite transmitter, transponder, it sends this to the satellite.

Satellite then relays it to another, potentially through another medium to the dish at the other end which then connects back to your friend. In fact satellite calls used to be very popular earlier and there used to also be satellite phones. So, there are many possible methods by which your calls or communication can be established, but all of them or almost all practical systems today, barring a few, directly rely on converting the data to bits and getting them back as bits. Now why is that the case? That is something which we will see. Now who will benefit from this course? This course is primarily targeted at third and fourth year undergraduate students of Electronics and Communication and related streams.

So this Electronics and Communication, Electronics and Telecommunication, Electrical, Electronics, several branches are present, they will all benefit by doing this course. This is also targeted at graduate students pursuing advanced studies in Communication Engineering and you will benefit from looking at some of the advanced topics or the way we cover it in this course and we are also targeting this at industry personnel who are working in Digital Communication, Physical Layer Technologies. The prerequisites are signals and systems, basics of signals, systems, convolution, Fourier transforms, all those. To a reasonable extent digital signal processing because we will rely on some aspects related to sampling and Nyquist theorem. Probability and random processes because we need random processes, power spectral density to comprehend some of the topics.

Optionally it is beneficial if you have seen some basics of analog communication such as you know baseband modulation and single sideband modulation, double sideband modulation but these aspects are not mandatory. We will cover these briefly as part of the course curriculum in this particular course. The way we have structured the course is that we will cover baseband, bandpass modulation, demodulation, equalization, synchronization and advanced topics and applications such as error control coding, quantization and so on. But again the key aspect I want to emphasize that it will not only be theory, immediately after learning a theoretical topic we will be implementing it on GNU Radio in a practical scenario so you can play around with the numbers and comprehend why a certain phenomena is being observed. So we will learn by doing, so I want to emphasize that about 50% of this course will be me building a system on GNU Radio to verify a concept and I want you to also parallelly build the same system on GNU Radio and verify that you are getting the desired results.

Once you get there then you can play around with it and make your own changes to see how it reacts and impacts and this is something that is key to the learning aspects of this course. We will also have traditional as well as some optional programming based assignments wherein you will build some systems on GNU Radio and see how well it works. Now let us just briefly cover analog versus digital signals. As you are aware if you and your friend or let us say your twin want to converse with each other, if you are in close proximity you can just directly talk and the way this waveform essentially is propagating is through air pressure. In fact it is going through the air and the air pressure essentially carries over to the ear of your friend and the friend is able to hear it.

If you are far away then you will realize that if you are in a room or outside very far away communicating over an air medium is very bad because it is very lossy and the signal gets spread and lost. So one way to address this is to have something like a microphone and speaker maybe with a small amplifier there it is highly directed. So your signal is being taken by the microphone which is also called a transducer because it converts energy from one form to the other. It converts your audio to an electrical signal. The electrical signal can then be transmitted over a wire and then again there is a transducer which is a speaker which can convert the electrical signal back to an audio signal.

This is a much much better way to communicate audio over longer distances. In fact therefore we need different media to transmit signals under different scenarios based on the need. So analog versus digital what would we have? See if you look at an analog waveform you are able to have all sorts of variations and in fact it is real valued and you have all sorts of variations that can be put there. But a digital waveform looks pretty simple and you know in fact less capable so to speak because this particular example digital waveform can only represent zeros and ones. So this is 1 0 1 1 0 1 1 0 1 0 1 0.

So it is very limited in terms of what it can do. But still we are saying digital communication we want to prefer digital. Why? Let us do a small exercise. This is a painting of a lady which you have a pencil sketch let us say and it is a big pencil sketch. You can here see some details about the way the artist has sketched the painting and you can see a small plant over here.

You can see a small building and you can see some trees and everything. You can see how her hands are folded and things like that. This is very good. This can be a proxy for the continuous waveform.

Let us make this smaller. If you make it smaller you can clearly see the lady, you can see the building somewhat, you can see this plant somewhat but the details seem to be lost. Let us say I want you to give me all the details from this image. In this image you can make out that there is a lady but the details are almost lost because there is hardly anything that can be seen. If you make it even smaller then you can almost not even make out what was in the image and all the details get lost. What I want to point out is that if you have a continuous time signal or the real signal the problem is that there are an infinite set of possibilities that it can hold and as you make it weaker and weaker or smaller and smaller, let's say in amplitude or in terms of your discernibility, it's very very difficult to tell what it is.

Let me instead give you a parallel exercise. Let us say that you want to discern black or white. So you have a square which is black. I show you this.

You say it's a black square. I walk far away and show you this. Is it black or white? You can still say it is black. I walk further away, I ask you if it is black or white. You say still it is black. Even at the smallest level, if you compare the black square and white square, you can still tell that it's black or white.

Why? In the first example, I asked you to discern one of an infinite set of possibilities. This can have a lady, this can have a tiger, this can have a building, this can have any kind of possibilities. But over here I asked you to choose between two. Is it fully black or fully white? It turns out that telling whether a signal is fully black or fully white is much much more reliable than telling whether, you know, than finding out what there was from an infinite set of possibilities. Of course, we have significantly dumbed down the detail to only one particular value and there is a price to pay.

That is, here you can make out a lot of information, here you can only make out one yes or no answer. But the reliability which you get by going with this approach makes this preferable as we will see. So if you now look at analog versus digital waveforms, you can see that, you know, just like the previous example, even if the amplitude reduces, the amplitude reduces over here, you sort of lose the details in the waveform. But if you look at this particular part, even if you lose the amplitude, you are still able to tell where the ups and downs are. So discerning analog signals is much more difficult because of the wide variety of possibilities than a comparable digital signal and that is the key aspect that we are trying to emphasize here, which is one motivation as to why digital communication can be considered preferable.

So almost all communication systems will have the impact of noise. So if you further couple noise onto this digital versus analog problem, in the case of the analog signal, the noise causes the signal to become very, very bad. If it's a weak signal with noise, it's not even easy to discern. But over here, with noise even, you know, I mean, of course the noise is very limited, you can still discern the highs or lows, of course.

It's not always the case. There is, if you give enough noise, then of course you lose the signal. But even with noise, discerning whether it's a high or a low is easier than discerning the full spectrum of possibilities of the waveform that you can have. Let us quickly go over the course outline. So in terms of the course outline, what we are going to see is this. Let's say that there is a signal, an analog signal or some signal that you want to transmit, it wants to be received or seen or heard at the receiver.

Now we'll first recap properties and signal, you know, properties of signals. We also motivate why we want to use digital. And we will then look at how we can convert signals to bits, bits to waveforms, transmit them, convert the waveforms back to bits and bits back to data signal. That is, our aim is to take bits, convert them to waveform because finally we can only send real signals over wires or over the air or over optical fibers. So the question is how do we convert these bits back to waveforms? Now the difference between the waveform we saw earlier and this waveform is that this waveform has a finite set of possibilities.

It's only a few waveforms depending on the bit pattern as opposed to the full spectrum of possibilities. So the aspect of converting these bits to waveform is modulation or digital modulation and converting them from the waveform back to bits is demodulation. This is something we will spend a significant amount of time on in this course. And we will then look at some other aspects which are related to channels and practical aspects. Almost every communication system that you will have is going to have channel and noise.

So you will have to have this waveform correction as well. So you have to correct for the channels by using equalization or potentially detect the bits sent in a different way. And we will also have a look at redundancy for robustness. In particular we will see how even in the presence of noise which change your bits you can still add redundancy and get back your bits. For that we will use error control coding to find out how you can add redundancy in a controlled manner.

We will also see the limits of these error control codes and what the capacity of the channel is in terms of the maximum rate that you can send. To summarize, this course will be on practical aspects of digital communication that you will do. There are several books that you can refer for various topics. I recommend these books, Fundamentals of Digital Communication by Proakis and Salehi, Digital Communication by Haykin and Principles of Digital Communication by Gallager. All of these are good references, optional but I strongly suggest that you choose some of these for various topics and learn them so that it reinforces the aspects discussed in this course.

So from the next lecture we will start with the basics of digital communication and I strongly recommend that you install GNU Radio on your computer and try the GNU Radio related experiments as and when we learn. Thank you. Thank you.