Basics of software-defined radios & practical applications
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Lecture – 02
Components of a software-defined radio

Hello everyone in the NPTL online certification code, software defined radio and it is practical applications we were discussing software defined radio components and architectures. We were basically discussing the RF transmitter and the server and how they interacts with each other. We have covered till now the digital portion which is the information in bits, it is coding, it is modulation and pulse shipping that the information is contained with it within a particular bandwidth.

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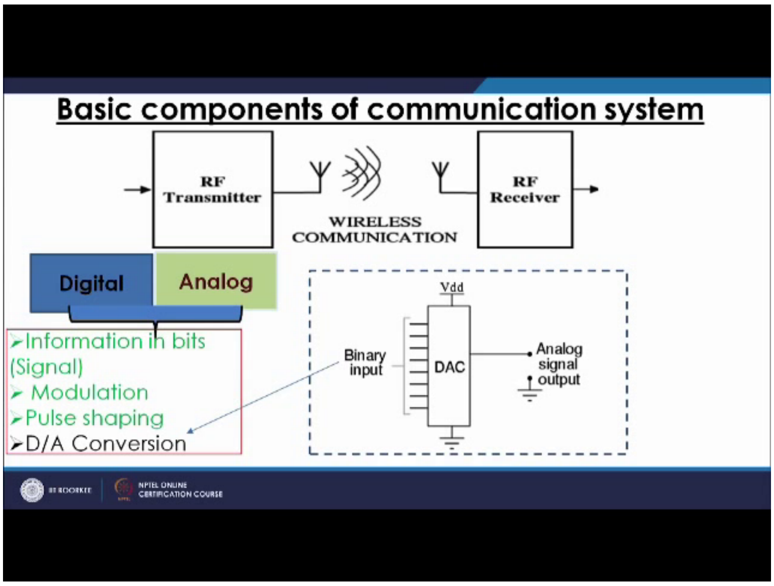

Basic components of communication system

- Information in bits (Signal)
- Modulation
- Pulse shaping
- D/A Conversion

Once we have our information in the digital domain completely then the next step comes to convert this digital information into analog information. Because, analog therefore, is something which is actually travel across the medium and it is not the digital information.

In digital to analog conversion our data which is which is in digital domain, it can be represented in binary input. If you see here, our data can be represented as 8-bit data, 5-bit data, 4-bit data and as we increase the number of how many number of bits we are using, it gives us more precision. For example, if we are having 8-bit data we will be having 2 to the power 8 level. This is this will provide us the precision to represent that input digital information properly. This digital information is converted into analog by using digital to analog converter this is the simple example of a digital To analog converter.

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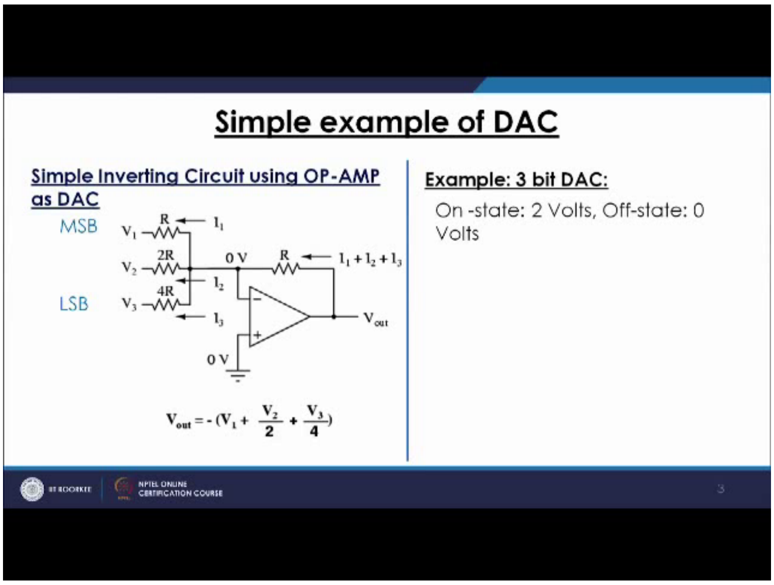

Simple example of DAC

Simple Inverting Circuit using OP-AMP as DAC

$$V_{out} = -(V_1 + \frac{V_2}{2} + \frac{V_3}{4})$$

Example: 3 bit DAC:

On -state: 2 Volts, Off-state: 0 Volts

This example shows a simple inverting circuit using OP-AMP as digital to analog converter. What is the fundamental of this operation? If we look here this operational amplifier it has a V out and it is attached as a inverting mode. Now that inverting voltage is given as 0 volt. With respect to this 0 volt, there are 3 branches each branch contains a different resistance.

The first branch contains resistance of R value R ohm, second one 2R ohm, third one 4R ohm. When we apply any voltage V1 V2 V3 on these branches the current flowing through these branches becomes I1 is equal to V1 upon R I 2 equal to V2 upon 2R and I3 equal to V3 upon 4R. Now, because of the Nortons theorem at any junction the incoming current should be equal to outgoing current. In the this inverting section of the OP-AMP our total current is Vout divided by R, which is actually the summation of I1 I2 and I3. Vout upon R becomes V1 upon R plus V2 upon R plus V3 upon 4R by doing this we can write it like this.

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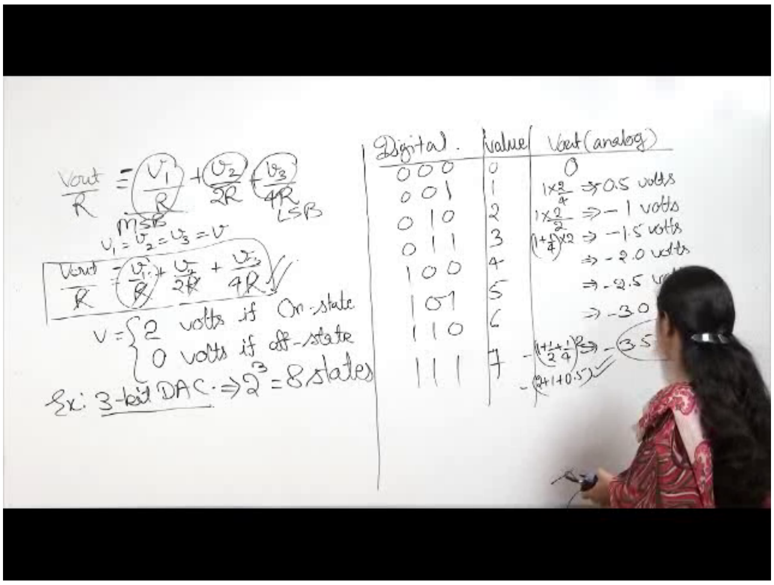

$$\frac{V_{out}}{R} = \frac{V_1}{R} + \frac{V_2}{2R} + \frac{V_3}{4R}$$

MSB LSB

$V_1 = V_2 = V_3 = V$

$$\boxed{\frac{V_{out}}{R} = \frac{V_1}{\cancel{R}} + \frac{V_2}{2\cancel{R}} + \frac{V_3}{4R}}$$

$$V = \begin{cases} 2 \text{ volts if On-state} \\ 0 \text{ volts if off-state} \end{cases}$$

Ex: 3-bit DAC ⇒ $2^3 = 8$ states

Digital.	Value	Vout (analog)
0 0 0	0	0
0 0 1	1	$1\times\frac{2}{4} \Rightarrow 0.5$ volts
0 1 0	2	$1\times\frac{2}{2} \Rightarrow -1$ volts
0 1 1	3	$(1+\frac{1}{4})\times 2 \Rightarrow -1.5$ volts
1 0 0	4	$\Rightarrow -2.0$ volts
1 0 1	5	$\Rightarrow -2.5$
1 1 0	6	$\Rightarrow -3.0$
1 1 1	7	$-(1+\frac{1}{2}+\frac{1}{4})2 \Rightarrow -3.5$ $-(2+1+0.5)$

Right. If I choose my V1 is equal to V2 is equal to V3 equal to a fixed voltage then basically V out can be given as V out upon R is equal to V upon R plus V upon 2R plus V upon 4R.

Now, if our voltage V can have only 2 states. Let us say V capital V volts if on state and 0 volts if off state. If we look at it like this and these are representing our relation between V out and in incoming voltage V. We can see here that R will be canceled and basically it is a just relation between V out and VS. If this V voltage R represented in represented as just a voltage positive voltage V and 0 when there is no voltage no it is a off state. Then we can see that first branch which is corresponding to V1 upon R. It has a direct relation to V out, the second value has it has impact of 1 upon 2 ratio with respect to our output and this has 25 percent 1 upon 4 voltage with respect to output.

If you look at this circuit and if you look at our binary digits, then we can say it is the least significant bit. Because it has lower weight there and it is there MSB most significant bit because it has the most impact in this schematic. Let us take this example we are saying that whenever we have a signal it is an on state we will take 2 volts and off state we will take 0 volts. For example, of 3-bit DAC now this 3-bit DAC will have 2 to the power 3 or 8 a states basically. It can represent 8 different information by using 3 bits. Let us say, our input signal conditions are these 0 the second level is 010 011 100

101 110 and 111. This is the digital information we have which is representing a particular value which is 0 1 2 3 4 5 6 7.

It is actual value in the integer form can be from 0 to 7 here now by applying about this method for the 3-bit 3 - bit DAC and this is the 3 with DAC we are showing here right we have chosen over v to be equal to 2 volts. This V here it becomes for this example it is 2 volts now let us take our first example our V1 V2 V3 they all have 000. V out which is given by this relation basically. Let us again call it V1 V2 V3 because it is taking on off equation according to this relation right. 000 our V out becomes which is a analogue output right which we can see from our eyes. It will become 0 now next is 000. This digit is one and there are 2S 2S are 00.

What will be the value it will be V3 divided by 4 because these 2 values are equal to 0. It will become 1 divided by 4 into 2. Into 2 which is the voltage divided by 4 and it will be 0.5 volts not 0.5 degree minus 0.5 volts because it is an inverter circuit. There is a correction it should be negative here yes, we can see here. Basically, for the second digit this one will be one other 2 are 0. It will be 1 into 2 divided by 2. It will be minus 1 volts what about next one? Now these 2 will be one and it is 0. It will become 1 plus 1 by 4 into 2 minus 1 0.5 volts right. If you keep calculating like this it will be the next one will be minus 2 volt for this 1 if you minus 2.5 volts for this one it will be minus 3 volts and for the last first will be minus 3.5 volts.

We can check for any random data. Let us say last example 111 it will be 1 plus 1 by 2 plus 1 by 4 into 2. Let us do this calculation 1 plus 1 by 2 plus 1 by 4 and all into 2. Are we correct here. Let us check it here it will be 2 plus 1 plus 0.5 with the negative sign. It is correct here.

What we see here? As if a digital signal is going from 0 to 7 values we are actually able to see our voltage increasing it was point minus 0.5 it was 0 then minus 0.5 minus 1 minus 1.5. It is a step wise it is increasing as we are represented by digital information in analog domain we are able to see the variation and there is a fixed step with each bit and that is step is of 0.5 volts. This is simple example of DAC and there are some higher advanced examples for this also, but it gives us some idea that how we can convert from the digital to analog domain.

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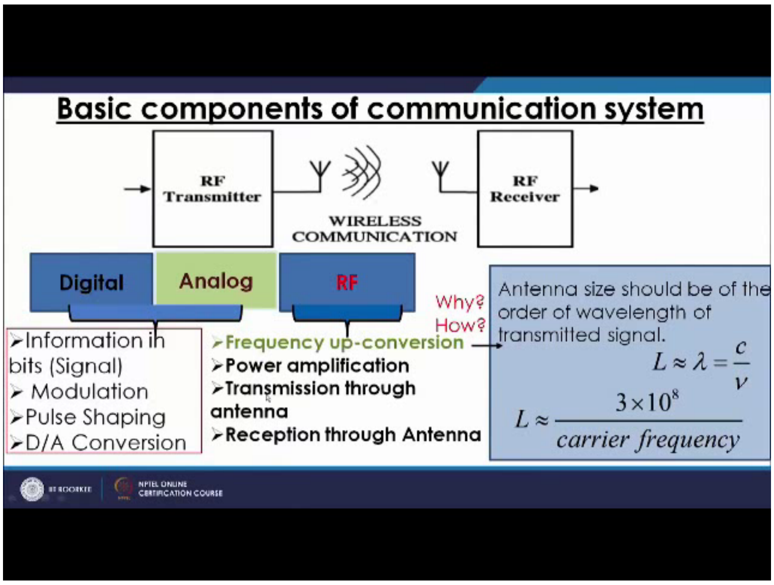

Basic components of communication system

- Information in bits (Signal)
- Modulation
- Pulse Shaping
- D/A Conversion

- Frequency up-conversion
- Power amplification
- Transmission through antenna
- Reception through Antenna

Antenna size should be of the order of wavelength of transmitted signal.

$$L \approx \lambda = \frac{c}{\nu}$$

$$L \approx \frac{3\times10^{8}}{carrier\ frequency}$$

Now, in the series of this digital to analog conversion now our data which we have with us it is in analog domain and it is frequency is a still near 0. Now next step is actually frequency up conversion. If you look here why it is required? And how we can do this? Frequency conversion is related to the concept of antenna size. Basically, antenna size should be the order of wavelength of transmitted signal which is the size of the antenna is equal to lambda which is the wavelength and C is the speed of light and this nu is the carrier frequency. If we look here suppose of a carrier frequency is 1 kilo hertz right if I use one kilo hertz what should be my l.

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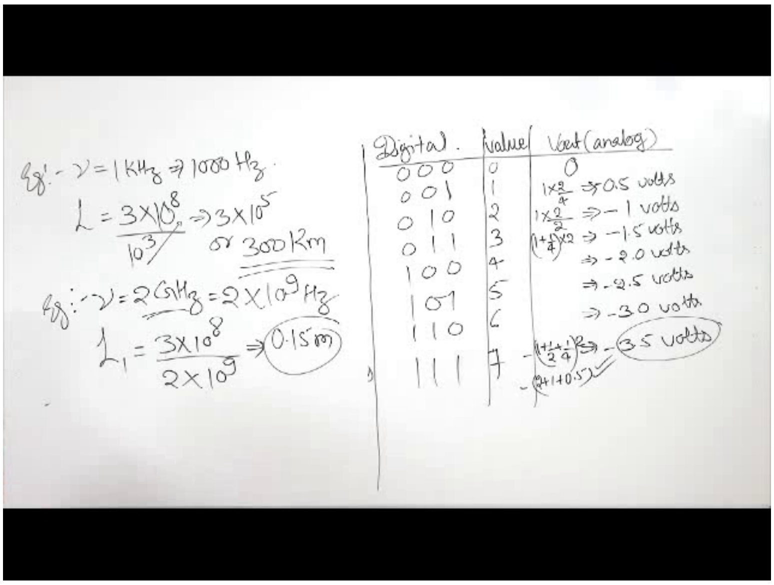

Eg:- $\nu = 1\,KHz \Rightarrow 1000\,Hz$.

$L = \frac{3\times10^{8}}{10^{3}} \Rightarrow 3\times10^{5}$ or 300 Km

Eg:- $\nu = 2\,GHz = 2\times10^{9}\,Hz$

$L_1 = \frac{3\times10^{8}}{2\times10^{9}} \Rightarrow \boxed{0.15\,m}$

Digital.	Value	Vout (analog)
000	0	0
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010	2	$1\times\frac{2}{2} \Rightarrow -1$ volts
011	3	$(1+\frac{1}{4})\times2 \Rightarrow -1.5$ volts
100	4	$\Rightarrow -2.0$ volts
101	5	$\Rightarrow -2.5$ volts
110	6	$\Rightarrow -3.0$ volts
111	7	$-(1+\frac{1}{2}+\frac{1}{4})2 \Rightarrow -\boxed{3.5\text{ volts}}$ $-(2+1+0.5)$ ✓

Let us say nu is 1 kilo hertz or 1000 hertz then our length is actually 3 into 10 to the power 8 divided by 10 to the power 3. It will be R the length of this antenna will be 300 kilometers.

Of course, we do not want our antenna to be that big as we keep increasing our frequency here this l will go down for example, we take a simple example of nu is equal to 2 gigahertz frequency. Which is actually 2 into 10 to the power 9 hertz. What will be l in this case? L in this case will be 3 into 10 to the power 8. If you calculate this it is coming out to be 0.15 meter not is a small antenna and this is an antenna which we want to have.

Working on the higher frequency gives us this smaller size of antenna. This is one usefulness of choosing this. Frequency up conversion is actually required. Another point here is that we do require higher carrier frequencies, but those carrier frequency values how to choose them are decided by regulatory bodies. We just can not use any frequency for the transmission of the signal we actually have to have some criteria decided that you can only transmit on this frequency the these are fixed frequency for example, for W CDMA wimax lt they have separate bands there and apart from that the this service providers.

They are also given this particular frequency bands to deal with. They cannot just simply transmit at any frequency there are some bands for that now how do we do that. We normally do this by using a component called mixer.

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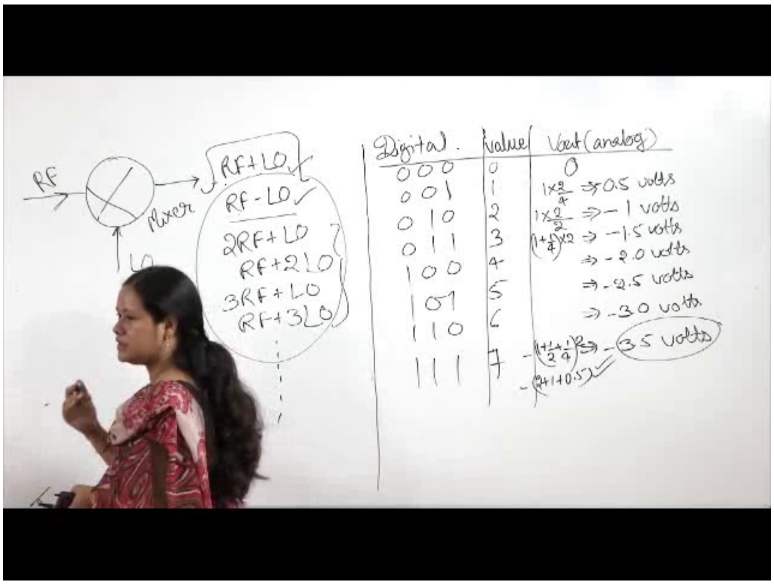

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Mixer is the component basically which is a non-linear component. In this we provide a LO frequency and this is the incoming signal which can be analog or RF and if this is the input of this mixer then output can be RF frequency, plus LO frequency, RF frequency, minus LO frequency and it is harmonics and so on other combinations also. These are the outputs they are the main outputs and these are harmonics which have a little bit a smaller amplitude. Basically, if I want to up convert my signal I take this component I filter out this component and I suppress all these components.

The output frequency is the frequency of the incoming signal plus the frequency of LO and the signal is up converted to a new frequency which is given by RF plus LO frequency similarly at the receiver side when you want to dine down convert we choose this frequency. In this case we do the down conversion we go to the lower frequency range. Frequency up convergence is done by using non-linear mixers. Now, based on up conversion down conversion process there are some few definition in the literature which are used continuously.

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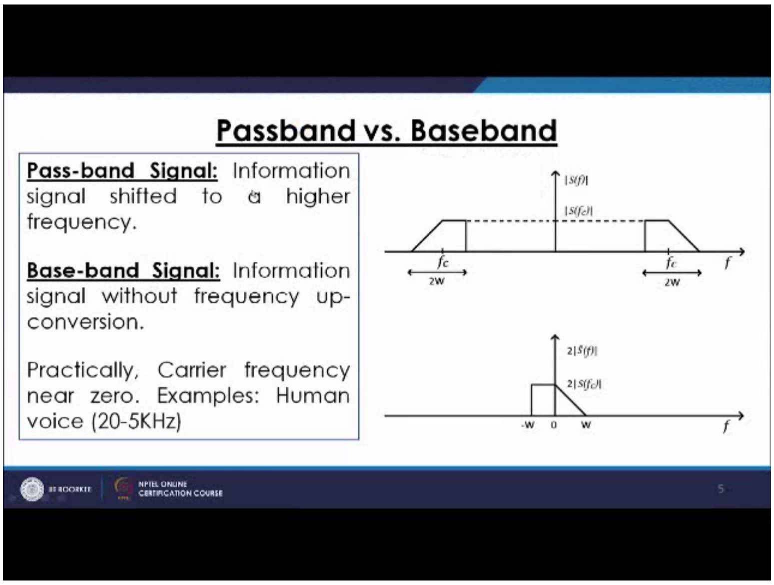

Passband vs. Baseband

Pass-band Signal: Information signal shifted to a higher frequency.

Base-band Signal: Information signal without frequency up-conversion.

Practically, Carrier frequency near zero. Examples: Human voice (20-5KHz)

For example, pass band signal is the signal which is at the higher frequency range. In this then same information is shifted to a higher frequency. If this is this carrier frequency FC is being shown it is the pass band. Baseband signal is basically the frequency in analog domain.

However, information signal is near 0 frequency whenever in the literature we hear about the baseband signal. It is a signal which is very near to baseband ideally it should be 0 frequency, but practically carrier frequencies near 0 are also considered baseband signa.l the frequencies which can be handled in digital domain by using now oscillator etcetera now this comprehensive we will be covering later in this course. Next stage is power amplification. Why do we require this power amplification? First of all, we have discussed that for the frequency up conversion we.

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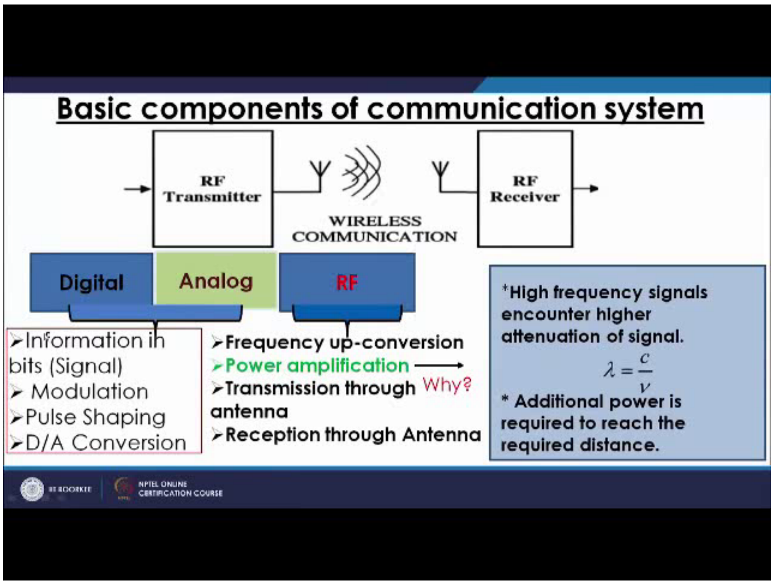

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- Frequency up-conversion
- Power amplification ⟶ Why?
- Transmission through antenna
- Reception through Antenna

*High frequency signals encounter higher attenuation of signal.

$$\lambda = \frac{c}{\nu}$$

* Additional power is required to reach the required distance.

Convert the frequency of the signal to a higher frequency range. Now the problem with the higher frequency is that higher frequency signal they encounter higher attenuation of the signal. This again looking at the formula that wavelength is equal to C upon nu. C is the speed of light and nu is again our again our carrier frequency, if I increase the carrier frequency my lambda the wavelength it goes down.

What does it mean actually? What is the wavelength actually? Wavelength is the des distance travelled by a wave during 2 crest.

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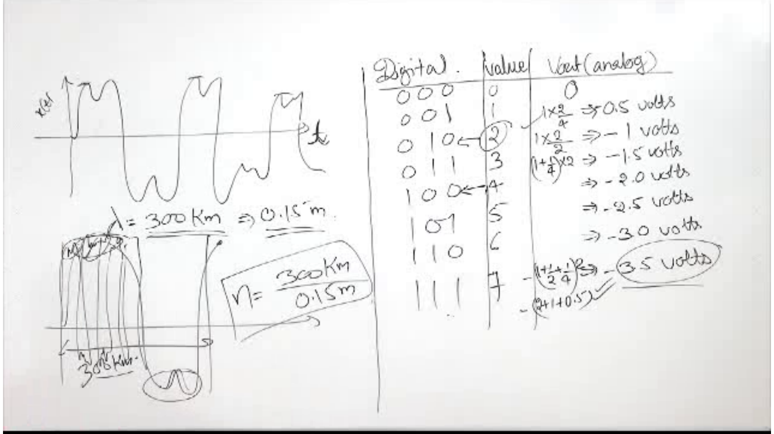

$\lambda = 300\text{ Km} \Rightarrow 0.15\text{ m}$

$\nu = \frac{300\text{Km}}{0.15\text{m}}$

Digital	value	Vout (analog)
000	0	0
001	1	$1\times\frac{2}{4} \Rightarrow 0.5$ volts
010	2	$1\times\frac{2}{2} \Rightarrow -1$ volts
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Let us say, this is our signal and it is repeating here it crest is here. Normally whenever we talk about the signal processing we have terms like time period frequency what is the time period? The time duration after which the signal repeats now wavelength is the distance traveled during that time when the crest has again received.

While the time period is dealing with the time the lambda wavelength is dealing with the distance traveled. Now we have to take into account if over lambda is big lambda is 300 kilometers, as I said before in our previous example in this case suppose my signal has to travel 300 kilometers in itself in 1 lambda 1 wavelength in 300-kilometer meters it will be showing it is crest this distance covered will be 300 kilometers.

During this duration the signal has reached to pick at 2 instances, but if my lambda is small. For example, the second example of the 0.5 meter then within while traveling this 300 kilometers it has so many peaks to cover all this distance. How many peaks? 300 kilometers divided by 0.5 that many crest will be there. In this case 300 kilometers divided by 0.5 meter this is the frequency how it will be repeating itself. This many times this higher peaks will be dealing with the attention of the environment. Initially it has only this time period well first dealing with that attenuation now it is dealing with those attenuation regularly. More most of the energy is dissipated in the into the environment in the form of heat and the signal power will go down.

Now, because signal power has gone down, we require the additional power to be given to the signal if it wants to reach that 300-kilometer distance theoretically right. That is why the power amplifier comes into picture. Power amplifier is boosting the power of the same signal.

Now the signal is that a higher frequency because of this step of the frequency up conversion and now we have given it the power, it has also the power to reach that distance. Now, once it is done our signal has power which transmitted through antenna what is the antenna actually? We had shown the earlier that when we were converting from digital to analog. Then our signal was in the form of electrical symbol. It can be current or voltage now antenna is something which captures and or transmits radio electromagnetic waves according to that electrical signal.

If we see the variation in voltage, it sends some radio electromagnetic waves according true to that pattern of the input incoming voltage signal. These electromagnetic waves they can travel in the wireless media in the speed of light. What is it is main function main function is to transmit this signals through the media. Moreover, while designing this antennas it is it also works as the band pass filter it means it only allows a particular range of frequencies to pass for others it does not work that well.

It attenuates those. It works as the band pass filter. Moreover, it provides the directivity to the signal that at which location and in which direction the signal should go. This is the main aim of the transmission. Once the signal has traveled through the wireless media and received by the receiver through antenna then our RF domain data, our RF domain processing is done. Again, we want to go back to analog domain and the digital domain that we can retrieve our original information.

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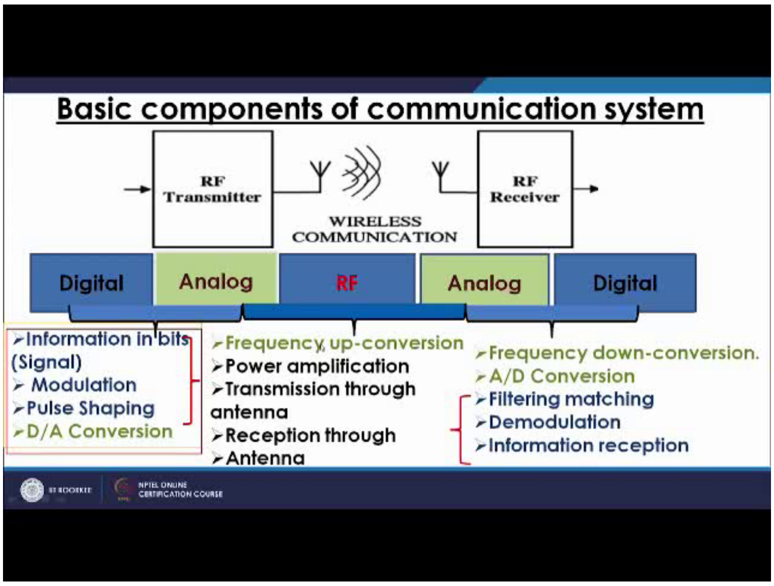

Basic components of communication system

- Information in bits (Signal)
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- Pulse Shaping
- D/A Conversion

- Frequency up-conversion
- Power amplification
- Transmission through antenna
- Reception through
- Antenna

- Frequency down-conversion.
- A/D Conversion
- Filtering matching
- Demodulation
- Information reception

Once we have received our data through the same antenna again the antenna will have a particular bandwidth operation it will get only few selected frequencies of the incoming signal. Which for which it is tuned and when it is achieved then the first step will be frequency down conversion.

Now, frequency down conversion is a step which is opposite of the frequency up conversion. As I showed you earlier by using non-linear mixer we can select the subtractive component RF minus LO frequencies and the frequency will come down to the analog domain. Now we have our analog domain signal which we have here in the transmitter section. The same information we have here in the receiver section now we want to extract our digital data from this information.

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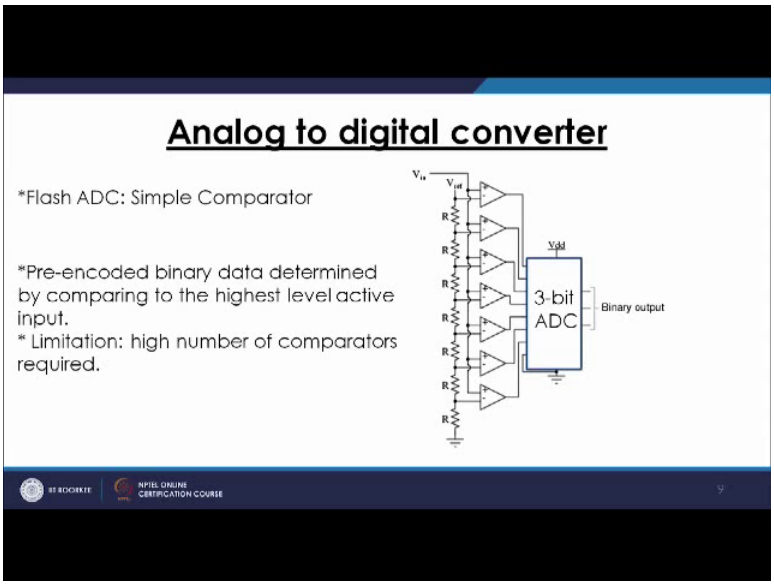

Analog to digital converter

*Flash ADC: Simple Comparator

*Pre-encoded binary data determined by comparing to the highest level active input.

* Limitation: high number of comparators required.

This is a simple example of the analog to digital converter. Again, they are much more sophisticated examples than this, but it how the working of the ADC is done. Basically, it is a simple competitor what is happening in the circuit again it is 3-bit ADC. The example we had done earlier for the 3-bit DAC it is opposite to that 1. Our data is in the form of voltage and you want to get about binary digit out of it.

As we can see here, we have 8 inputs one is 0 state and other 7 hours from 1 to 7 states and the output will be 3 bits digits how does it actually works? That we make a table like this table here and we know that when this particular voltage level is reached, then it means the value is 2 and it means our digital information should be this 1. Basically, we read this voltage values and we look in the table and we say it is near to this value. It should be equivalent to this value which is in binary domain should be 100 if it is the value is 4.

As we are showing here this is the incoming voltage which is applied to the ADC analog to digital converter then we have a reference voltage which we can tune beforehand and it should be equal to the highest voltage reference level. For example, in previous example of DAC where highest voltage level was 3.5 volts actually minus 3.5 volts it is different that is the difference only now incoming signal is being applied here and this v reference it is automated by R. Some voltage will drop here it is twice will drop here is thrice will drop here. Basically, it will have all the full voltage and then it will have you know 1 8th portion here, then one 7th portion here and so on. Voltage is dropping at the each node now what happens this OP-AMP they are working as a comparator it means they compare the voltage level here with respect to incoming voltage. If this incoming voltage level matches with the V reference level it outputs that level.

If this output voltage which is being shown here it compares and it gives the output voltage. The highest level of output voltage achieved by this is considered by this 3-bit ADC. For example, let us say our input voltage is coming out to be minus 2.2 volt. It is near to this value minus 2.2 volts. Our registers they will they will be able to show this value this value this value this value, but it will not be able to show these 3 values.

In this adc it will be seeing from the least significant bit because it is dropping all the v reference here it is the least significant bit. It will be seeing 0 there then it will be seeing minus 1 minus 1.5 minus 2, but it will not be giving any output from these. Because, this reference level is high lower then these values. Among these 3 values it will pick the highest one which is the minus 2. According to that minus 2, it has a LUT which will read that it is value 4 and it will output 1 1 0 0 and this will be fed to the digital circuit.

This is how we are able to see the analog component binary output for this analog signal. Now, what is the limitation it is very simple idea it should work very fairly accurately? The limitation is that we can see here for 3-bit ADC we has to use 2 to the power 3 minus 1 comparators if I want to use 8 bit ADC it will be 2 to the power 8 minus 1 comparators. Complexity is increasing all the time. Based on this they are some other kind of analog to digital converter.

We are not covering all of them here, but you have basic idea that what kind of circuit can work here. We have our data which is in digital domain here, now once we have our data in digital domain and it is constrained within a particular bandwidth. We want to do something opposite of the pulse shipping. We have a filter which is matched to the pulse shipping filter of the transmitter and we get our data back in the digital domain and then we have to demodulate it. What are the modulation scheme we have chosen earlier, we have discussed PSK, it can be QPSK or it can be quadrature amplitude modulation.

Now, little discussion qam signals because they are used basically in the LTE and LTE advanced concept. Earlier we have discussed about ask FSK and PSK and we have seen the example of BPSK 2 types of BPSK.

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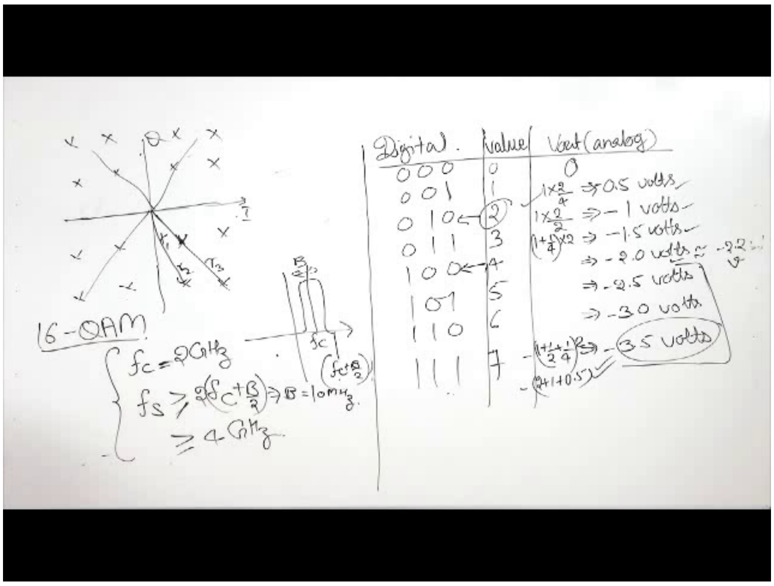

Now, among BPSK we had talked about constellation diagram. You had 2 positions here. Showing the 2 phase positions now QAM signal quadrature amplitude modulation is basically which is taking care of this says as well as amplitude modulation 16 QAM. 16 QAM modulations, it is having actually phase locations here rotations, right missing this direction that direction in that direction in that direction as well as amplitude modulation because some of the them have this much R and some of them has separate R value. Amplitude modulation as well as phase modulation is there and basically their data in the wattage diagram it looks like this.

Demodulation occurs. That we can read this value back from their constellations and our data is available in bit form there and then we do the decoding techniques which is a positive the encoding techniques used earlier and then we have our information.

Then we compare this information with the original version to check bit error rate etcetera. This is the whole basic component of the communication system. Among this communication system if we pay attention there are a digital domain operation which is shown by this red arrow here, and then their analog domain and RF domain. Now because this course leads to the software defined radio let us see the limitation of digital versus analog circuits when we are talking about the analog counter.

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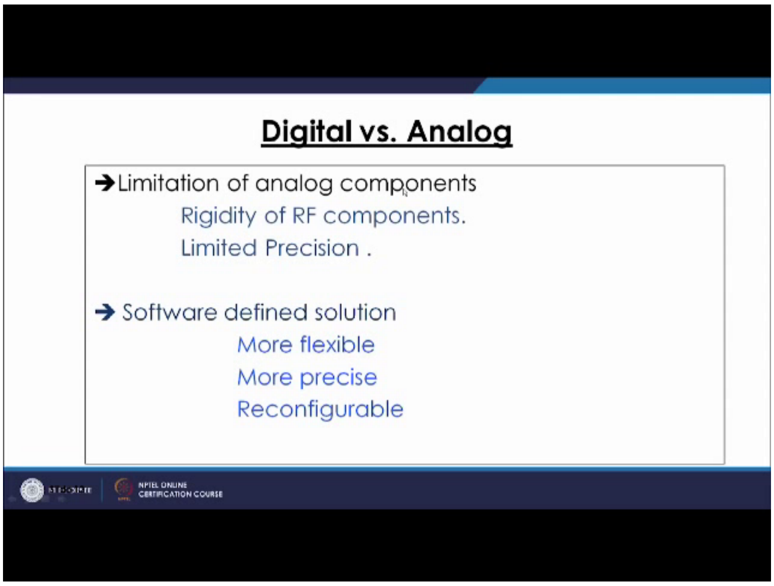

Digital vs. Analog

- Limitation of analog components
  - Rigidity of RF components.
  - Limited Precision .
- Software defined solution
  - More flexible
  - More precise
  - Reconfigurable

Parts and compo components with respect to the digital components the analog components have a rigidity because once you have fabricated them you have to you cannot configure them. You have to again design a new component in the analog domain and use it. Now, due to fabrication process and different process analog components are inherently not that precise.

They have limited precision, they are not flexible and they have limited precision and it includes some distortion in the system. Some non-ideality in the system as opposed to analog system, if we can have complete digital system, it can be more flexible if your scenario changes you can just change the coefficients and you will have better precise solution there. It is recoverable in nature. Whenever, your incoming signal changes or your channel condition changes, you can reconfigure it. Even if your frequency changes in the analog domain you cannot do it because you design for that frequency. In digital domain, you can simply use the new frequency you can define it like that.

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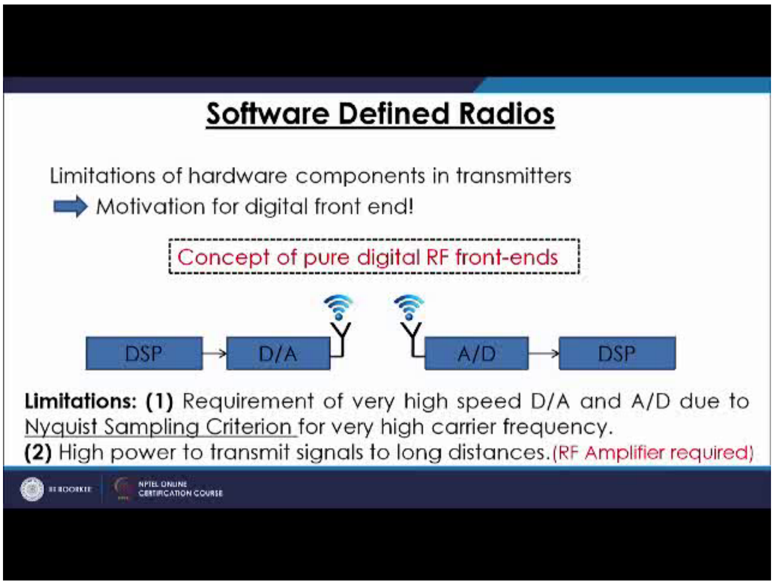

Software Defined Radios

Limitations of hardware components in transmitters

➡ Motivation for digital front end!

Concept of pure digital RF front-ends

DSP → D/A   A/D → DSP

Limitations: (1) Requirement of very high speed D/A and A/D due to Nyquist Sampling Criterion for very high carrier frequency.
(2) High power to transmit signals to long distances.(RF Amplifier required)

Of course, software defined radio solutions are better than the analog components. What is stopping us? Basically, the limitations of the hardware component in the transmitter we want to remove them and this is the motivation for the digital front end. Software defined radios are, but proposed initially as a concept of pure digital RF front end. Ideally, it was proposed that we can do everything in digital domain and after that only we have to do digital to analog conversion and transmit it through antenna receive it and then everything can be done in the digital to in the digital domain. What is the limitation in this ideal definition of software defined radio first of all, requirement of very high-speed D to A and A to D converters.

We know from the our nyquist criteria that our sampling rate should be higher than twice of the maximum incoming frequency when we are dealing with the very high RF components. For example, I have told you that we should work at 2 gigahertz frequency that we have the smaller antenna size. Right in that case what should be the sampling frequency of this D toA or A to D of course, for FC of 2 gigahertz sampling frequency should be greater than equal to twice of fc plus whatever is the band of that signal.

If this is the FC and this is the bandwidth theoretically for the nyquist calculation this will be the highest frequency. As I should be greater than this one now, if FC is 2 gigahertz and bandwidth is 10 megahertz. You can see from here it has to be easily more than 4 gigahertz, right? Now this is very high sampling frequency.

A state of the art D to an A to D converters they cannot have that much high speed although there are new inventions in the vlsi technology and there people are trying to reach it is still a limitation and if we go to even higher frequency ranges for example, mm wave etcetera then of course, it becomes a very hard limitation. There are some way around it and we will be showing those methods also how we can avoid this limitation or find solution for this limitation, but the another requirement which is of the high power to transmit signal to long distances.

We cannot avoid RF power amplifier now RF RF power amplifier by design is a completely RF component analog component. This will always be there and it has many issues many distortions related to this component. In this course we will also be covering the limitation of RF power amplifier. The limitations of the A to D and power amplifiers we will be discussing this limitation and what can be solutions to this limitation in this lecture further.

Thank you.