VLSI Data Conversion Circuits
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Lecture - 57
DAC mismatches in DSMs

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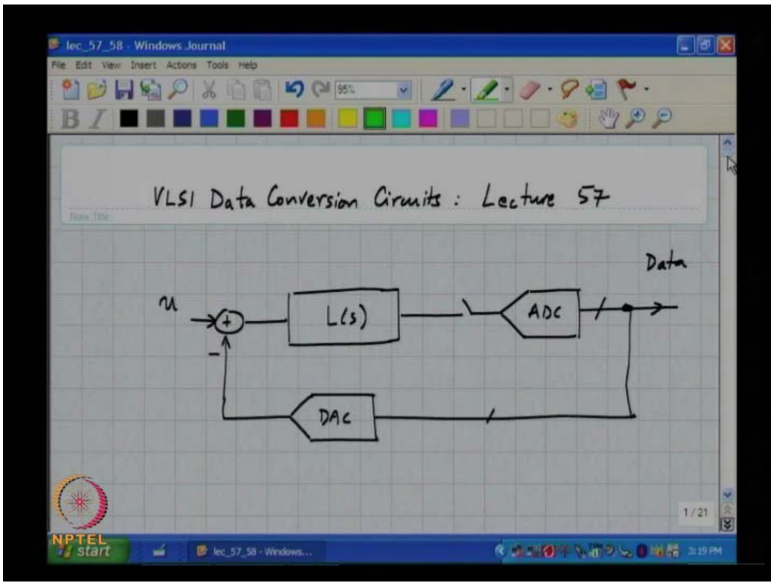

This is VLSI data conversion circuits lecture fifty 7 over the course of several tens of lectures we have covered the basic building blocks of a delta sigma modulator and taking a specific example here, where I am assuming a a c I f f type loop there is an ADC there is a DAC this is the digital data this is u. So, we have discussed in detail what this is and how 1 goes about realizing the loop filter, we have gone and seen in detail how 1 can go and design a converter which is got low latency and the most commonly used version of the ADC architecture is the. So, called flash ad c architecture where the time between the sampling instant and time at which the data is available is as smallest possible, then the flashes you know gives out data or bits in thermometer form and the DAC can also be realized as a thermometer DAC, we have seen all the advantages of a thermometer decoded version when we discussed DAC's.

So, we have seen this part of the puzzle too, one thing that we saw when we were discussing DAC's is that no DAC will be perfectly linear in the sense that the step size will not be the same for all codes, and the basic reason for this to happen is that whichever way you realize the DAC whether it is a bunch of conductance's coming together in parallel or whether it is a bunch of current sources which are switched there will always be device mismatch and the moment these devices are mismatched the levels will not be the same, now the details of whether you choose a binary weighted architecture or a thermometer decoded architecture are all just that they are details, but one thing that we must accept is whichever way we implement the DAC we are most likely to get stuck with non-uniform.

Student: Step sizes.

Step sizes and at present the only way there seems to be of making the uniformity of the DAC steps you know better is to.

Student: Segmentation.

Pardon.

Student: Segmentation.

Well segmentation makes the d n L smaller right, but if you have to improve the inherent matching what should you do. I mean the bottom line is that you must choose passive elements or transistors which are fundamentally better matched and that is only possible by making.

Much larger.

The devices or conductance's larger and larger and larger right the same holds for capacitors too though we have not taken a look at capacitor DAC's all right, now there is of course, only a finite extent to which you can go on making the DAC elements larger and larger right. So, if you want to improve matching beyond a certain point it may though it may be possible than principle, it is not practical simply because the DAC will now have to become. So, huge that the commercial viability of the whole converter is called into question.

So, today we will see how DAC mismatch effects a delta sigma loop, and see what we do about it in a way that does not increase the matching requirements of the DAC elements. In other words we would like to get in principle at least the ideal s n r, that you see in mat lab, where you assume perfect matching correct, but because the DAC elements are mismatched the levels will not be uniformly spaced a will go quickly over. What happens to the performance of the modulator as such given that the DAC levels are not uniformly spaced then we will see why this happens, and then we will figure out what all one can do in order to fix the problem you understand.

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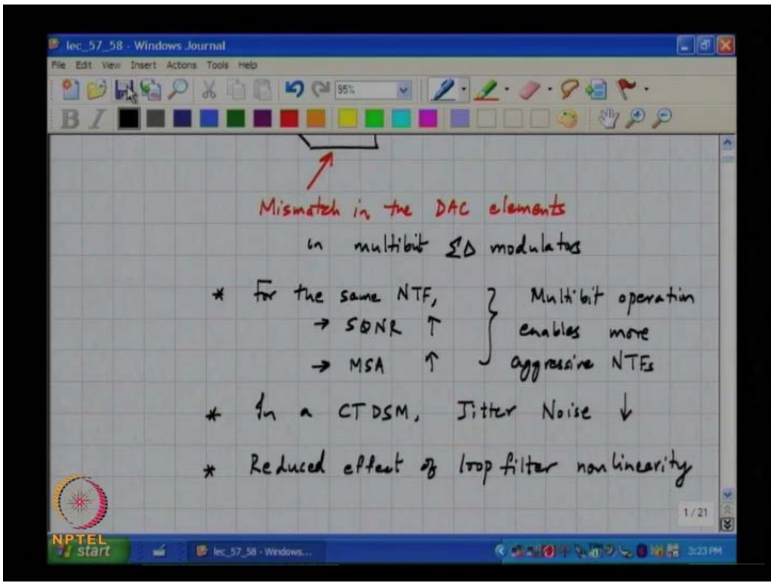

So, what we’re going to be looking at in summary let us see what happens when there is mismatch in the DAC elements; obviously, this is only relevant to a DAC with several levels if you have only a signal bit modulator then.

A single bit modulator is inherently linear because there’re only two levels and through any two points you can draw a straight lines. So, in principle there is no problem with mismatch at all when you have a single bit modulator; however, we have extensively seen all the advantages associated with multi bit operation namely what all advantages can you recall of using a multi bit modulator over a single bit one.

Student: Yes let us recall them quickly.

Pardon.

Student: For same NTF.

For the same and for the same NTF what happens what all happens.

(( )) not actually (( ))

SQNR goes up MSA.

(( )).

Also goes up all right then what else.

(( )).

In a continuous time DSM jitter noise not jitter, but jitter noise goes down what else.

Op amp nonlinearity.

since the input into the loop filter is the modulator input minus the.

Feedback.

DAC.

Feedback DAC output.

The feedback back output which is the input plus shaped quantization noise correct. So, what is going into the loop filter is that difference between the two and which is.

(( )).

Largely shape quantization noise. So, if the step size becomes smaller the peak to peak amplitude of this shaped quantization noise, also becomes smaller there by the loop filter is excited with signals which are smaller in amplitude which means that.

Nonlinearity (( )).

Nonlinearity is reduced all right what else can you say for a single bit modulator what we will choose the NTF to be.

(( )).

Pardon

Op amp and g m should be (( )).

How much.

One point three.

For a single bit modulator typically you find that the modulator becomes unstable if the outer band gain is much larger than one and a half whereas, for a multi bit quantizer you can use.

(( )).

A more aggressive noise transfer function because the stability of the modulator is in a lot better. So, in other words you can also use multi bit operation enables more aggressive NTF s does it make sense now

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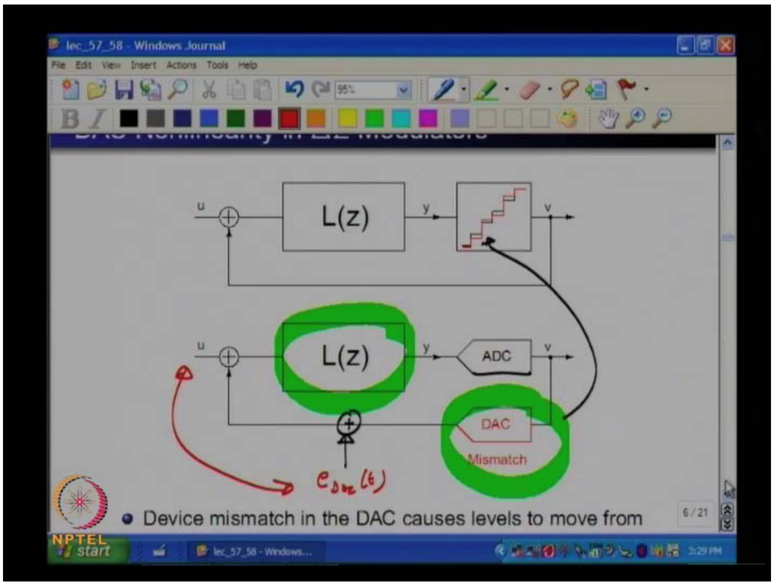

Let's see how one realizes the quantizer this is again just recap of the old stuff the quantizer as you all know is an ADC and DAC in cascade, and device mismatches whether they are in the ADC or in the DAC will cause the behavior of the quantizer to become not what you anticipated it to be correct.

So, if there is device mismatch in the flash ADC what happens to the behavior of the quantizer.

(( )).

Pardon

(( )) almost (( )) step is (( )).

What happens to the quantizer as such the quantizer is the ADC and DAC in cascade.

(( )) modulator shape.

Now, what happens to the characteristic of the quantizer once there is mismatch in the ADC itself.

(( )) are vertical.

Yeah. So, the key point is to note that if.

Four

The ADC has mismatched in other words there are the devices inside are not perfectly matched then the it is like moving the thresholds of the horizontal threshold of the quantizer which can also be thought of as adding some error here and fortunately this occurs in a same place as the quantization noise. So, the components of this error sequence which are in the signal band will get.

Shaped out

Shaped out by the entire noise shaping process. So, in other words while mismatch effects both the ADC and the DAC the effects of mismatch in the ADC are not within codes visible to the outside world simply because they are.

(( )).

Shaped out by the noise shaping process. So, we do not really need to worry about the mismatch in the ADC causing a change in the thresholds it is all noise due to mismatch is noise shaped outside the signal band all right, now let us see what happens when there is mismatch in the DAC now the elements inside the DAC are not matched either which means that.

(( )).

What happens to the how do you behaviorally module this as far as the quantizer is concerned.

(( )) providing the (( )).

The horizontal thresholds remain the same because the ADC is fine what changes the the output levels of the quantizer as shown in red in this picture if there is mismatch here it shows up as non uniform threshold in the DAC now the question is what happens to the performance of a modulator once the DAC has mismatch and at a very vague level one can say hey, if the errors are in the DAC levels one can model this as some kind of noise wave form or error wave form being injected at the output of the DAC right, but this is injected the same place as the input correct.

So, the poor loop filter cannot distinguish between what is.

The (( )) input.

The input and what is the in band component of this.

Error.

This error wave form right. So, the modulator at you know to a first degree will simply say am going to digitize as far as the modulator is concerned you can think of it as digitizing.

U plus e DAC of t U plus e DAC of t right. So, the in band component of e DAC of t will show up in the output spectrum is this clear

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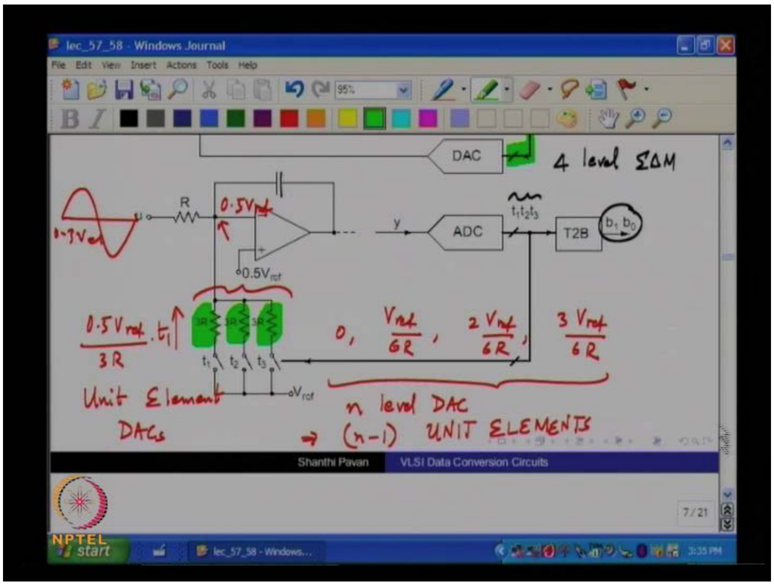

Now, let us see what exactly happens by taking an example and before that, I did like to remind you again that the flash ADC typically produces a thermometer code all right, and its quite convenient to use that thermometer code to drive the DAC directly if the DAC is also implemented as a.

Thermometer decoded DAC and most of the time the resolutions of the quantizer are modest may be 4 5 bits. So, implementing it as a full thermometer decoded DAC is not really a problem all right and this represents the.

(( )).

Thermometer to.

Binary decoding this can be done outside the loop there is no need for doing this in the loop doing in this loop is simply going to add to excess delay, because the DAC anyway takes a thermometer code, if you convert from thermometer to binary inside the loop then you need to convert back from binary to thermometer again which of course, is a apart from being a waste of resources is also bad in terms of delay. So, most of the I mean. So, it makes sense to do this thermometer to binary decoding outside the loop all right now to take simple example I have assumed a four level modulator.

So, how many comparators will be there.

Three (( )).

There will be three comparators and they will put out a thermometer code with three lines t 1 t 2 and t 3 and these will get converted into a two bit binary code b 1 and b 0 all right, now the DAC of which I have shown an example here is simply three conductance's of value a 1 by 3 R in parallel, and the three thermometer decoded lines go and control these switches t 1 t 2 and t 3, if t 1 is high the switch is closed and what will happen to the current.

(( )).

What will this voltage be.

Assuming (( )).

Assuming the op amp is ideal this is half way V ref and this is V ref. So, this current will be.

(( )).

It will be point 5 V ref by 3 R times t 1 if t 1 is 0 the current is 0 there only reason I have chosen this strange half V ref and V ref is. So, assuming that we are working with a single supply system where u is centered with half V ref and then rides over that half V ref is this clear.

So, the levels of DAC are 0 when all the 3 bits are 0 V ref by 6 R all right 2 V ref by 6 R and 3 V ref by 6 R. So, if you have I mean this is probably obvious, but if you have an n level DAC you need to how many conductance's.

N minus one.

N minus one.

You need n minus one conductance's there is no wholly reason to choose conductance's 1 could have had.

Current.

Current sources instead and in either case each of these elements are called unit elements, because they provide each element provides one step of the feedback DAC wave all right, DAC's like this you could I guess also call them thermometer DAC's in the delta sigma literature they are often called unit element. DAC's is this clear unfortunately these three conductance's are not.

(( )).

Mismatch.

Exactly identical to 3 R there will be small random variations between the 3.

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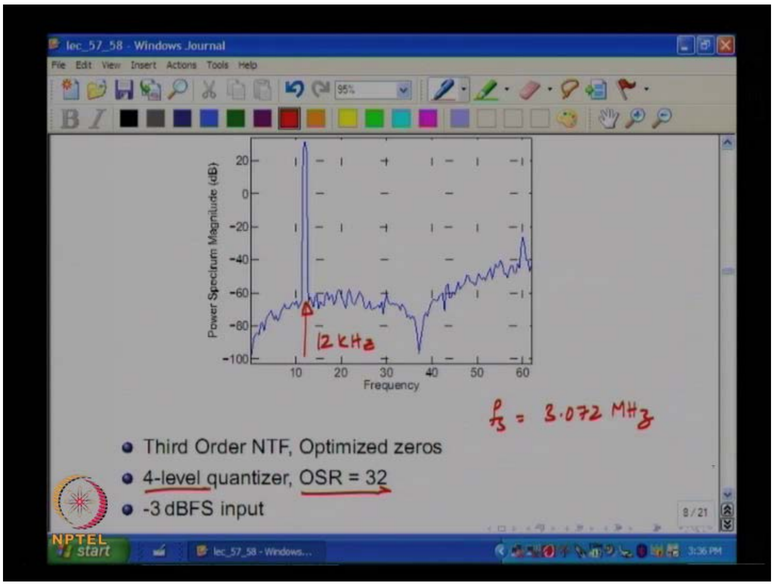

Now, that we have got this out of the way let us run an example where I have simulated a third order noise transfer function sampling at 3.072 megahertz of 4 level quantizer please note 4 level not 4 bit though zero sampling ratio is about 32 and the noise transfer function is such that the zeros of the noise transfer function not all sitting at z equal to one right, there are 2 of them are moved on the unit circle. So, as to minimize the in band noise and from your assignment you must have seen that for a third order modulator moving the zeros making them complex conjugate improves the SNR over that where all the zeroes are at z equal to 1 by 8 d b all right.

So, as you can see there is a shaped quantization noise, this is the input tone sitting at twelve kilo hertz all right this is the spectrum at the output of the modulator without.

Mismatch (( )).

Without any DAC mismatch all right the moment I have put in DAC mismatch in the three elements I have chosen quite randomly a five percent random mismatch in the elements.

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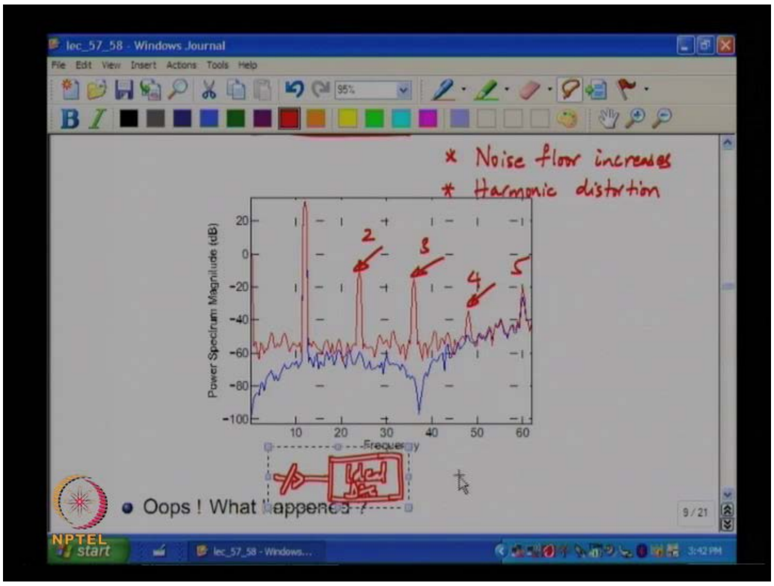

And low and behold the in band spectrum which I was expecting or wanting to look like this now looks very different all right. So, what all do you notice is the difference between what I want and what I have.

Noises its increased.

Its noise floor has (( )).

So, two things are evident.

(( ))

One noise floor increased and two.

Harmonic distortion strangely you see or you might say strangely at first sight you see al harmonics not just you know second or third harmonics, which are commonly used to seeing in when you do amplifier designs you will find that other harmonics are way lower, but here you see that not only do you see second third fourth I mean a gamut of harmonics right.

So, the question is a why is the noise floor rising and b why is the distortion right. So, can we any intuition on why these observations make sense why you think this make sense.

(( )) when the (( )) to inputs. So, noise floor will definitely go up.

Ah well I do not know why.

Gap mismatch typically gives you (( )) with an (( )) with an (( )) adding 2 input to input.

That's correct the that tells about spectral property isn't it. So, why do you think this makes sense.

(( ))with nothing when nothing is (( )).

what kind of noise will occur, and why do you rather how would you conclude that you are multiplying the input which input.

with a.

Nonlinear (( )).

and how did you get this observation.

(( )).

No let us build on what he is saying.

(( )).

He observes that the distortion is happening because you are taking the DAC sequence and multiplying it by a nonlinear.

I mean well by multiplying it by a non-linear curve what he actually means is that he is taking the DAC sequence which is sequence of integers in this particular case going from zero to the DAC sequence is what how many levels are there in the DAC.

(( )) 4 level.

It is a 4 level DAC. So, the outputs are integers going from 0 to 3 ideally that is without mismatch with mismatch it is you can think of this as the ideal DAC

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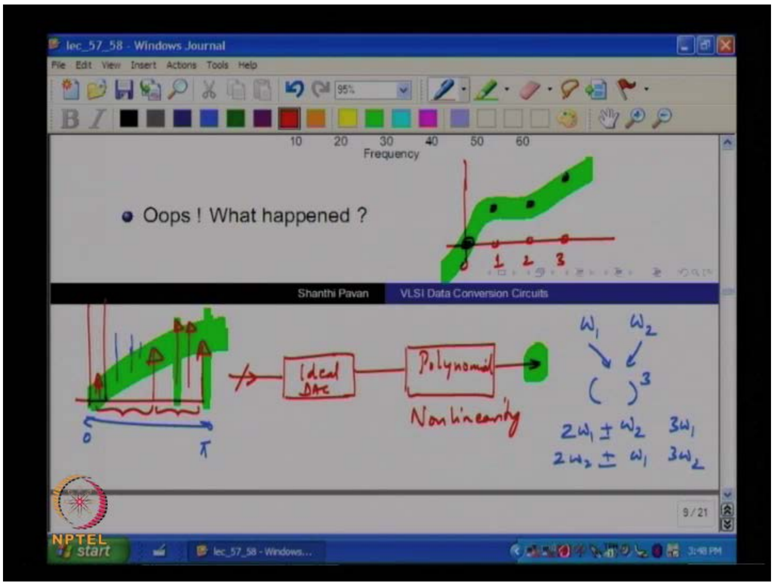

And the real DAC is putting out sequence you can think of the real DAC with mismatch as putting out a sequence where the step sizes are not linear or the step sizes are not equal. So, you can think of this as a mapping which takes 0 1 2 3 and generates something which kind of struggles a straight line, if there was no mismatch the outputs of the real DAC should also have been 0 1 2 and 3, but what is actually happening is that the outputs are different. So, instead of staying on a straight line the output voltages have weird off, and you can think of this as I mean in many ways 1 way thinking about it is I take this sequence and pass this through some non-linear curve all right, and the only thing I need to worry about since the input is a discrete bunch of points is that I all that need to do is find some function, which fits these 4 points clearly that'll not be a straight line because the points are weird off due to mismatch. So, in this particular case you can think of a third degree polynomial which will fit this input output data is that clear. So, this is some kind of nonlinearity clearly this. So, called non-linear curve will have a large linear component and very small terms of the form you know x square x cube and so on, but what happens when you take the input spectrum of the DAC is say something like this is the signal and this is the shape quantization noise what happens to the spectrum here after you take this sequence and pass it through a polynomial.

(( )) receive a.

What will happen.

(( )) harmonics (( )).

first we should expect of course, harmonics right what else .

And alias with d c voltage.

What aliasing I am taking a discrete time sequence and I am passing it through nonlinearity so.

(( )) the out of band noise can it can mix with the moist in some other component and.

so in other words we seem to have a had a handle on how to explain distortion, now it seems as if it does indeed make sense there is distortion, because you have taken a sinusoid and passes through a nonlinearity, now when you take this DAC input whose spectrum is not only signal, but also consists of shape quantization noise it has got frequency content all the way from 0 to pi right. So, if you take 2 sinusoids at omega 1 and omega 2 right and you add them up together right that is what this spectrum is telling you is telling you that there's some component at some frequency omega 1 there's some other component at frequency omega 2 and. So, on right when you take a sum of sinusoids and pass them through a nonlinearity what happens for example, if you take 2 sinusoids at omega 1 and omega 2 and pass them through a cubic nonlinearity what all components can you expect.

We can expect a inter modulator (( ))

You can expect components at 2 omega one plus minus omega 2 two omega 2 plus minus mega 1 and of course, three omega 1 and three omega.

So, if there was a component here and a component here when these 2 pass through a third order nonlinearity what you will get is stuff here 2 f 1 minus f 2 is equally spaced from you know f 2 and. So, 1 will be 2 f 2 minus 1 and other 1 will be 2 f 1 minus f 2 all right similarly, if you have 2 closely spaced tones and you pass them through a second order nonlinearity what will happen, we will get f 1 minus f 2 and that is sitting in.

In base band right in the in the band of interest is this clear. So, this should explain or at least give you some intuition as to why 1 not only expect to see harmonics of the input tone, but also arise in the in band noise.

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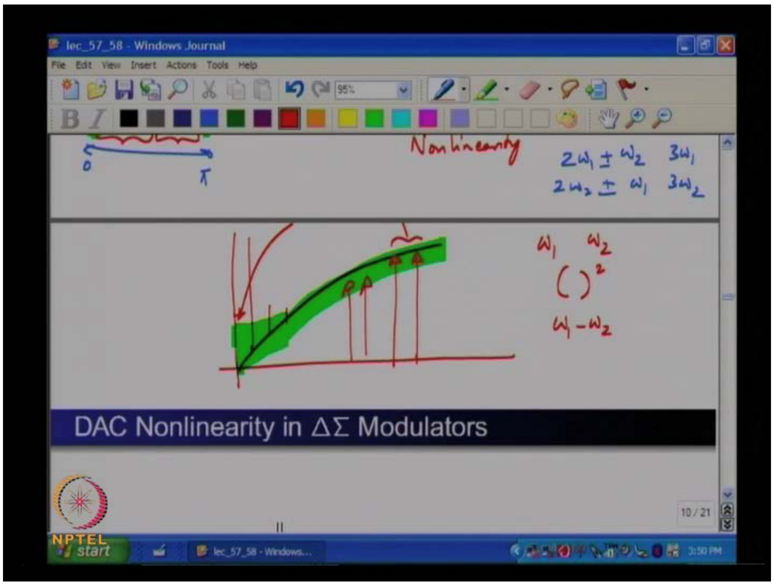

That in band why do that (( )) are very close to the there’re close each other there that will only come back.

No the input to the DAC is like this. So, I can find any number of tones which are close to each other.

Close to each other and these 2 will inter modulate through the second order stuff and fold back and these 2 will do the same thing and so on, and so on right.

(( )) even if the (( )) if the sum is more than pi then be equivalent to the adding differentiate to (( )) suppose now 1 is a pi by 2 and other is at say pi by four.

No you will get the difference, if you have omega 1 and omega 2 and you pass them through a second order nonlinearity you will get a component at omega 1 minus omega 2 all right. So, this within codes very vague intuition as to why 1 must expect the in band noise floor to rise you must understand that finally, all these you must talk about in terms of auto correlation function and power spectral density right, because we have assumed that quantization noise is white and uniform and all that and the spectral density of the noise is the shaped thing all right and. So, you have to actually to calculate the in band noise what 1 would have to do is to find the auto correlation function of a sinusoid plus shaped noise upon passing through a polynomial type nonlinearity this is in general is a is a difficult problem to solve right, and at any rate it is quite messy to solve and in any at any rate we are not really interested in you know the exact value of how much in band noise is there and so on right.

We are more interested in eventually what to do to.

Is to get rid (( ))

Get rid of the problem. So, its sufficient if you have intuition as to why this is happening is this clear ok.

Sir

Yes

We assume that the noise due to DAC; that means, DAC level mismatch is white.

Ah no why.

I mean if we if you have only 1 DAC and the input is input is some binary code.

Which is equal states. So, the mismatch of the DAC will be some of white why.

No why

Because when you in the assignment that we did we gave white we gave the DAC levels should be.

No the mismatch in the DAC levels will be uncorrelated right.

Yes

But please note that that spectrum is going through some nonlinearity. So, as you can see the error is definitely not right there are there are tones. So, all you can say is that this error wave form will have definitely components within the.

Signal band.

Signal band and you must also not forget that when you take a sinusoid plus noise and pass them through a nonlinearity the sinusoid is also interacting with the noise. So, I mean this is a grand mess. So, the only thing you can say for sure is that in band you will see both harmonic's of the input tone as well as the noise floor rising all right I mean I guess I could also kind of hoped against hope that somehow this error wave form we know that adds in series I mean at the same place as the input, but if somehow as serendipity it turned out that the spectrum of this error wave form had no in base band components or no in band component then we would not have to worry about mismatch at all you understand is this clear.

The problem is unfortunately that when you take the signal plus shaped quantization noise and pass it through nonlinearity you will get harmonics as well as an increased in band noise all right. So, now, let us try and understand why this is happening ok.

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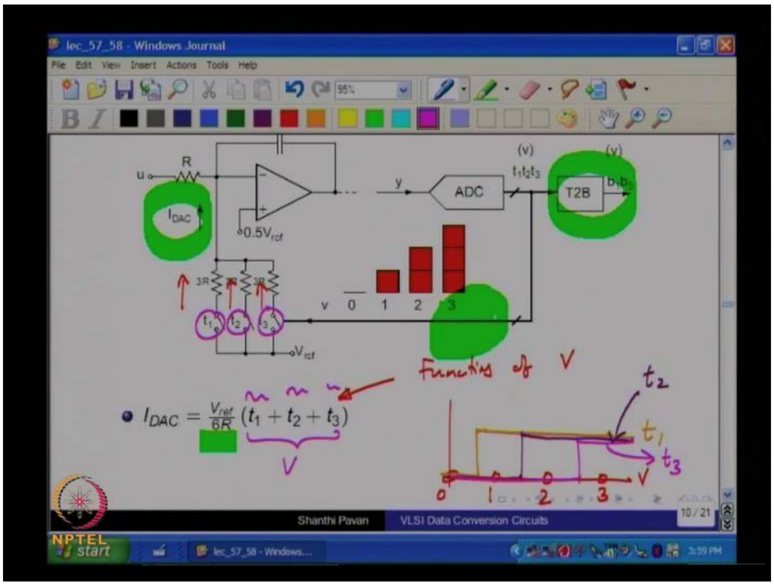

So, we have the intuition about why we should expect tones and raised noise floor let us you know look at it in a little more detail hopefully this will give some intuition on as to what to do to fix the problem, again let me go back to the thermometer DAC example that I was showing you earlier the DAC current I DAC is simply half V ref by 3 R that is V ref by 6 R times t1 plus t2 plus t3 all right, now t1 t2 and t3 these are the thermometer code outputs correct and these are clearly functions of V right and its another matter, that we decide to implement this thermometer to binary conversion outside, but if you had conceptually considered the ADC as producing a binary code v all right from which you internally produce the thermometer code then you can say that these 3 drive signals for the 3 elements unit elements of the thermometer DAC are functions of the output of the ADC is this clear yes no. So, what functions are these how are t1 t2 and t3 related to V what all values can we take on 0 1 2 and 3 all right and what values can t1 take on value 0 or 1.

Only t 1 t2 and t 3 can only take on values 0 or 1.

So, let us start by drawing within codes the transfer curve for t1 as a function of V right and what is the motivation for doing this t 1 clearly depends on V in some fashion we are trying to figure out what that.

Pardon.

For v other than 0 (( )).

So, for v other than 0 t1 will be one. So, I would not be inaccurate if I say that t1 can be related to V by a transfer curve of this nature what about t2.

(( )) you shift to d by a then 1 to the (( )) quantum (( )).

So, t2 is related to V in this fashion.

(( )).

T 3 is related to V in I can draw a similar picture for t three.

(( )).

Is this clear all right and why I am. So, curious to try and find t1 t2 and t3 as a function of V the reason is that the I DAC can be thought of as coming from three components right t1 t2 and t3 each multiplied by V ref by 6 R V ref by 6 R are constants. So, we would not have to worry about it. So, what you can think of this thermometer DAC as doing is its taking the signal V it is separating it into.

(( )).

Three paths right and.

(( )).

Converting each path or converting into 3 signals t 1 t 2 and t 3 such that t 1 plus t 2 plus t 3 is always equal to.

(( )) t1 plus.

No what is t1 plus t2 plus t3 V.

t 1 plus t3 equal to V correct all right. So, you can think of the thermometer DAC as doing the following it is taking the input sequence V separating it up into.

(( )) 3 common.

Three common.

Three sequences right converting each one the sequences into a current and adding the currents up you understand, now how is it separating the input sequence V into these three sequences.

(( )) thermometer.

I mean or in other words how are t 1 t 2 and t 3 are related to V.

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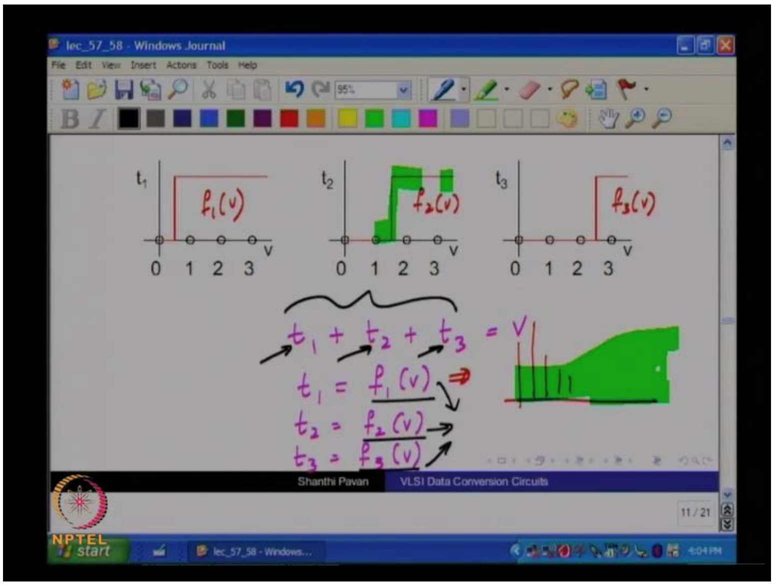

It is the thermometer plus d c.

t1 plus t2 plus t3 thermometer (( )).

t1 plus t2 plus t3 equal to V that is correct right and what I wish to point out is that t 1 t 2 and t3 are nonlinearly related to V correct t1 plus 2 plus t3 is always equal to V and t1 is some non-linear function f 1 of V t 2 is some non-linear function of f 2 of v and t3 is some non-linear function f 3 of V all right and the non-linear functions I have shown here this is f 1 this is f 2 correct.

Now, if you take a sequence V whose spectrum looks like this and passes the spectrum through a nonlinearity of this form what can you expect in general how will the output spectrum look like in other words how will the output spectrum of t1 look like.

You will have harmonics, because this seems like a pretty stiff nonlinearity correct. So, you can expect all kinds of harmonics and what else.

In band noise the noise floor in band noise floor in band noise floor will also increase because you have taken this sequence with this spectrum and pass it through a nonlinearity right. So, just like we discussed earlier you can expect that the p s d or the spectrum of f 1 of V which is the same as the spectrum of what is f 1 of V.

(( )) the output f 1 of V.

What is f 1 of V.

(( )).

T 1 correct. So, the spectrum of t1 can expect can be expected to be consisting of not only the input right, but also its harmonics as well as some the in band noise is no longer small because you have taken V which has got no in band noise a very little of it at any rate and pass this through a nonlinearity and this nonlinearity will cause frequency components from everywhere to fall into the signal band is this clear. So, all right similarly for both f 2 and f 3 in other words the thermometer DAC is splitting up the input V into 3 components which are non-linear functions of V you can think of it as converting each of these 3 non-linear sequences into wave forms and adding up the results correct

Now, if there was a perfect matching even though f 1 f 2 and f 3 are horribly non-linear functions of V when you add these 3 together what spectrum must you expect.

I mean t2 plus (( )).

Pardon

(( )).

T 1 plus t 2 plus t 3 is v.

(( )).

Correct all right. So, even though the spectrum of f 1 of v f 2 of v and f 3 of v which are the same as t1 t2 and t3 respectively right have a lot of distortion and an in band noise floor which is very large when you combine these 3 signals together magically.

(( )).

R t s by construction the distortion and all goes away and the noise floor does down, also goes down and it will reach I mean it will be V. The spectrum of V you understand is this clear

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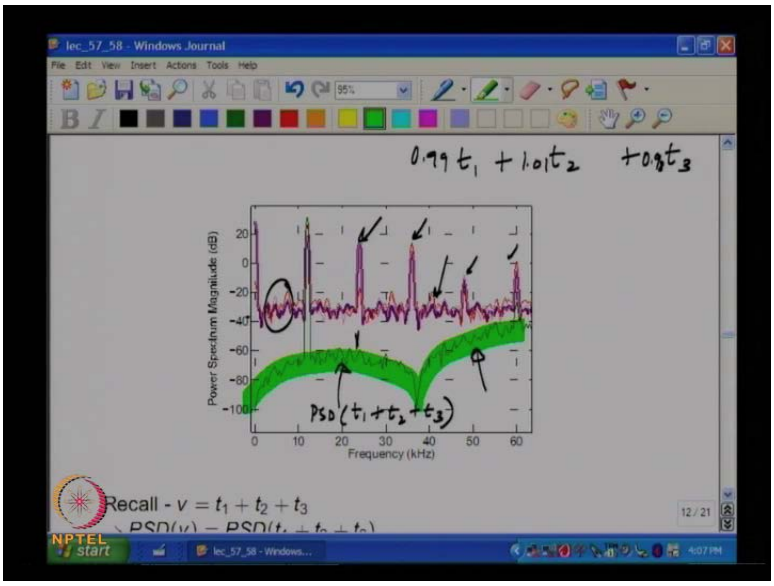

So, this is what I show here all right. So, these are there are actually three spectra here corresponding to each of the thermometer code drive wave forms, and you can see clearly that each of them has got awful amounts of distortion and an in band noise floor which is very large; however, this is the PSD of t1 plus t2 plus t3 and these wave forms are precisely such that when you combine them with exactly weights 1 1 and 1 right all, these harmonics exactly cancel and these noise components also add in such a way that the resulting noise is this that is simply the shaped quantization noise which is characteristic of v in the first place does it make sense so far.

Now, what do you think will happen if. So, in other words if t1 and t2 and t3 are precisely combined with weights 1 1 and 1 you will get this spectrum. So, the weights are off by small amounts. So, instead of 1 1 and 1 let us say this is point 9 9 1 point 0 1 and point 9 8 what do you think will happen. The cancellation will not be perfect. So, you will see some.

(( )) incremental noise.

You will see some.

Harmonics.

Noise floor harmonics

You will see some residual harmonics and some residual.

Harmonic noise floor.

Noise floor and if that happens to be much higher than the shaped quantization noise then that is the 1 which will dominate does it make sense we will continue in the next class.