CMOS RF Integrated Circuits
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Module - 1
Introduction
Lecture - 1
RF System - Basic Architectures

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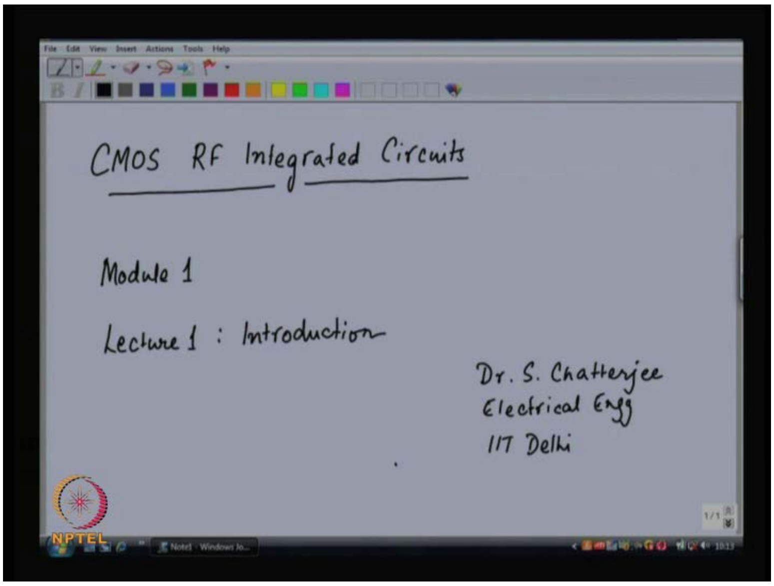

Hello everybody. This is a course on CMOS RF integrated circuits. And I am Doctor S. Chatterjee from IIT Delhi. So, this particular course will focus on the three sets of words that we have over here. The first word is CMOS; the second one is RF; and the third phrase is integrated circuits. So, we are going to be dealing with integrated circuits number 1 for radio frequencies. And secondly, we are going to be making sure that, all of these integrated circuits are for CMOS technologies; that is, complementary metal oxide semiconductor devices will be there all over the place. So, this is the basic understanding of the course. Number 1 is CMOS integrated circuits; and then, of course, it is radio frequencies.

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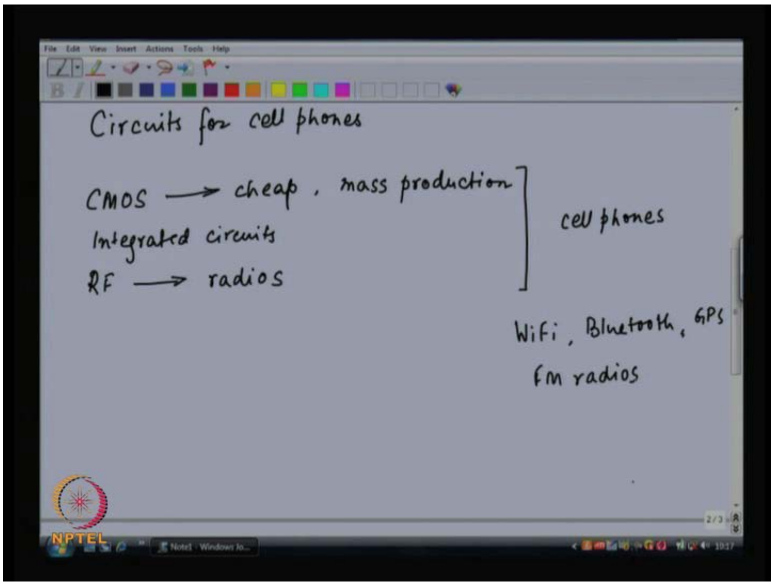

So, another way of naming this course would be to call it circuits for cell phones. So, you may or may not appreciate why I am saying this; why I am calling this course circuits for cell phones; but, it is like this. The word CMOS implies that, it has got to be cheap and it has got to be mass produced – suitable for mass production. The second important phrase – integrated circuits implies that, the course has to be about things that are extremely highly integrated – highly integrated circuits. So, it has got to be cheap; it has got to be mass produced; it has got to be integrated. The third thing is radio frequencies. So, all radios come under this category.

So, what are cheap mass produced integrated circuits that are also radios? Cell phones; cell phones are the largest market ever; and largest electronic market ever is in cell phones. And these are becoming tiny, compact. So, they are highly integrated; they are cheap. Everyday cell phones are becoming cheaper and cheaper. And of course, there are extremely efficient radios insides cell phones. So, this course in other words is going to be about circuits for cell phones. So, yes, we are going to call it this fancy name – CMOS RF integrated circuits. But, in other words, this course is going to be about circuits for cell phones.

So, now, that we understand this, let us go back. What else are we going to cover? Is it just cell phones or a few other applications also? Not many more. So, apart from cell phones, maybe the other radios that I can think of – that are also cheap and mass produced are WiFi, may be Bluetooth, may be GPS. So, a few more here and there – may be FM radios. So, not many more other than cell phones. Now what is going to be the basic architecture of a radio that has a transmitter or a receiver? A cell phone has a transmitter and a receiver; FM radio has only a receiver. The cell phone has a transmitter and a receiver. We are mostly going to be talking about the handheld unit for the cell phone. So, the phone, not the base station; the base station need not be integrated; the base station need not be compact; and the base station need not be cheap. So, it does not qualify the requirements of this course. Then, it has got to be cheap; it has got to be compact; and it has got to be a radio. So, the base station is a radio, but not the other two. So, we are going to focus on the cell phone handheld client – the mobile unit.

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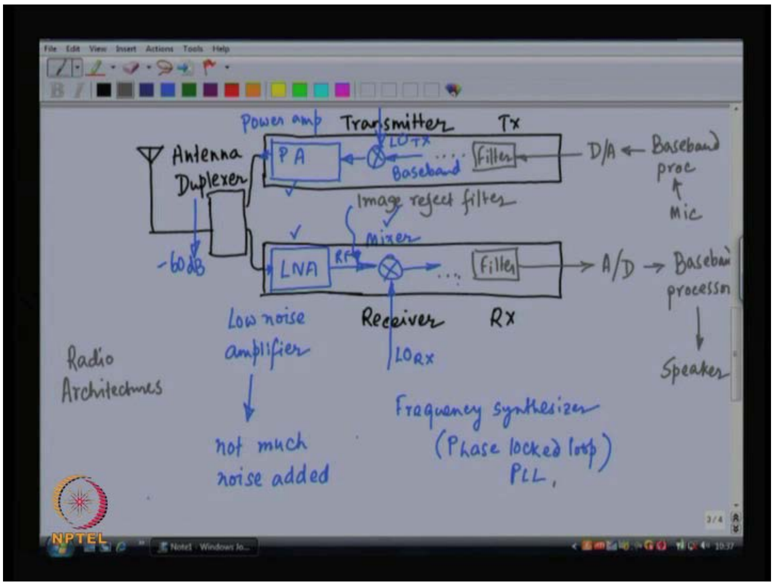

So, what does it have? The first and for most thing that it has is something called an antenna. This is the symbol for the antenna. The cell phone has inside it an antenna. This is not going to be part of our course. The discussion of the antenna is not going to be part of this course. Now, there is a transmitter and there is a receiver. So, abbreviations that will be used routinely in this course are Tx for transmit; Rx for receive; anyway. So, there is a transmitter; there is a receiver; both are going to be using the same antenna. How is it possible? How can both the transmitter and the receiver use the same antenna? Now, for this, there is something; it is like a switch; it is called a duplexer. Now, this switch separates the transmit path from the receive path. So, this is commonly used. Unfortunately, this is also not going to be part of our course.

In fact, theories behind the duplexer are mostly not going to be covered in any electrical engineering course at all; it is a mechanical component. So, it is something; it could be a piezo; not a piezo; a surface acoustic wave kind of component; it could be a piezo-related something; it could be a crystal; a MEMS component. Invariably, it is not going to be electronic at all. It is a mechanical component; it is a mechanical switch. The reason why is that, you really need to isolate the transmitter from the receiver; otherwise, the receiver will hear everything that the transmitter is broadcasting. Instead of receiving, what your friend wants to tell you, you are going to hear your own voice – the echo of your own voice.

So, that is why this duplexer has to be a very good duplexer – something that separates the transmit chain from the receive chain; it could be a filter; in which case, it has to have an extremely good isolation. It could be a switch maybe when the transmitter is working, the receiver is not working. In that case also, it has to have very low attenuation; typically, it is a semi-mechanical switch; anyway. So, we are not going to talk about the duplexer in this course at all.

Let us look at the receiver side now. What do I need once I have isolated the transmit from the receive path? The first thing that you need is something called a low noise amplifier. It has got to be an amplifier. You are receiving a tiny signal from the atmosphere. And this tiny signal has to be amplified, so that you can make sense of what was spoken on the other side. So, it has got to be an amplifier. Second thing is it has to be low noise. Low noise here means that, it does not add too much noise on its own. I need you to understand this sentence. A low noise amplifier does not add too much noise; does not add much noise. Now, common parlance would tell you that, probably a low noise amplifier throws out the noise and keeps the signal? No, you can throw out the noise. Once there is noise in the system, it cannot be rejected. Therefore, a low noise amplifier cannot throw out the noise and keep the signal; it has to handle both the noise and the signal that it has already received.

What it does? Every system unless it is a passive lossless system, every other system adds noise. If it burns power, it adds noise. So, a low noise amplifier is most probably going to burn power; in which case, it is going to add noise. Now, what we are going to try to do is to make an amplifier that adds as little noise as possible on top of the signal. So, this is the low noise amplifier. This is the first block in the chain. What is going to be the last block on the transmit chain? Just before throwing out the signal to the antenna to the duplexer, what we need is something called a power amplifier. We want to blast as much power as possible into the atmosphere, so that the base station can here me clearly. So, that is a power amplifier. That is the last block on the transmit chain. So, the power amplifier is easy to understand; low noise amplifier – there is a little bit of technicality. In this course, we are going to cover the low noise amplifier, the power amplifier.

What is going to be the next block in the receive chain? So, let us try to understand that, a cell phone; when you are receiving signal, it is probably going to use 800 megahertz or a 1600 megahertz or some extremely high frequency. If it is an extremely high frequency, we do not like these extremely high frequencies, because it is hard to work with them. So, the first thing that we need to do is to bring it down to a lower frequency. So, how do we bring it down to a lower frequency? We use something called a multiplier. Or, in other words, it is called a mixer. So, a mixer is something like a multiplier. And it down converts the high frequency that you received to something that is more manageable. And this is done right after the LNA. What is going to happen right before the power amplifier? Something very similar; you do not want to work with high frequencies. So, you want to work with low frequencies as much as possible. So, the last block before the power amplifier is the mixer.

So, LO stands for local oscillator. The local oscillator for the transmitter is typically different from the local oscillator of the receiver; you do not want transmit and receive to be working at the same frequency band. So, these two frequencies are generated on chip; they are different. And these two frequencies mix with the RF signal or with the baseband signal and create the low frequency or the high frequency whatever you want depending on Rx or Tx. So, we are going to talk about the mixer as well in this course. So, as I was saying, the transmit side local oscillator will be oscillating at a frequency different from the receive side local oscillator; why? Why does it have to be the case? Why cannot I transmit and receive at the same frequency? Because if I do not have them different, then mostly, what I am going to be hearing on the receive is an echo of what I transmitted.

Let me put it a little differently to you. When I am farthest away from the base station, then the amount of power that I am receiving is the lowest. At the same time, the amount of power I am transmitting is the highest. So, I am transmitting a really high power; it is going through the duplexer; the duplexer is a good piece of switch, but it cannot do a thorough job. A little piece – little portion of the transmit leaks into the receiver. And this portion that leaks into the receiver is again mixed by the Rx local oscillator and it is converted to baseband. So, all you are going to hear is what you transmitted. So, typically, a good number for rejection for a duplexer is about 60 dB. So, when you buy a duplexer, this is as much as the mechanical switch can give you. Electronic switches give you even lesser. So, forget it; forget electronic switches. The mechanical surface acoustic wave, duplexer or whatever it is, can give you let us say 60 dB of isolation from the transmit to the receive.

And, maybe when you are farthest away from the base station, the amount of power you are receiving is 100 dB less than the amount of power you are transmitting. So, in that case, the amount of receive power is so much; the amount of transmit power is so much plus 100 dB. The duplexer gives you 60 dB of isolation; which means that, the transmit power that you have received is 40 dB more than the power that you would otherwise want to receive – the signal that you would otherwise want to receive.

So, it basically kills what you want to hear; you do not want to hear this. So, that is why typically, the local oscillator for the Rx is going to be different from the local oscillator of the Tx path. How can you generate these two frequencies at the same time or maybe at different times depending on what a protocol you are using – time domain multiple axis or code domain multiple axis or what is going on accordingly. But, how can the same chip – same integrated circuit generates these two frequencies? Also remember these two frequencies have to be synchronized to the base station frequency. So, let me say a something like this.

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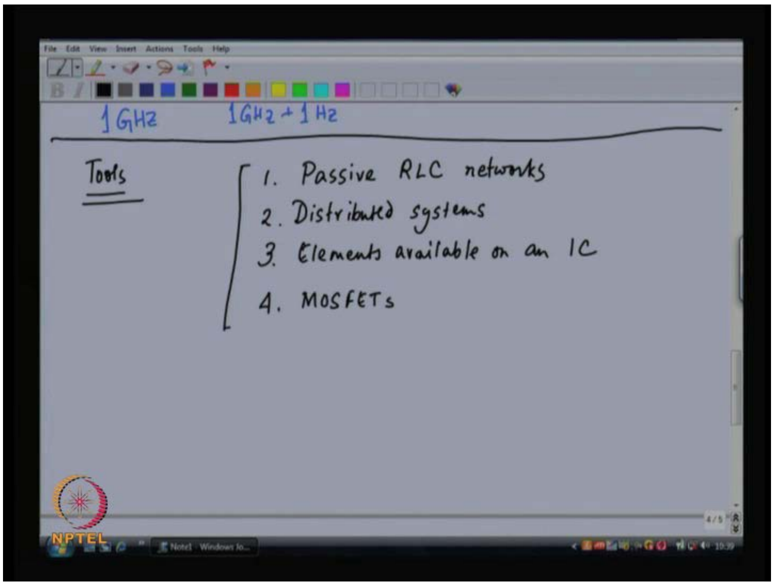

The base station frequency is 1 gigahertz for example. Now, if I am listening and I am not sure about what exactly 1 gigahertz is, I think that, 1 gigahertz of the base station is actually 1 gigahertz plus 1 hertz. So, instead of generating 1 gigahertz, I am generating 1 gigahertz plus 1 hertz. So, I am off in frequency from the base station. Then, what is going to be happen? A few clock cycles later – a second later, I will miss my slot. So, when I wake up to here, what the base station has to tell me; I am not going to hear what is indented for me; I am going to hear what is intended for someone else.

So, I need to have extremely accurate synchronization between the base station and the handheld; which means that, the frequencies have to match exactly – precisely. Also, the frequency of the transmitter has to match to the frequency of the receiver. So, they need to be synchronized. So, for this, we are going to study in this course something called a frequency synthesizer. So, frequency synthesizer synchronizes to a global clock. And basically, there are phase lock loops inside the frequency synthesis technique, uses phase lock loops and it generates the transmit local oscillator and the receive local oscillator.

Now, if you have studied your communications, etcetera, you would probably know that, there are a few more components after or before the mixer. If you are using a heterodyne receiver or a super heterodyne receiver, then between the LNA and the mixer, you need an image reject filter. This is only if you are using heterodyne or super heterodyne. If you are not using heterodyne; if you are using a homodyne receiver or a direct down conversion receiver, then you do not need the image reject filter; you can directly go to base band. However, there are other problems; there are offset problems, etcetera; we are going to discuss all of that also in this course. And there could be a few more blocks after this; there need not be. After that, there is going to be a baseband filter and there is going to be an A to D converter. After that, it is going to go to the baseband processor. After that, it is going to go to the microphone; not microphone, the speaker.

On the transmit path, there could be a few more components here; then, there is going to be a filter; then, there is going to be a D to A converter. Then, this is going to come from the same baseband processor. This is going to come from microphone. So, this is the transmit and the receive chain. Now, I am omitting a lot of details; all of these details depend on what is the precise architecture of the radio that we are talking about. Is it a heterodyne receiver? Is it a super heterodyne receiver? Is it a homodyne receiver? So, depending on all of these different scenarios, the architecture keeps changing. So, we are going to talk about architectures – commonly used architectures of radios in this course. And this is basically the course plan. So, the objectives of this course are to discuss the power amplifier; to discuss the low noise amplifier; to discuss the mixer; and to discuss the frequency synthesis procedure. So, these are the primary objectives. After we have covered, reach these objectives, we will talk about different radio architectures and finish up. So, that is the idea.

Now, unfortunately, we would not be able to start with the low noise amplifier right away. Before we can start with the low noise amplifier or the power amplifier or any of the subsequence topics, we need to ramp up with the tools that are needed to understand these concepts. So, we need a few tools; we need some basic understanding. So, first, we are going to study passive RLC networks. I am sure you have all studied passive RLC networks prior to this course; but, we are going to give it our own spin. Next, we are going to talk about distributed systems, transmission lines. So, we need this background. And we are going to talk about the different elements that are available on an IC. Then, the fourth thing we are going to talk about are MOSFETs only after we cover all of these four aspects are we going to be able to start with low noise amplifiers. So, it is going to be a while before we are able to do that. Most probably, we would not be able to start with our objectives in the first half of this course. So, LNAs will start only in the second half most probably.

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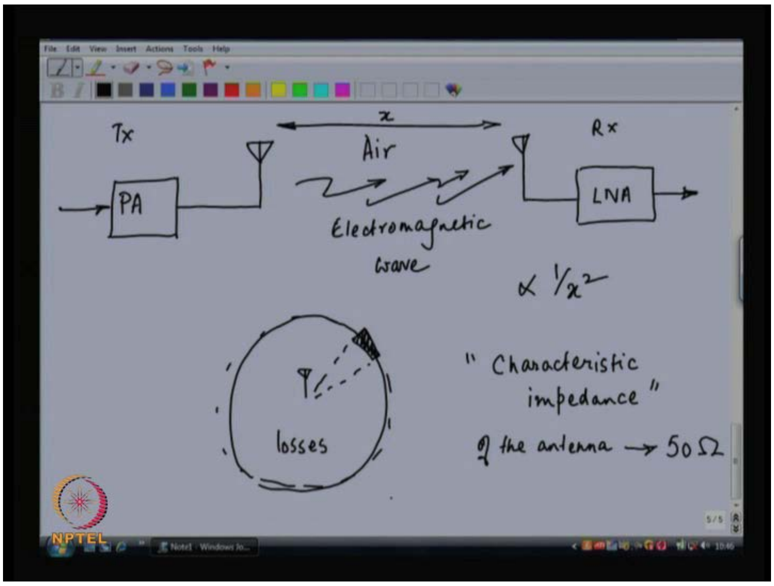

So, the first thing that we need to talk about; so I am not going to draw the duplexer; the duplexer is assumed… So, the first thing is as follows that, we have a transmitter on the base station. And we have a receiver on our handset; or, we have a transmitter on the handset and we have a receiver on the base station – both cases. Between the two antennas of the base station and the client, we have air. So, in this medium, the signal that is being transmitted travels as an electromagnetic wave. Now, electromagnetic waves are acceptable to reflections. Also, as the distance between the transmitter and the receiver decreases, the power received on the receiver antenna decreases by the square of distance – at least by the square of the distances. Actually, that is typically an overestimation. It is actually much more drastic than that. So, if the distance between this is x, then the power received on the received antenna is theoretically proportional to 1 by x square. This is not really true. In practical situations, it is actually much worse than 1 by x square.

The antenna has some directivity. So, we are not going to talk about the antenna in this course; but, even then, the antenna has some directivity. And we typically treat this as something called an antenna gain. The antenna also has some area. The larger the area of the antenna, the more signal it can be receive; naturally. You have a point transmitter; and think of a sphere surrounding the transmitter; the transmitter is transmitting in all possible directions. And suppose the receive antenna is the entire surface of a sphere surrounding the transmit antenna – arbitrary radius – entire area. In that case, all the power that has been transmitted by the antenna by the transmit antenna is received by the receive antenna; it has nowhere else to go. Does it? Mostly it has nowhere else to go. So, if it does not go anywhere else, then all the power transmitted is received no matter what the distance is; which kind of tells you that, the amount of power received by the antenna is proportional to the area of the antenna. So, if antenna is this big, then it receives that portion of the transmit power – total transmit power.

Now, there is also this other thing about losses. All the power transmitted by the transmitter are not really received by the receiver; some of it is lost in air; in the atmosphere, some of it is lost as heat. So, we typically like to minimize losses. We also like to handle as much power as possible. And under all of these circumstances, we choose a certain characteristic impedance of the antenna. So, I am going to come to this word again and again; right now, just treat it as a word – characteristic impedance. So, once again, we choose a certain characteristic impedance of the antenna. This characteristic impedance is chosen to minimize losses and also to handle as much power as possible.

We do not want to have a lightening striking across the transmitter and the receiver; that is also not something very good. We want to handle as much power as possible; at the same time, we want to minimize losses. So, both of these considerations lead to a certain characteristic impedance of the antenna. What this thing is we are going to talk about very soon. But, this is chosen to be 50 ohms; and impedance has units of resistance – ohms; units are ohms. Now, mind you this is not a resistance; this is the characteristic impedance. So, the characteristic impedance of the antenna is chosen to be 50 ohms; this does not mean that, the resistance of the antenna is 50 ohms.

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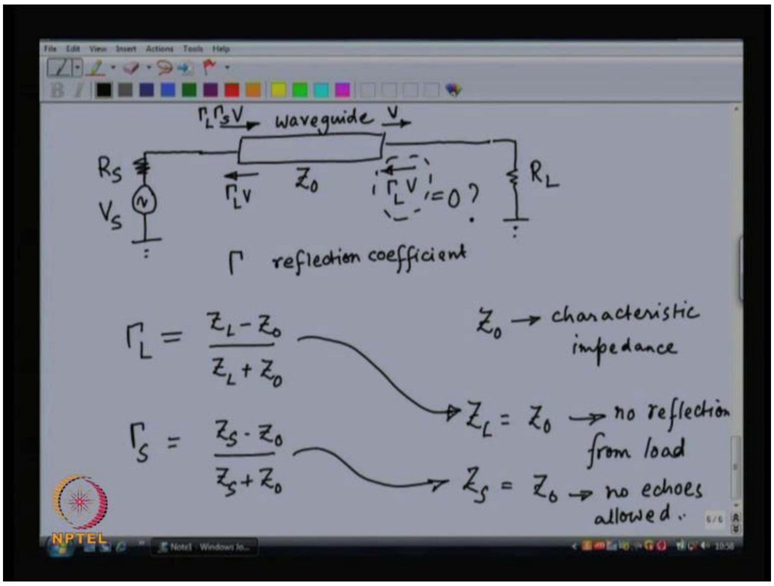

So, it is like this that, if I have any electromagnetic waveguide; an electromagnetic waveguide could be a wire; it could be a real waveguide; it could be the atmosphere; could be anything. If I have a certain waveguide and I want to transmit a certain signal; and I want to receive the same signal; now, whenever I have a voltage source; I have drawn the transmit as a voltage source; it is really a power source – a source of power. So, typically, you want to transmit as much power as possible, etcetera; does not matter. A voltage source is inseparable from some source resistance. So, let us say I have a voltage source V S; this voltage source is inseparable from its corresponding source impedance – source resistance, that is, R S. You cannot decrease R S. If it is a battery, there is some built-in source resistance. So, you want to transmit this V S over a waveguide and you want to receive it at R L. So, this is the situation.

Now, electromagnetic theory, transmission line theory, waveguide theory, optic fiber theory – all of them end up to the same result. And it is more or less something like this. We are going to do this derivation later on; but, I just want to give a head start first because it is going to be important in the development of the introduction to this course. So, the idea is this that, I define something called gamma. Gamma is the reflection coefficient. So, if there is a wave – it is a waveguide; there is a wave hitting a certain object; a portion of the wave gets absorbed into the object; a portion of the wave reflects back from the object.

So, what portion of the wave is reflected back from the object is given by the reflection coefficient. So, if I have a wave of amplitude V hitting the load; then, gamma times V is going to reflect back from the load. Gamma L – gamma subscript L basically means the reflection coefficient at the load. Similarly, if I want to transmit… If this particular wave – reflected wave hits the source, then a portion of the reflected wave is reflected back again. So, this is how it works. So, you transmit a wave; let us say it is a voltage wave; this wave hits the load; part of it gets reflected back. The portion that gets reflected back hits the source and gets reflected again. And this keeps happening back and forth. You also have to understand that, this waveguide that we are talking about is something quite long and it takes time to travel from the source to the load; speed of light is not infinite. So, whatever it is, it takes a little bit of time to travel from source to the load; and these reflections keep happening.

Now, in future, when we do the theory for all of this, we are going to find out that, at the load, this reflection coefficient is Z L minus Z 0 divided by Z L plus Z 0; where, Z L is basically R L in the case that I have drawn; and Z 0 is the characteristic impedance of the waveguide in question. So, this is how we are going to understand the reflections. So, the reflection coefficient happens to be equal to this. At the source side, it is going to be something very similar – Z S minus Z 0 divided by Z S plus Z 0; Z S in this case is the source resistance of the voltage that has been applied; all right? So, this is the basic stuff.

Now, when we are talking about the antenna, the antenna is something like a waveguide that has characteristic impedance. The antenna hands over the signal to the atmosphere, which also has similar properties. Then, the atmosphere hands over the signal to another antenna, which is also a waveguide. And that antenna finally, hands over the signal to the low noise amplifier. Now, observation number 1 – when is the reflection from the load equal to 0? Can I make this reflection equal to 0?

Now, looking at the formula, it is very easy to do that. All you have to do is make R L equal to Z naught. So, what that means is as follows that, I have a signal coming to the antenna; the antenna is passing over the signal to the low noise amplifier. If the low noise amplifier has an input impedance of Z L; and if the antenna – receive antenna has the characteristic impedance of Z naught; and if Z naught equal to Z l, then all the signal that hits the low noise amplifier is going to be absorbed by the low noise amplifier; nothing of that signal is going to be reflected back. This is something very good. You do not want echoes to happen; you do not want to keep reflecting and then getting a reflection of the reflection and so on and so forth; you do not want these echoes. You want to absorb all of the power that was transmitted to you and intended for you. So, as far as the low noise amplifier is concerned, we want to make sure that, the characteristic impedance of the antenna is equal to the input impedance of the low noise amplifier. I set the characteristics impedance of the antenna is chosen to be 50 ohms; you design the antenna, so that its characteristic impedance is 50 ohms; that means that, you would want the low noise amplifier to have an input impedance of 50 ohms; all right.

Next thing – let us look at the power amplifier – the source. The source is producing a signal; part of that signal is probably reflecting back to the source, because of some mismatch on the load side. Now, you do not want this reflected signal to reflect back again. So, you do not want to keep having reflections and allowing echoes to happen. Therefore, you want to gamma S also to be equal to 0. What does that mean? If gamma S is going to be equal to 0, then Z S has to be equal to Z 0. This means that, the output impedance of the power amplifier; that is the source resistance. Output impedance of the power amplifier is the source resistance. The power amplifier can be modeled; the Thevenin equivalent of the power amplifier is a voltage source in series with a source resistance. So, that is the output impedance of the power amplifier. That has to be matched to the characteristic impedance of the antenna. That will stop echoes being allowed at the output of the power amplifier.

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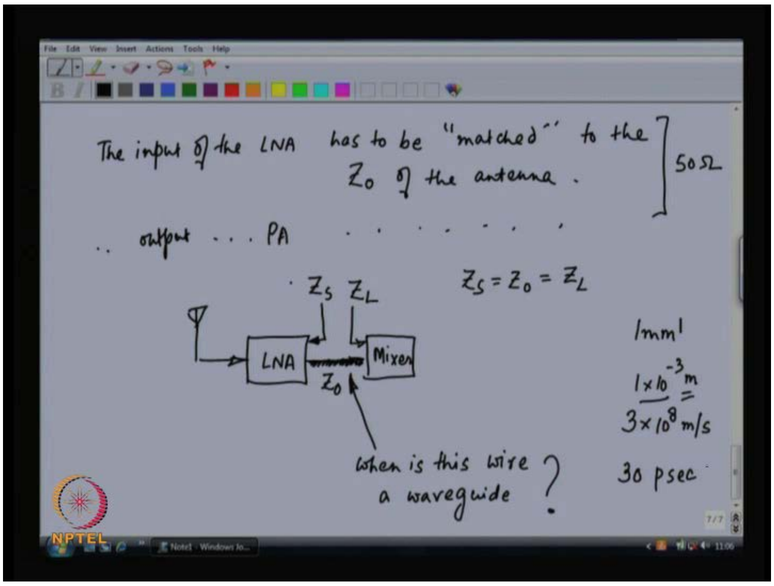

So, now that we understand this, the term that we are going to use – the kind of sentence that we are going to use is like this. The input of the LNA has to be matched to the Z naught of the antenna. The output of the PA has to be matched to the Z naught of the antenna. So that is the kind of sentence that we are going to use. So, when we are going to design the low noise amplifier or when we are going to design the power amplifier, the input or the output impedance of these two structures have to be matched to the characteristic impedance of the antenna; what else? So, I have the low noise amplifier; I am not allowing any reflections to happen from the low noise amplifier back. So, all the signal received by the antenna goes to the low noise amplifier, because you know I have done a careful job of matching, etcetera.

And now, I want to handover the signal to the mixer, so that I can down convert it. What has to be done between the mixer and the low noise amplifier? First of all, this handovering is going to happen through a transmission line – through a wire; a wire is a waveguide – transmission line. What needs to happen is that, the output impedance of the low noise amplifier has to be equal to the characteristic impedance of this wire. And that in turn has to be equal to the input impedance of the mixer. Does this have to be equal to 50 ohms? No, it does not; it does not have to be 50 ohms; it just has to be equal to the characteristic impedance of wire that is connecting the low noise amplifier and the mixer; there is no 50 ohms in this; 50 ohms is for the antenna. So, with this understanding, what about the corresponding portion for the power amplifier between the power amplifier and the mixer? The output resistance of the mixer has to be matched to the characteristic impedance of the wire connecting the mixer and the power amplifier; which has to be matched to the input resistance of the power amplifier.

Now, the next thing is when do you consider this wire to be a waveguide? From whatever you have learnt before – circuits and systems, network theory, Kirchhoff laws, a wire is a wire. If you apply a potential on one side, the other side potential is same; potential on the other side is the same. Now, this is approximately true under the following conditions. Number 1 condition is that, the wire should not have a resistance; it should not burn power. Number 2 condition is that, the amount of time it takes for information to travel from one side of the wire to the other side of the wire has to be much much much smaller than the amount of time you can measure. Say if the wire is small; let us say the wire is 1 millimeter in length; then, how much time does information take to travel from one side of the wire to the other? So, it is about 300 picoseconds or 30 picoseconds – 30 picoseconds.

So, if you can measure 30 picoseconds, does not matter whatever the time is; if you can measure that amount of time. By measure I mean if it means something to you. If the signal is at 1 gigahertz; that means 360 degrees of the signal is 1 nanoseconds; that means 30 picoseconds is about 20 degrees phase. So, if 20 degrees phase is something important to you; if you can measure 20 degrees of phase, then it is not a wire; you have to treat the wire as something over which information is flowing overtime; it is a waveguide.

So, let us quickly summarize what all we have talked about today. So, the first thing that we have to understand is that, this course is for circuits for cell phones as I have renamed the title of the course. The real title of the course is CMOS RF integrated circuits. What we are going to do is circuits for cell phones. Other than cell phones, the other applications that I can think of right now are WiFi, Bluetooth, GPS, FM radios; may be a few more – wimax. Briefly, a cell phone handset is going to have a transmitter, a receiver; they are both going to use the same antenna. To use the same antenna, I need something called a duplexer.

Now, blocks in the receive chain are the low noise amplifier; then, maybe there is going to be an image reject filter – may not be. Then, there is going to be a mixer. After that, there is probably going to be another filter. Then, there is going to be an A to D converter, baseband processer. Finally, it is going to go to the loudspeaker. On the transmit side, the last block I need to blast as much power into the atmosphere as possible. So, I need something called a power amplifier. And right before the power amplifier, there is probably going to be a mixer, which will convert the low frequency signal to something at higher frequencies. Before that, there is probably going to be a filter. Before that, D to A converter, baseband processor; maybe the signal is coming from microphone. So, this is the transmit chain.

Now, in this course, we are going to discuss the power amplifier, the LNA, the mixer and techniques for frequency synthesis. In all, we are also going to study different radio architectures in this course. Now, these are the objectives of the course. Unfortunately, to reach these objectives, we need a few tools. So, we are going to discuss… Our tools are going to be basically passive RLC networks, distributed systems; what are the elements available on an IC, MOSFETs; some mathematics that needs to be done, etcetera. And after that, we dived direct into the subject and we were talking about something called characteristic impedance. So, this important to remember is that, the characteristic impedance is not the resistance. And antenna is not supposed to burn power; it is not a lossy element; supposed to be lossless. You do not want to finish off all the power right in the antenna; you want to use the antenna to capture the power from the atmosphere and hand it off to the rest of the receiver. So, the antenna is not lossy or rather you do not want it to be lossy. And the characteristic impedance is not a resistance. And then, we talked about how we do matching to stop reflections. With this, I am going to stop this lecture.

Thank you for your attention.