Basics of software-defined radios & practical application
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Lecture – 20
Digital Predistortion Techniques for Linear as well as Nonlinear Distortion in SDR

Hello everyone, in the series of basics of software defined radios and it is practical applications. We were discussing digital pre-distortion techniques for linear and non-linear distortion in software defined radio. So, continue with that discussion today, we will be covering the IQ imbalance in the transmitters. Earlier in the course in the previous lectures we have covered this effect which is happening because of the IQ imbalance in the modulators.

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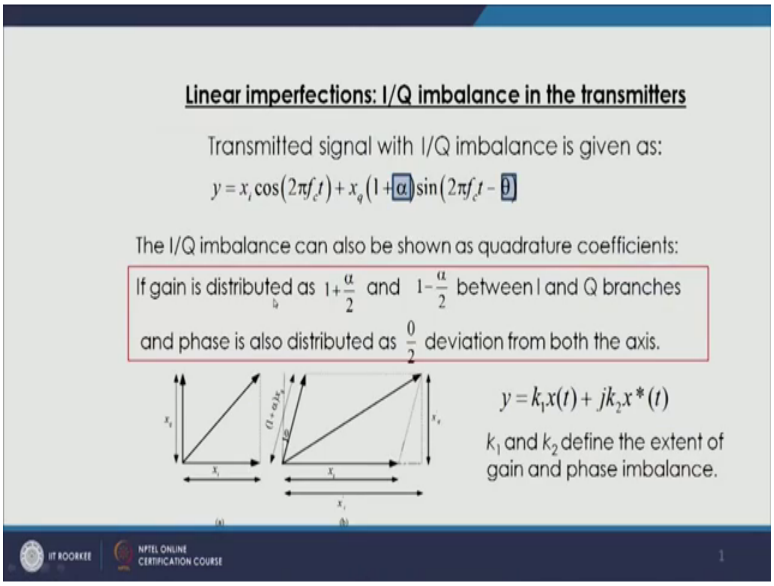

So, what happens in this effect? If you remember that instead of having a 90-degree phase between I and Q components; there is a tilt there is a phase shift of theta and because of that our actual values of xi which is the in-phase component and the out of phase component it changes. Eventually our rf signal which transmitted it is seeing something like that xi cos 2 pi fct plus x q 1 plus alpha sin 2 pi fct minus theta this alpha and this theta these are 2 values which are introducing this IQ imbalance.

Now, we have also discussed that this kind of effect actually can be represented as k 1 xt plus jk 2 x conjugate t where this xt is our basement signal in analog domain. Similarly, this analog domain signal can be represented as n. So, it will become yn in baseband in digital domain k 1 xn plus j k 2 x conjugate n in the discrete domain this k 1 and k 2 they can be tuned to define the extent of gain in a phase imbalance in the system which are observed at the system output.

So, what happens because of this IQ imbalances we also discussed earlier that if we are not considering even the power amplifier non-linearity. And only this IQ imbalance in the modulator path is into focus then if we are dealing with the intermediate frequency then you will see the.

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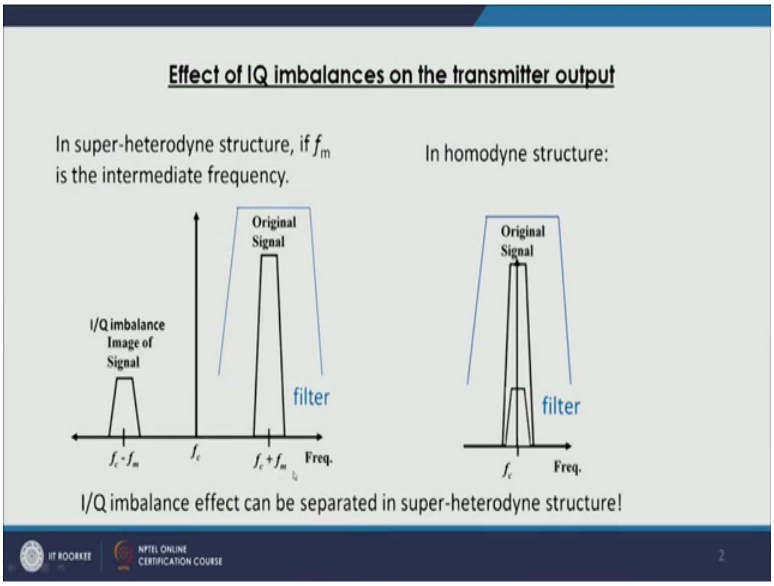

Original signal at fc plus fm which where fm is denoting your intermediate frequency because, of the IQ imbalance you will see one component and image of the signal at fc minus fm. Higher the IQ imbalance and higher will be the magnitude of this IQ imbalance image signal.

Now, in the case of if you also discussed that in the heterodyne structure, because image is at the fc minus fm. We can actually filter out of our original signal in this kind of a structure, although in homodyne structure because fm is equal to 0 this image is hidden inside the original signal. So, we can say that super heterodyne structure is better than homodyne in selection of the original signal, but we have also discussed that homodyne structures are basically more portable and more cost cost friendly. We have to spend less money for small structures. So, if we can somehow remove this image then we would like to go for this homodyne structure.

. So now, we will have a look at the techniques where we can remove this kind of image because of the IQ imbalance in the system without actually just doing the filtering. And we are able to remove these images which is even hidden inside the direct converger transmitters or homodyne transmitters. So, this is a structure of the homodyne transmitter and.

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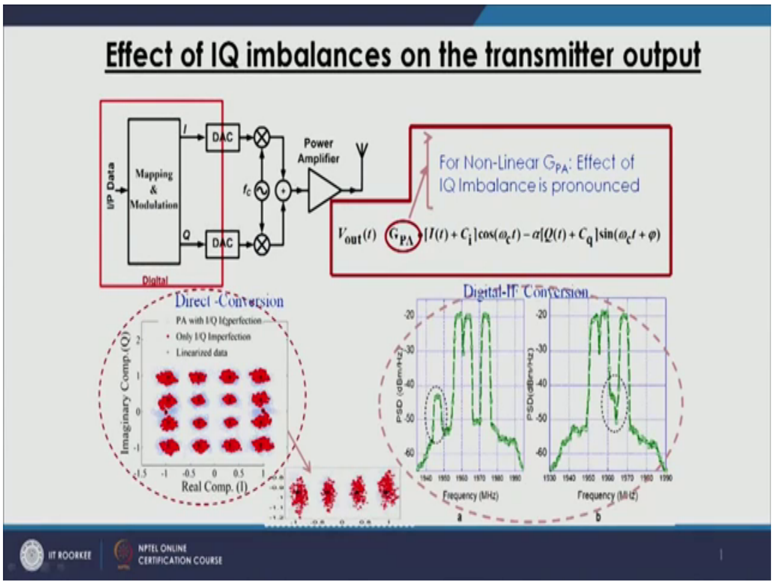

We have just given the fc which is the carrier frequency. So, we are not giving it a ie frequency there. In this case, our image is hiding inside it and we are showing our component alpha which is showing the gain imbalance and this phi which is representing the phase imbalance in the system. This Ci Cq are actually dc offset which we have discussed earlier.

What will be effect of such kind of system in transmitter when the PA is also there? So, of course, when we have discussed earlier we were not taking this PA into account. The distortion which is coming from the modulator when this distortion passes through this power amplifier, it becomes even more prominent there. Distortion level has gone upto a notch higher than what it was supposed to be earlier. In the form of constellation diagram, if you look at here this plus black sign these small signals are the original positions of the constellation diagram. or be called it linearized data this after removing this effect of power amplifier and the IQ imbalance. if we have only IQ imperfection imbalance is there then this red data is showing the distortion there the scatter from the original position of the constellation points.

If we magnify single row of this constellation point, we can also see the tilt and this tilt is coming from the phase imbalance phi in the system. If this pass if this data is passing through the power amplifier then this power amplifier with the IQ imperfection is given by this blue color data. and you can see it is even more distorted. So, of course, the impact of PA nonlinearity as well as IQ imbalance is more detrimental on the signal quality.

Now, what will happen? If it is at homodyne and distill if is there. So, if we look in this graph our center frequency is 1. 9 gigahertz here. And this signal is if shifted by 5 megahertz here. So, because of that the signal was 1101 around 1.9 6 and this is the if shift there. So, because this is the if shift. So, around it image will appear for this signal. So, how this image will work?

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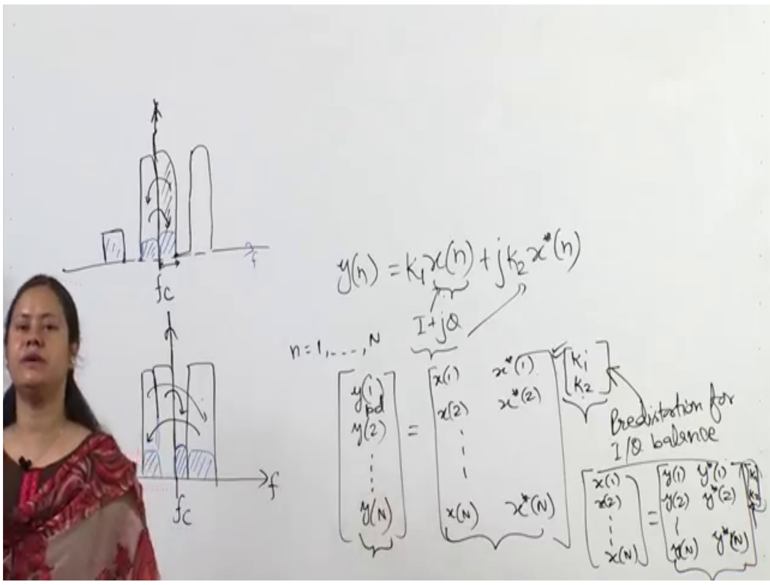

So, basically this was the original signal and signal carrier frequency is here. And this is the if this is the if value. So, what will happen because of that? It was the carrier frequency axis.

now, we know that because of the IQ imbalance image appears at the if distance. So, image of this carrier is falling on top of this carrier, which might be something small here, because of this you will have something like this here one image. Because of this carrier you will have one image here also.

Let us say it will be the image of this carrier in here because of this space because there is no carrier. So, there will not be any image here, but because of this signal at this distance we will again see one image, this one right. So, this will be image components these image components are hiding inside the signal. So, from our eyes in frequency domains we will able to observe only this one this signal here. So, it is frequency and this is actually the magnitude of the signal.

So, this is what we are observing here. This signal here is the image of which is appearing here and their other images also, but they are hiding inside the signal same signal 11 0 on now we are shifting and taking the data around this point the middle point. So, the same signal, but fc is not here anymore same signal 1101 previously our signal was here. Now, we are saying that our fc is here. So, around this point we will be seeing the replicas.

So, what we can expect there? Because of this carrier it will be having image here, because it is the image position for this one. So, it is image is hiding somewhere here we cannot see it because it is inside another signal. Because, of this signal there should be this image here. So, we will be seeing something here where there was nothing before before of this signal because of this signal, we will be seeing something in this carrier. So, we will be seeing a image here. We will not be seeing because we already have a carrier here. So, eventually what will we see? At the output because of IQ imbalance these carriers and then this this image which was not there and of course, there are other images also, but we are not able to see them from our eyes, because they are hiding behind the carrier. So, this is what we are seeing here this portion it is image of this carrier here.

So, in IQ imbalance case, for the digital life conversion we can actually see these components. In direct conversion, we are not able to see them, but both of them are detrimental for our signal quality and we should try to remove them. What is the set of IQ imbalance on the phase and gain characteristic? If you remember we have discussed digital pre-distortion and we try to model this signal in a inverse way. So, that it is able to cancel the nonlinearity of the system.

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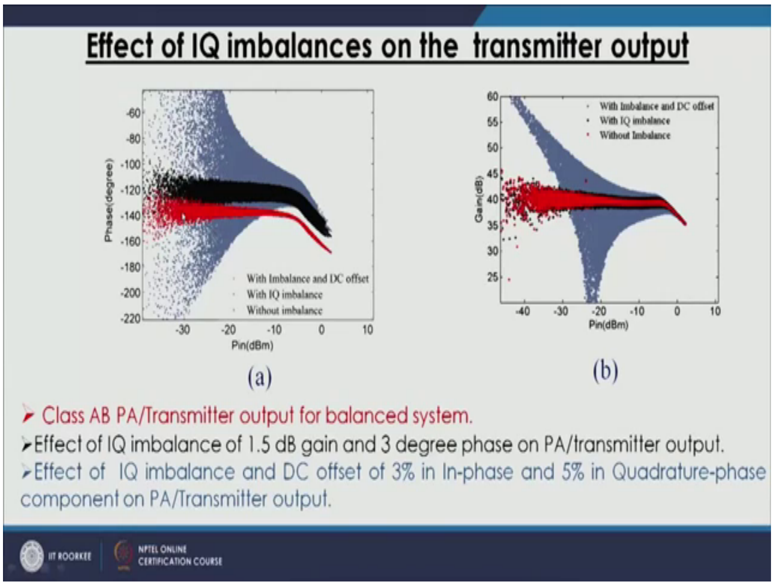

Now, if you look at the system, we are showing the data for a class a b power amplifier which is being used in a transmitter. For a system where there is no IQ imbalance the red one is showing this and we can see this is the phase nonlinearity is there and gain nonlinearity is also there. Once we have a system IQ imbalance of 1.5 dB gain and 3-degree phase on PA and transmitter output this black one is actually our output of the transmitter.

So, we can see that it has shifted by a phase ah. So, few degrees and it is the intent of the phase distortion here. Moreover, because of the IQ imbalance more dispersed kind of system we are seeing here. In the gain also we can see mode distortion the black one over the red one. And if dc offset is also there 3 percent in the I phase and 5 percent in the quadrature phase, then this blue one is the output of the power amplifier respect to input power and we can see it is it is very much broader it is much more noisy and it should be difficult to model, because they are. So, so much dispersion here.

So now we have seen the impact of this system at the p output. We know that what kind of modeling do, we require. And there are 2 approaches to remove the distortion because of linear and the non-linear.

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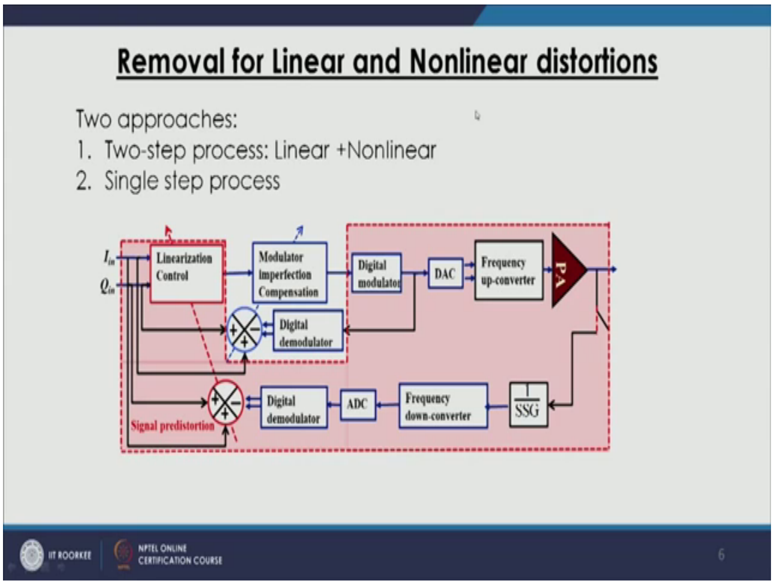

Distortion as we have discussed earlier these IQ imbalance effect they are called a linear distortion because, they do not contain non-linearity orders. So, yt or if I say in the basement domain for IQ imbalance yn was the function of k 1 actually the baseband function xn plus j k 2 x conjugate n. This xn is again I plus jq format it is a complex function in both of the cases.

So, basically if you if you look at this what is a this is a linear function? if I want to make a model for this it will be a linear model how we will make it if I am talking about and from 0 to n then not 0 integral value 1 y 1 y 2 up to yn. You will have only 2 coefficients like we are showing here. So, you will have x 1 x conjugate 1 x 2 x conjugate 2 and so on up to xn. And you will have only 2 parameters k 1 k 2 right.

So, the algorithms we have discussed earlier least squares least mean square. We can apply here in this case it is our output vector, this is our observation matrix and these are the coefficients we want to find. So, you will capture trainee sequence of n data and you will arrange them in this term and by using least squares you can easily find k 1 k 2. So, those k 1 k 2 will tell you the extent of IQ imbalance. So, those k 1 k 2 will tell you the extent of IQ imbalance.

So, this is one technique that first of all if you look here IQ data is being processed through the modulator through the DAC and then before digital to analog conversion after the digital modulator. We take the feedback and do the digital demodulation and get a IQ imbalance only because of the IQ path mismatch. So, we are not giving this data to PA. So, it is 2 step process first of all we take data before the digital to analog converter. we apply our predistortion here. So, how will we do the predistortion? By swapping x by y.

So, predistortion for IQ imbalance in offline mode we will do the mapping of x 1 , x 2 , till xn , y 1 y conjugate 1, y 2 y conjugate 2, to yn y conjugate n, it will be of this matrix and then you will have your k 1 k 2. this k 1 k 2 are not shown your IQ imbalance they are finding the coefficient of the predistorter.

So, we have swap the input by output output by input because modulator is not giving you any gain. power amplifier case you had gain which you removed in this case you do not have to worry about about that. So, when you find this coefficient then you can actually apply those coefficient in the actual path. for the original data and this y will be y pd here when you apply this data IQ imbalance will be removed once it is done an IQ imbalance is removed then you give that data to power amplifier and for this new data you will do the normal digital predistortion which we discussed earlier after removing the linear predistortion, sorry linear imbalances imperfections of the IQ imbalance.

Under the approach can be single step process in this process we simply take the data at the p output which contains the distortion, because of the power amplifier as well as the ADC and DAC paths the IQ imbalance between the 2 paths I and Q and we make a single model and digital domains. So, that it is able to remove the effect of both of the systems.

So now, let me show you a demo how we can pursue the 2-step process? And then I will give you a hint how we can apply the single step process?

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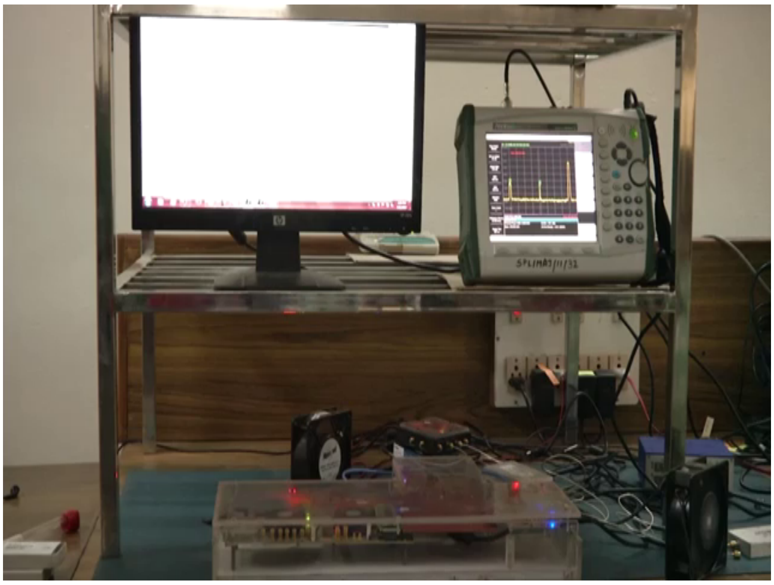

So, this is the setup which is using an FPGA and this FPGA can interacts with transmitter as well as receiver both of them. We are using 2 fans here and we are using power supply to provide the supply like 6-volt, 5 volt, etcetera. Whenever it is required apart from other receiver we are using an extract spectrum analyzer as a receiver. So, that we can observe the performance at the output of the transmitter and we are using personal computer for doing the processing of the setup.

We also have one local oscillator and this is the local oscillator which we are using to provide the carrier frequency to our system. And this local oscillator can be controlled by using the GUI provided by the Texas instrument.

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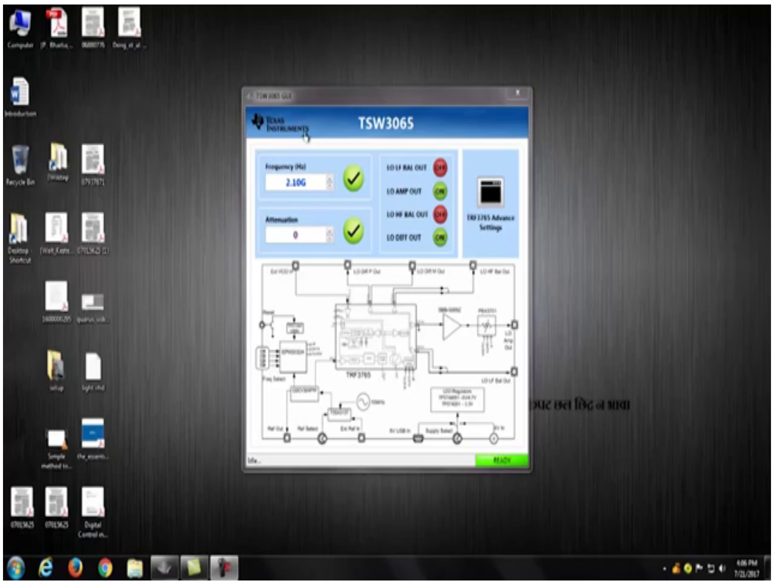

So, this is the GUI, as you can see here we can choose our frequency and we have selected frequency of 2.1 gigahertz. And by choosing this frequency our care frequency is decided we can also select power by this tab we are not by choosing the attenuation.

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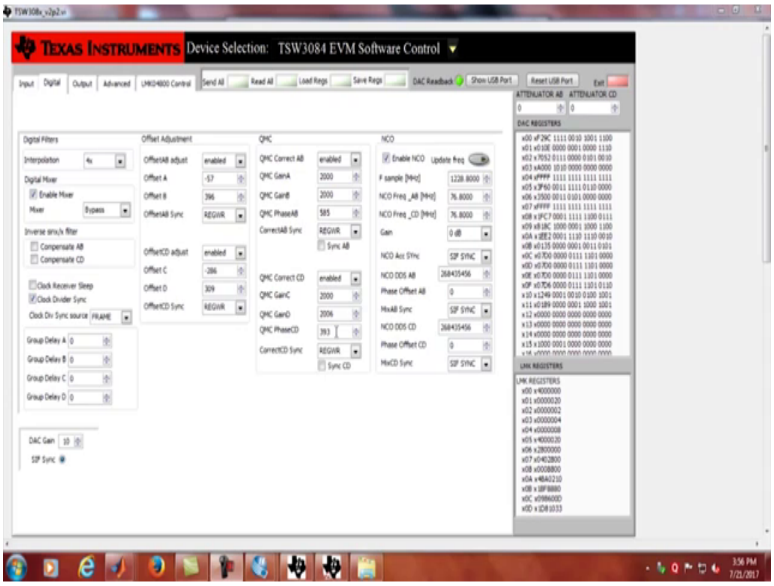

So, this was GUI which is coming with the transmitter. In the transmitter, you can see we have first input first output offset settings which we can select to avoid timing errors. Now, we have LVDs delays which again we can provide delay in terms of Pico seconds to I and Q paths and different lines in the within the lvds lines within FPGA to avoid the clashing.

We also see that we have data routes abcd. So, a b is representing first transmitter I and Q path c cd is representing I and Q path for the second transmitter. Now, we are giving them a sequence 01 2 3. So, this sequence 01 2 3 means we have already give given some particular data ah. So, priority number one data will go to a then to b to c and d we can also select, we can change this priority order and by doing. So, we can send different data there.

So, here apart from that we have some pll settings we are not using any pll setting right now, but we can select 2 cover pll there. Apart from that, we can choose our input data format your data which you are providing it can be 2s complement or you can choose any other meta by yourself. Apart from that we have parity styles, parity check and block parity we are not using them right now. This is the mean control panel you can see here that we can do.

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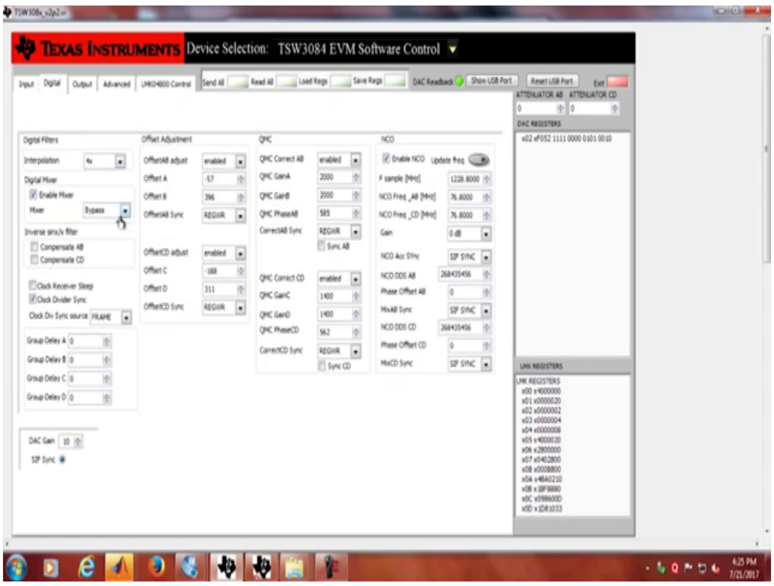

The IQ imbalance correction here by choosing different value of gains for the I and Q path. We can also put the phase directly by using Q mc phase.

. So, similarly for the dc offset we have settings a b for the transmitter 1 and c d for the transmitter 2. So, we have 2 transmitters here then we can use inverse sync function we discussed earlier that to move thus sync effect inverse of sync. We apply there and we can adjust group delay and by this group delay we can also reduce some of the IQ imbalance in the system.

Now, if we look at this compensation for ab and cd path for the sync filter, we can do them separately for both the paths if required. Moreover, interpolation we can choose for the sampling frequency what we want to keep. For example, we have 307 point 2 megahertz sampling frequency with the interpolation of 4 times we can select it to be 307.2 into 4 there are other options 1 2 8 and 16 we have chosen 4 which is suiting purpose.

now we can select the mixer or we can avoid the mixer. Now, this is the sampling frequency which we are getting after getting 307.2 into 4 and co frequency is actually digital if frequency which discussed earlier. So, we are choosing 76.8 for both the path we can change it easily and that will be the digital if shift of the system. So, apart from that we also have gain options there which we can use for both the path. We have 2 options we can have 0 dB gain or we can choose 6 dB gain which will be provided to each of the paths.

Now, we can do the synchronization by by using the sip sync function here and they are then aligned every time we do this. So, keeping this in mind we have the option of enabling NCO. So, we can either choose digital I f or if you want to use the homodyne way then we we can disable this nco.

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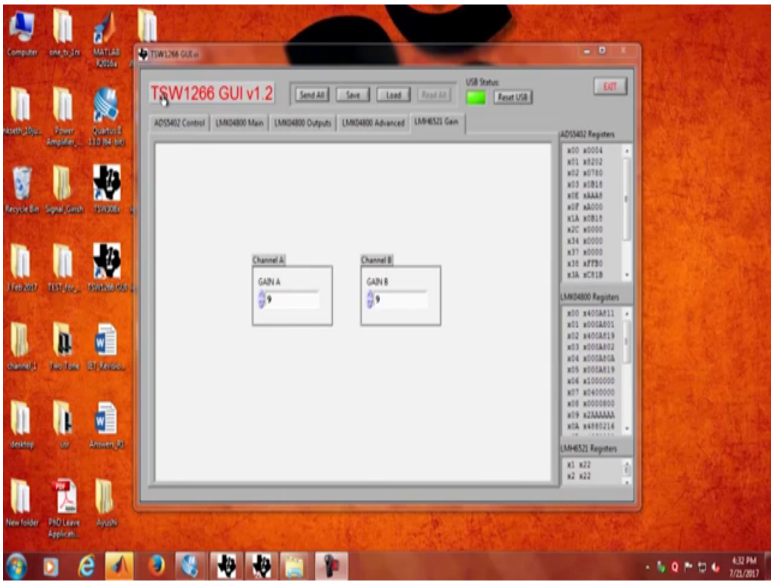

. So, in that receiver which are we are using is in TSW 1 2 6 6 in that GUI they also give the option of adjusting your gain of a and b both the paths.

Now, in this demo we are showing the IQ imbalance and you can see at the carrier frequency you have dc offset. And you can see on the right-hand side your signal and you can see small image appearing at the left-hand side. So, this is the IQ imbalance effect which we are facing from actual transmitter there. So, how can we reduce this? as I told you that we can use 2 coefficient just to tune it.

So, in this case instead of using least square and digital predistortion in 2 step, first step we are adjusting the IQ imbalance by tuning this k 1 and k 2 value. How can we do that? We have gain value c and d and in the ab path we have again different gains a and b. So, we can select those that we are also given the option of choosing the phase. So, we will be tuning these values to remove the effect of IQ imbalance.

for example, we are taking our data right now, from the lower path. So, we will start tuning these values similarly for the DC offset, we have offset a and b value which is dc offset in the both paths and for the second transmitter, we have c and d paths we can choose for both of them.

So now, let us see what will happen if we choose change these values. So, we start changing the phase of the path c d because we are taking data from the second transmitter right now. Which we are showing in the spectrum analyzer and if you observe here at the image this image is changing with the change in the value. So, they start taking big steps there for changing this offset value and you can.

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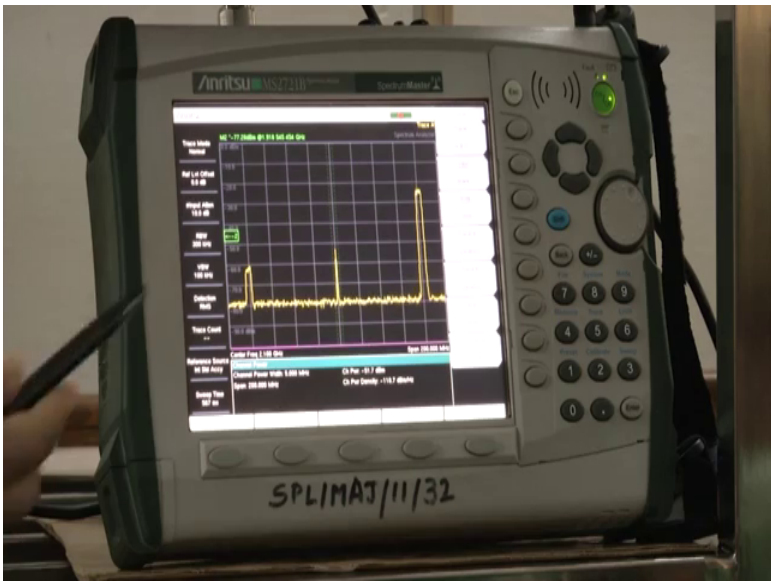

See that is IQ imbalance is reducing because we are tuning this coefficient k 1 k 2 by changing the phase variable there. So, by clicking it tuning by hand we are reducing it and you can see it is much smaller as compared to the previous 1 and if you keep tuning it in terms of gain and phase. So now, we are going to the gain of the d path you can see that we are again tuning. And it can go up and down now with the only phase and the d part 1 path we are able to reduce IQ imbalance almost completely image is gone now.

Now, we will focus on the DC offset which is appearing at the middle frequency. So now, when we are doing this we have set with the d path and once we are done with the d path, we will go to the c path to do this. Now, again on this field we are concentrating on our dc offset which is appearing as a carrier at the central frequency. So, we keep clicking there tuning there, we are not using any method there, but because they are only 2 coefficient Ci Cq and alpha and theta as we discussed earlier. So, by this tuning this DC offset is also going down. So, hit and trial method we are using and it will keep reducing and eventually it is almost gone. So now, our system is free from the IQ imbalance.

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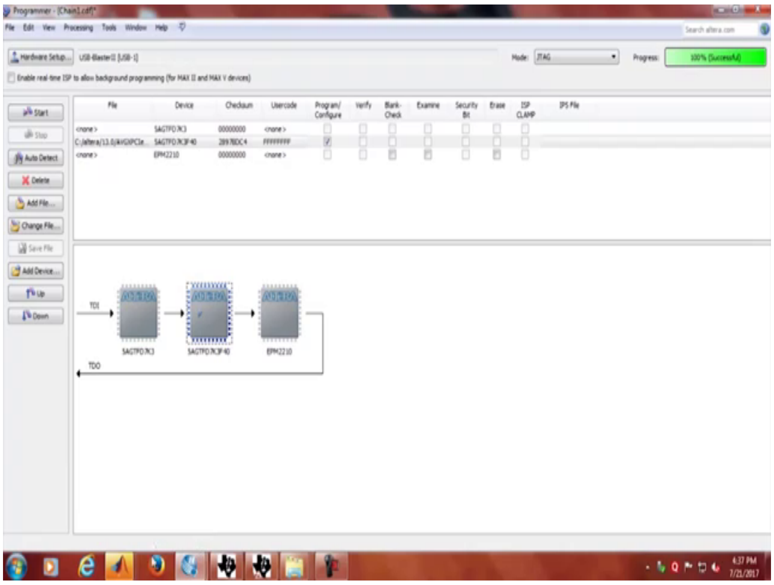

So now, we are sending our data for the transmission because we have removed the IQ imbalance in the previous step. We are controlling our FPGA from there we are engaging our device there. E and we have already coded the system which is standing data to our FPGA.

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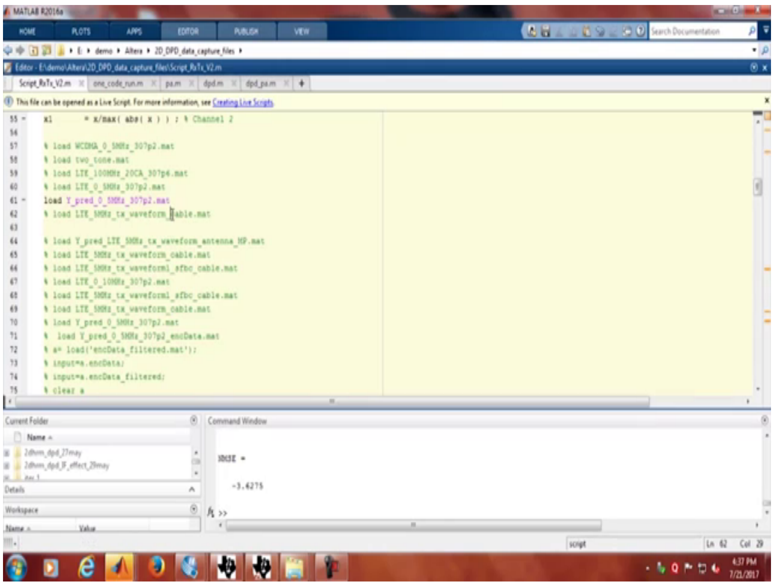

Now, in the MATLAB we are giving the command that this particular lte or w training signal should be loaded up there. So, that is done and they are running code and in the right-hand side spectrum analyzer it will see our actual signal, which is appearing there this is our LT signal which we are basically dealing with right now.

Now, we will be sending this data to the path where the power amplifier is attached. So, once we send the data to power amplifier you can see the jump in the spectrum analyzer and we can see auto band distortion. Suddenly the bandwidth of the signal has increase which is because of the distortion. So, this is what is being shown here and in the left-hand side our MATLAB plots are being plotted.

So, if we concentrate on that, we can see that our own receiver in the which is connected to FPGA it is also showing that distortion is there.

And it is also showing the error in the red if you perceive it closely and we are plotting mm mpm diagrams with respect to gain with respect to phase.

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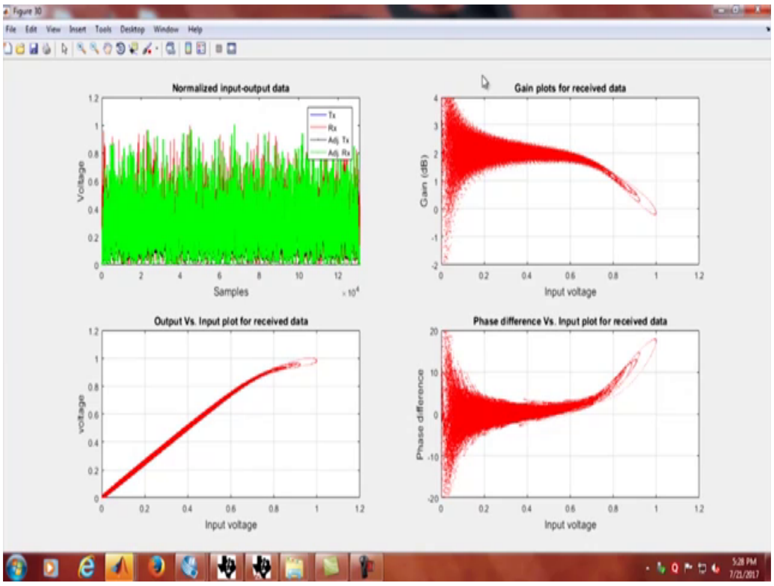

We can see that there is a compression of almost 2 dB and in the phase it is a compression of all not compression actually. Non-linearity but the expansion of almost 10 degree here if you see in terms of p out we can see that the power was linear for a reason and after that it became compressed. So, we are able to find the get the data from here and now we will use this data to do the pre-distortion.

So now, we have found our data, we have done the modeling, we have generated our previous sorted signal, we are sending that signal, we are running that program to send that signal here , we have made of a inverse model and we will be seeing that impact here by sending that data. And once we send this data you will see that suddenly though all the distortion will be gone down by applying that data. So, code has run and you will see suddenly our data is linearize because of p data is passed through the power amplifier. So, linearization has been acquired.

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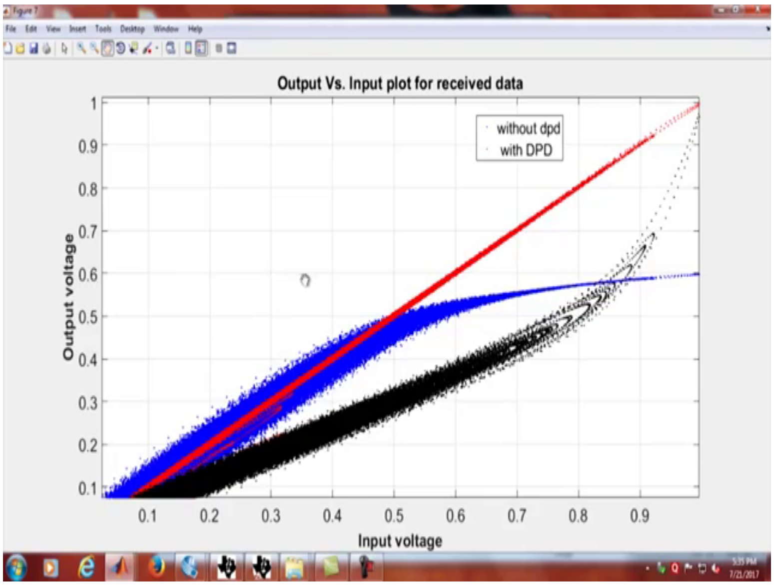

So, this is the linearized data and we analyze this in MATLAB also. So, we are plotting the data which we saved earlier the red one is actually one linearized data the blue was the data original data power amplifier data and the black 1 is the output of our model. So, you can see it is actually inverse of the actual data here and eventually their combination is giving the red data which is the linearized data. So, this is what was expected and we received it and in the spectrum laser, we are able to see the distortion which was out of band is also gone.

So, in the 2-step process we removed IQ imbalance first and then we removed the effect of nonlinearity by using DPD in single step we use the same set of for removing them IQ imbalance and the nonlinearity of power amplifier. Only difference is that we do not have to use 2 steps we simply use the tpt algorithm. the novelty is in the model itself.

So, earlier IQ imbalance we were showing here, it was by getting this coefficient value and applying them. So, this step we will not be using. We will be using a new model street and that model will be compulsarry for both the IQ imbalance as well as power amplifier nonlinearity.

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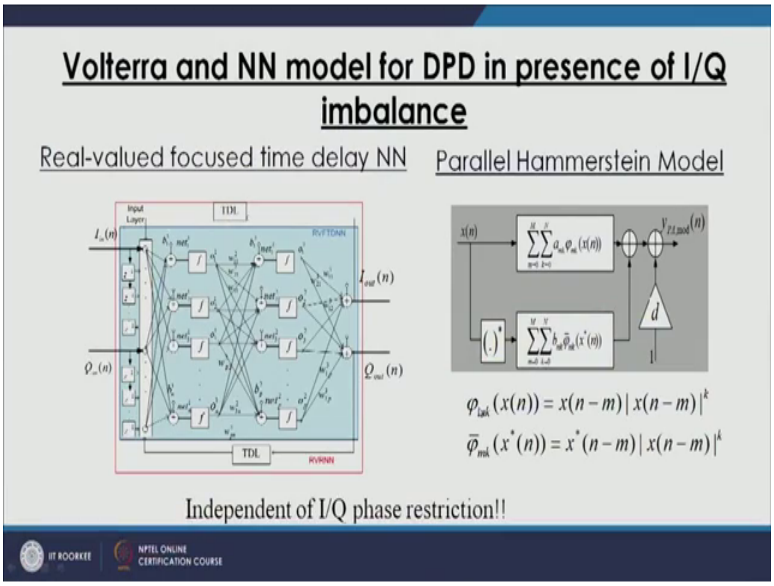

So, these are 2 popular models in the literature one is neural network-based model , the novelty here is that instead of applying I plus Jq we are applying 2 different inputs I and Q. Now we have made this I and Q independent of each other. So, k 1 and k 2 can be tuned by using these weights. So, input to this nueral network is I and Q data and the output is also in phase and out out of phase component itself. And all the distortion including PA as well as IQ imbalance is tuned by using this weight vector by using neural network technique ah.

Similarly, for the polynomial model we have this model here. We are using our polynomial term like we have used over the power amplifier, but instead of using only the power amplifier terms we have repeated the same term for the conjugate. So, in essential we are doing this term, but with the nonlinearity order norm. So, we can expand this matrix.

So, now, we do not have only 2 coefficients, but more than that.

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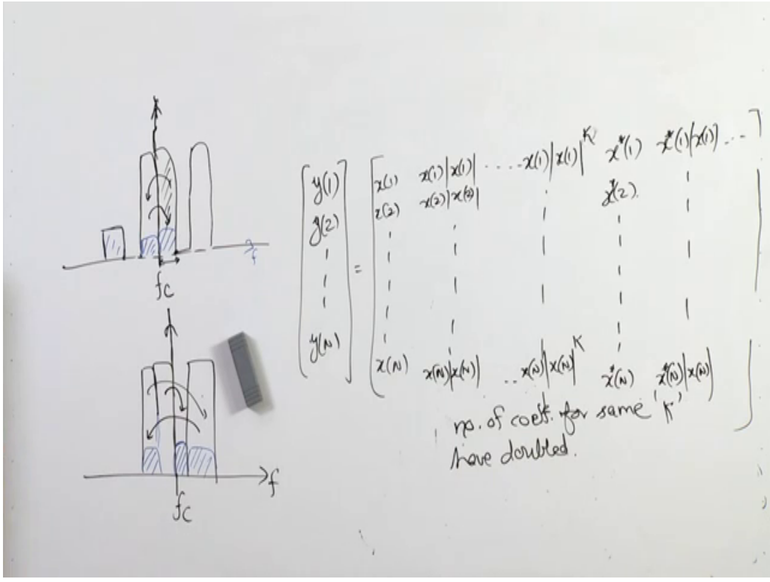

So, our data for the PA modeling in this case, becomes x 1, x 2, xn, x 1, mod of x 1, x 2, mod of x 2 and if you remember this was our polynomial model earlier to the power n. Which we wanted to work with or not n we were taking the parameter to be k k the nonlinearity order here.

So, same thing here xn, and xn, to the power k but after these kernels or these rows and this rows and columns we have decided we have a new column which will be having this these terms n non-linear terms of these terms x conjugate n and till to the power k. So, we will have all these terms. So, of course, the number of coefficient which were there earlier for the memory polynomial model they have doubled, because we are using the complex values here also. So, number of for same k and k is nonlinearity order have doubled, if we want to include the effect of IQ imbalance also.

So, what we have done? Because this effect was linear and the PA effect is non-linear we can merge them together give a new model and this model will be able to take care of both the effects simultaneously. So, one model of the neural network which takes I and Q in separately. So, that it is able to model k 1 k 2 effect or the polynomial model which takes the conjugate. And it it is conv it is more in line with it it is actual theoretical theoretical analysis by using this model.

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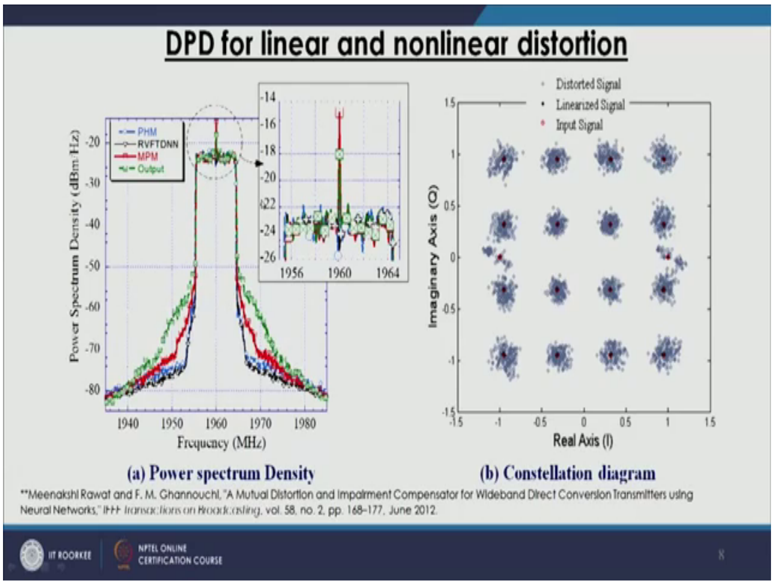

We are able to get the auto of band distortion in control and there are some results, in the right hand side, we can see the constellation diagram and the red marker here, circle is was the original input the distorted signal because of the IQ imbalance in the PA nonlinearity is the blue one and after linearization by using our model and digital model this black signal is falling clearly on top of the original signals. So, it has got perfectly in the real practical scenario.

In frequency domain, if you observe it the output v is given by the green signal. You can see the auto of band distortion here you can see that dc offset is appearing at the carrier frequency of 1.96 megahertz. So, this is the dc offset by using memory polynomial which does not take into account IQ imbalance. Some of the out of band distortion is going down, but if you look for the dc offset it is even getting higher. So, it is not good for this if we calculate the NMSE it will be very much for.

now, the proposed model of neural network which we have shown for IQ imbalance and PA nonlinearity. It is given by the red the black curve and we are able to see that it has reduced both IQ imbalance dc offset as well as auto of band distortion and same with phm model which is parallel Hammerstein model it is also able to compete here and it is given by the blue curve here. It will also removing the effect of IQ imbalance and PA nonlinearity. So, either we can go for the 2-step process as I had shown in the demo or we can use simply one model, we do not have to composite for IQ imbalance and one step it can be taken care of.

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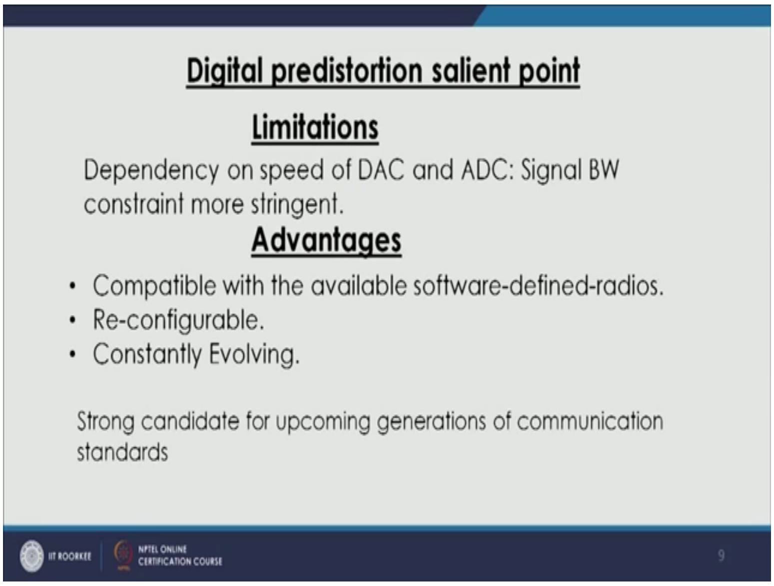

So, to summarize the digital predistortion cell yield point one limitation is dependency on the speed of DAC and ADC because signal bandwidth constraint becomes more stringent what do I mean by that? If signal bandwidth was 5 megahertz earlier, now you can see it is much higher than that as a rule it can be up to 3 or 5 times higher than the bandwidth of the signal. So, of course, the signal bandwidth requirement has increased by 3 or 5 times. Because we have to capture all this signal if we want to process the signal in digital domain.

If we filter any of this out it will not make a perfect model because we are missing the distortion data ah. So, this requirement is a stringent especially when we are going towards 5 g where we they talk about 200 megahertz bandwidth signal or 400 megabits bandwidth signal , then it will very difficult, because we will be dealing with 1 gigahertz sampling rate of the DAC and ADC.

So, this is no limitation and limitation is coming from the digital circuits, but the advantages are there also and they are very attractive for example, it is compatible with the available software defined radios as we are shown in demo just by using front end small front ends and the FPGA kind of devices. It is compatible because you are doing everything in digital domain supported by the software.

So, it can be ported from 1 place to another in another system easily. And because we are already using software defined radios for deciding the frequency and other parameters. So, we might as well use this for the digital predistortion to remove the effect of power amplifier non-linearity and IQ imbalance.

It is reconfigurable in nature it means, if a power amplifier changes or our IQ imbalance property changes, then we can tune our coefficient easily and we do not have to change anything hardware wise. So, it is a greater advantage because in analog circuits you have to change the whole circuit if anything changes in the main dut.

third main advantage is it is constantly evolving. Because it is main limitation is coming from the digital circuits of the DAC and ADC speed etcetera. And VLSI technology and properties of the DAC and ADC they are evolving very fast each day they are providing more and more high speed. So, it is constantly evolving. So, in turn it is also supporting our digital predistortion method very nicely. So, to conclude this digital predistortion technique is very strong candidate for upcoming generation of communication standards and with this I thank you for your attention.

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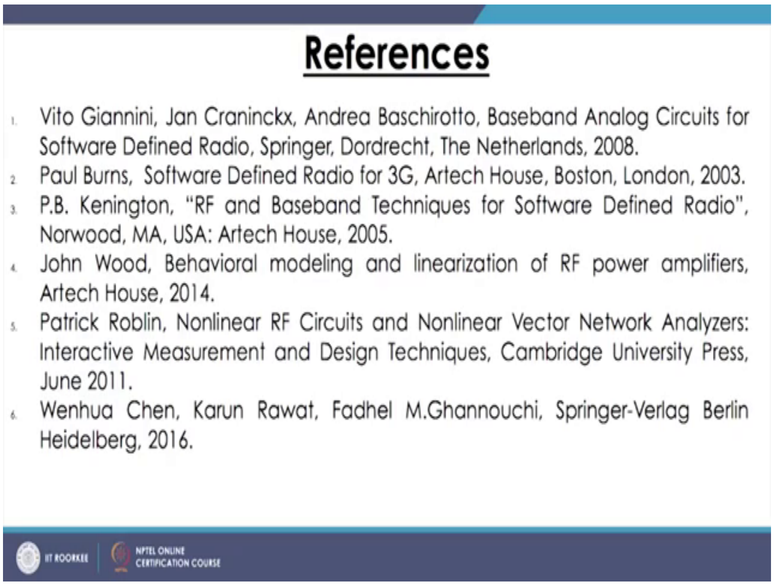

Thank you.