Design for Internet of Things
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Lecture - 24
Buck Converter - 02

Welcome back. What we were discussing was about the buck converters right? Let me point you back to this picture here.

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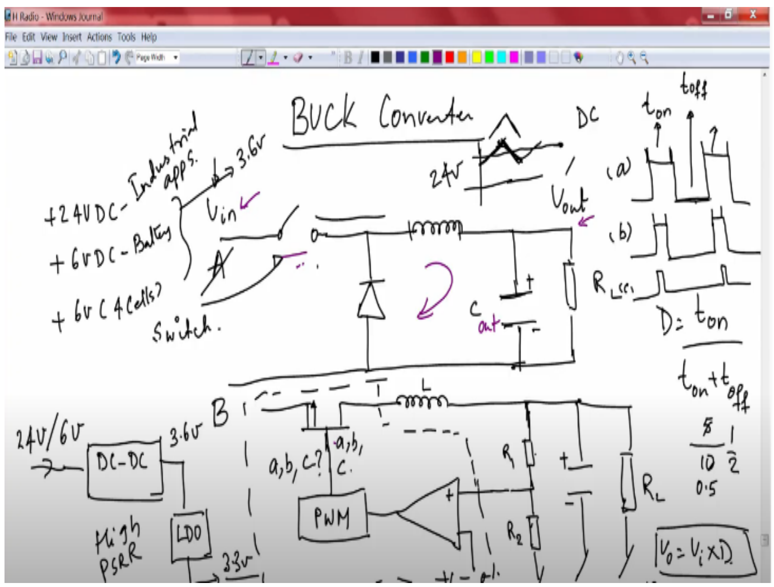

We showed that this is a simple picture of a buck converter. What do you have here? You have input voltage and you have an output voltage coming here. The input has to be higher than the output voltage. That is when you call it a buck converter and you have a transistors switch here and you have the diode for the off condition of the transistor. So, that the current continues to circulate in the circuit here. And this is the output capacitor.

This is C out and this is the load resistor and we said equivalently you can replace the switch that you see here with this MOSFET here. Then you have the PWM signal being generated based on the comparators output and that is controlling the gate that you can see here and this is the output inductor, these are the sensing resistors. This is the output C out which is the output capacitor and this is the load. This picture we understood very well. How practical this picture is the question?

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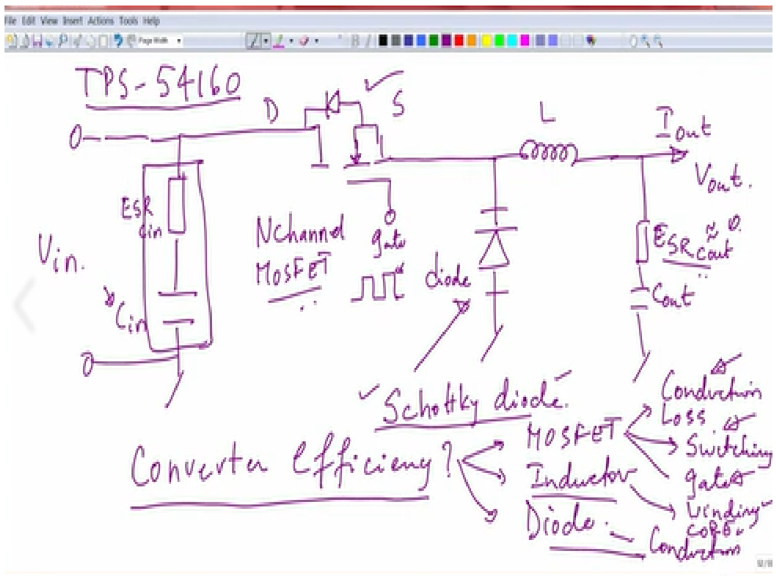

So, let me show you a practical picture. This is a practical picture. If you go and pick up the data sheet of TPS-54160 this is from T I, Texas Instruments. In fact, I just took this as an example so that our discussion will go well. This is your input capacitor which I never showed here. Strictly there is an input capacitor here and here in this picture it should be here. This is the C in and the input capacitor I have also shown along with the parasites of this capacitor.

C in is the capacitor and it is associated to the equivalent series resistance of the capacitor is shown here. So, together is actually the capacitor. This is a parasite which you will never be able to see but you can actually measure. The manufacturer of the capacitor would have told you what is the; ESR of this capacitor. Note that ESR ideally should be zero so that there is no drop across the voltage drop or power dissipation across the capacitor.

You do not want to have a dissipating capacitor you only want a capacitor that stores energy. So, ESR should be as close to zero as possible. So, that is what is shown here. Now TPS-54160 uses n channel MOSFET and that is shown here. You can see that the input is connected to the drain. This is the drain of the MOSFET. This is the source and this is the gate. I have not shown the circuit related to the gate drive circuit which is essentially coming from the output of the error amplifier and then connected to a PWM.

So, you can say that this is what goes into the gate, some signal like this. So, that it will put the series pass into conduction and it varies the conduction based on this duty cycle of this PWM. Output inductor is shown, L is here. There is a diode which is typically a Schottky diode and you have again ESR of C out and this is the output capacitor okay. Now the most important parameter for any buck converter is its converter efficiency.

And where do you think that efficiency takes a beating? There are three important components that take the beating. Therefore, your data sheet when you read you should look for these important parameters. For example, MOSFET that is this guy, he contributes in conduction loss. He will contribute in switching loss, he will also contribute in terms of gate drive, gate loss. All these three things are dissipating components, there are three dissipating elements. Take the inductor.

Inductor you can manufacture in different ways, you can use different windings, you can have different materials for making your inductor. So, winding and core are important parameters which will determine the efficiency of the inductor. And diodes of course, because of conduction there is a loss element. So, whenever it is conducting it is not actually contributing to anything in terms of output efficiency; improving the efficiency but because it has to conduct.

And therefore, it will dissipate a certain amount of power across itself which is a sort of a drawback in terms of when you compute the overall efficiency of the system. You cannot do anything right. This has to switch; the diode has to conduct during the off condition of the MOSFET. So, it has to dissipate power across itself. That is a loss in power. What can you do? I mean this is the best that you can think of.

Imagine the situation if you did not have a Schottky diode and you already replaced it with a normal diode. The drop across that normal diode is much higher compared to the Schottky diode. So, therefore, the voltage drop typically is 0.2 or 0.3. It is about 0.3 volts for the Schottky and it will be maybe 0.5 or 0.6 in the case of a normal diode. So, keep this also as low as possible. That is why you choose a Schottky diode.

Again here, you do not want the ESR to be any value because it is going to become a power dissipating component. You want to do energy storage and not so much charge storage rather than dissipate anything across the capacitor itself. So, this should be close to 0, ideally, which is not really the case. It does have a finite amount of equal and series resistance and therefore it will also dissipate some power.

So, input power to output power; if you take these are all the elements which are contributing to the overall loss in power. But folks, that is negligible compared to what the LDO does all what we discuss is very negligible. That is why you get very high efficiency close to 90% and so on with the switching regulator. Even if you consider all that I said about the MOSFET, about the inductor and about the diode and its dissipating characteristics.

So, what is the efficiency? How do I know what is the efficiency of this TPS-54160? The best thing is to look at the datasheet here.

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TPS-54140. Straight away you can go to this picture. The x axis is load current; the y axis is efficiency nowhere the efficiency has dropped below, even if you take the highest current consumption, nowhere has the efficiency gone down below. It is about 80%. And it is anywhere between 85 and 80% , it is not in the 90% range. But it is definitely in the 80 to 85% range. And of course, the efficiency is best when you have the load currents which are typically less than 1 ampere, about 750 milli amperes and so on.

It gives you the best efficiency and after that it slowly tapers down. So, folks, under what condition was this measured? Very clearly shown here. Your input is 12 volts, your output has to be less than 12 volts which is 3.3. Here is the problem. That means you are dropping a significant amount of voltage between 12 and 3.3. Just take the difference and that is the voltage that is being dropped across the inductor.

And obviously, if V out was 6 volts and input remains 12 volts your drop will be less and therefore your efficiency will be higher. This is the point folks. Do not choose just arbitrarily any you know buck converter. You must look at what is the condition under which you are designing your SoC system, your IoT node and choose those parameters based on the data sheets that you read. Read the data sheet, understand it because I have given you the background.

You must be able to interpret the data sheet very efficiently. Look at the picture on the left. This is not hard also folks, not at all hard. What is it saying V in, what is your V in? V in should be connected to the drain. This is the drain. Where is your output inductor connected? This is your output inductor connected. Where is this connected? This must be the source, correct. This is the source. Is this not the low side diode, Schottky diode? This is a Schottky diode.

Is this not your output capacitor? Yes, it is indeed. These are two sensing resistors which are connected to V SENSE. Where is the error amplifier? Well, I have not shown it. But you remember, when we draw the initial picture of the buck converter, we had the error amplifier. So, this is the SENSE resistor, this is ground. Now this is Power Good. We will come to that. That is an important point. But we will come to that.

Enable or disable, if you do not want to enable, if you do not want this switch to be this buck converter to be on down then you are not using it. You push it down then you ground it and then it will get disabled. These are some other related switch pins which are specific to this chip. You can read it further but essentially it captures everything that we know so well about the buck converter. So, what is the datasheet saying? So, let us look at the datasheet.

And this will also not be very complicated if you take the important parts of the datasheet. This is saying if you take it gives you 1.5 amperes, 60 volts step down DC/DC converter with Eco-mode. These are all some terms and names which the vendor is saying. You should read it carefully. If you think that they are important for your design you should consider this chip. But that is not the, that is besides the point. Look at the features. Typically, any vendor would put these features.

Input voltage 3.5 volts to 6 volts that means you can feed any input in this range. High-Side MOSFET RDS this is nothing but the RDS on. It is 200 milli ohm High-Side MOSFET. Folks, lower the better, right? - because you do not want MOSFET to be a contributor for the loss in efficiency due to dissipation across the MOSFET. So, you do not want a very high, high-side RDS on value. Well, of course, this will largely depend also on what is the input voltage and what is it you want to buck it to.

That is on the one side. But anyway, he has given a typical number. It is 200 milli ohms. High efficiency at light loads with pulse skipping eco-mode. If your current drawn is very low you still want to provide extremely high efficiency. He has packed a lot of features into this buck converter. Now UVLO is an important thing. TPS-54160A has tighter enable threshold than this for more accurate UVLO. Folks, you must exploit this UVLO. This is under voltage lockout.

You must use it folks. Suppose you are driving an important load from this buck converter and you find that the input is through an energy harvesting source.

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Or it is from a battery which is draining continuously and you know that your load will not function properly if the input voltage changes below a certain threshold. Then your circuit your software should be able to sense that and say that something is going wrong with the power regulator itself. Why not I exploit and see what is happening to the UVLO? The UVLO indicates something under voltage lockout.

Then use that pin and then do something to your software so that your load is disabled for instance. So, the current consumption of the load is reduced. Maybe then the buck converter will pick up and then you can use it again. So, these tricks have to be done in software folks. It is for me to say in one part, but then to implement is the key using these features of this hardware. Often programmers, computer people who are interested in software will not even look at the datasheet.

It won't work. You want a 10 year lifetime from your IoT node, look at the hardware and exploit it. You do not need super knowledge of hardware to use the hardware. It is quite simple. You just have to understand the specifications and if you are following this course, you will be able to come to that point.

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So, operating quiescent current - 116 microamperes, switching frequency - 100 kilohertz to 2.5 megahertz and the other related parameters. UV and OV power good output, use this in your software. Is the Power good to be used for connecting the load or not good to be used? You decide based on what this pin is trying to tell you. These are important things. We will come to that as we go along.

Now let us look at the data sheet in a little more detail and let us move on to understand it better. You see folks, x axis is junction temperature. See this is a power dissipating device. You are bucking it and you can go as high as two amps from this buck converter which means you have to note if two amps is flowing through this series pass junction, N channel MOSFET, it is going to heat up and that is going to change the junction temperature.

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So, that is important. You have to understand that it is heating. And you do not want bulky systems. Although it is switching you do not want bulky systems. So, you do not want to put a huge heatsink on top of it.

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Therefore, what is the rising junction temperature? You must know and that is what this picture is saying. It is saying if you give input of 12 volts and your output is 6 volts your difference is only 6 volts. You are dropping low across the voltage drop across the MOSFET is low and when that is low take value at 25 degrees. The TJ 25 degrees, you will see that RDS static drain source on resistance, in milliohms, you will see that it is here for 25.

But if your output is 3 volts, input is 12, and your output is 3 volts then it is going to have a different impact. You can see that the RDS ON has changed automatically. It has gone to a slightly higher value which means it is going to dissipate more. Clearly indicating it is not about input voltage it is the difference, the drop across the MOSFET which perhaps is holding the key to the rise in the junction temperature. So, this is how you interpret this view graph.

Similarly, you can go and interpret V ref. How does the V ref change? Because V ref is required for the error amplifier and how does the V ref get influenced? You show this at 25 degrees it is at some value as the temperature changes you are drawing more and more current for the load. The V ref also keeps shifting a little bit although not significantly. This will have an impact on the output. It is definitely going to have an output on the output DC voltage that you get.

And similarly switching current and so on. So, a lot of useful information is available from this data sheet. You can go and read this as thoroughly as possible.

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So, the point really is if you take an SoC and you start looking this LDO and DC-DC are inside the SoC. We have discussed an external TPS-54160. When should I choose their internal to the SoC like Nordic 840 or 532 any one of these systems it is a full integration of LDO and DC-DC inside. How do I choose them? This may be bothering you because it is still not connecting to the final SoC that we have.

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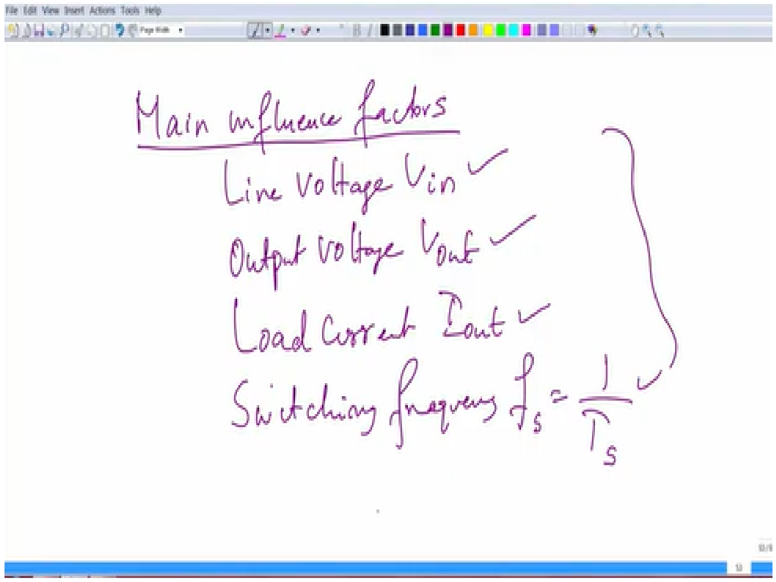

But I must tell you one thing for sure that if you look at the data sheet you will see that the line voltage, the output voltage, the load current, the switching frequency are all contributors to efficiency. And therefore, please note that you had to look out for these parameters when you look at the efficiency of the systems.

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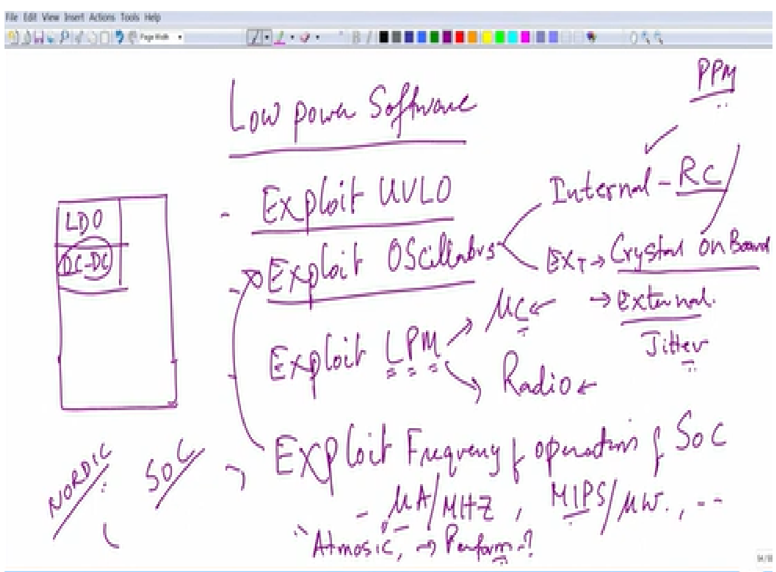

Having said that, we should move on and see how you write this low power software for exploiting these buck converters which are inside them. So, I want to just put down some very broad bullets for you, connecting it to the TPS discussion that we had just now. What is important is if you are not using the inside buck converter for any reason and you have external circuitry because if you are using let us say a battery, which is 24 volt.

And you are bucking it on to some reasonable voltage and then feeding that to the SoC. So, what does it mean? It means that the LDO and the buck converter decision that we took was to understand them because if you take a controller SoC we had the power block and we wrote always used to write like this. We used to write DC, let me draw it a little bigger so that you will connect it to what we are discussing now. We always said LDO DC-DC.

I explained not the inside DC-DC but I explained with respect to the TPS chip that we discussed now. The reason is a full-fledged understanding you should have. Why should you know outside the TPS system? Because it is similar to what we saw outside you will actually get integrated into the SoC. So, a lot of information is available already if you understand an external DC-DC converter then and all the parameters associated to motivate you to understand how to write low power software.

That is the key point. So, we have to connect it now. External is fine, we understood it well. Now how do I connect it to the inside one? I will explain that. If your internal DC-DC provides you UVLO - exploit it. What does it mean? Let us go back to the datasheet.

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Under voltage lockout is internally set to 2.5 volts. This is again I am switching back to TPS-54160. Please note under voltage lockout is internally set to 2.5 volts but can be increased using the enable pin. The output voltage start up ramp is controlled by the slow start pin that can also be configured for sequencing, tracking. An open drain, power good signal indicates that the output is within 94% to 107% of its nominal voltage.

See, this is the good thing about using those pins which are available. Under voltage lockout is set to some value. If it is going below that you just shut down the DC-DC converter. Because either you shut down the DC-DC converter or you shut down the load to which the controller is connected so that current consumption decreases almost becomes zero because you have shut down the load. Then this voltage will pick up again.

So, that is what I was trying to tell you about how to exploit the hardware hooks which are there with respect to the IoT node design. So, this is important. The output voltage the start up ramp is controlled by the slow start pin. This is a mechanism on how do you start the DC-DC converter.
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One part of what you should do if you want to write low power software how to use this pin as effectively as possible so that you do not drain the battery. And you allow you use the indicators which are available from DC-DC converters to drive the load or do not drive the load. So, that is one part. Then you have oscillators. Folks, we discussed this oscillator in the last class as well. You have an internal RC oscillator; you have an external onboard crystal oscillator.

Or you can have some oscillator clock which is coming outside the board. Sometimes we also said that outside the board we may want to keep the jitter under control. You do not want any influence of jitter which is coming from the board to bother you particularly when you are looking at it because the contribution of jitter there is significant for high analog inputs. We discussed that also.

Therefore, if you are going under low power and you are not doing any major operation and you are not even doing sensing, let us say or you are doing extremely low sampling frequency sensing, then choose this internal RC oscillator folks, you do not need anything more than that. If it is well within the budget of the analog values that you are okay with, choose an internal RC oscillator. Otherwise, you may want to choose crystal but look at the PPM value of this.

PPM values are important. The PPM will tell you how much it will drift and how it changes with respect to temperature and so on. So, that you will have to look up. External is very rare you may not want to use the external systems unless you are doing very high frequency input signals and jitter is a major contributor there. Exploit LPM, low power mode. This is another thing. You have low power mode for a microcontroller of the SoC, you have low power mode of the radio.

So, I think you should use these two hooks. Read the data sheets of the SoC of interest to you as carefully as possible. 840 and 832 I am only referring to Nordic because this is what I have been using for some time in the labs. Read the datasheet carefully and you will be able to see that you can exploit the low power modes. You can also exploit the frequency of operation of the SoC. You want to know the parameters we discussed them last time.

Micro amps per megahertz how much it consumes? And then you also know the MIPS per micro watt of that particular SoC. Look at these parameters of interest and then accordingly you will have to choose what frequency of operation of the SoC is actually suitable. It directly boils down to the kind of oscillator that you are going to choose folks. I have no dispute there. You will have to check the SoC, how much it takes for one megahertz of operation.

If you look at Atmosic it is appearing to give the lowest micro amperes per megahertz. But does it perform the way you want it? Is the performance okay? you will have to check this out. This is just a clue that Atmosic microcontrollers are indeed quite ultra low power. One final point about connecting back to the DC-DC inside the controllers. Let me point you to one discussion.

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I am banking on what is happening on the internet. Look at this. I have gone to the Dev Zone. This is nothing but the Developer Zone. And there is a discussion in the Developer Zone and I am just pointing you to that. It is a beautiful one. I just picked this as an example. Look at this I am using an external DC-DC converter to reduce my VDD from 3.7 to 4.2 to 1.8 volt before supplying it to this controller. So, he is using an external DC-DC.

I am still not clear whether to go with internal DC-DC or internal LDO after this. Same question you will also have. I can save two passives if I go with an internal LDO. Since the supply to NRF is at 1.8 volts from an external DC-DC, I feel using internal LDO may help you reduce supply noise in addition to saving passives. Also, no loss in power since external DC-DC already reduces the voltage to 1.8. What a beautiful question he has asked.

Most often you will have these questions. Now my system is intended for real time data streaming and this is the application. Now you see he has added all this now. It is meant for real time data streaming or sometimes occasional data streaming with some data processing done on this processor, Cortex M4F processor. I am not sure if this is considered low current drain or high current drain. Can you clarify this? He has asked a question on the mailing lists.

Also, in your reply you suggest with refresh mode enabled NRF52 can automatically switch between internal DC-DC and LDO. So, for refresh mode which schematic should I follow? The one with internal DC-DC or the one with internal LDO? Thank you in advance. So, folks, this was a question asked by somebody some developer 6 years ago and it is still so relevant in your overall understanding. Here is the answer.

If you use the radio, you will have a high current draw; using LDO you could consume roughly 6 milliamperes when transmitting at 0 dBm. But if you use an internal DC-DC, you will use 4 milliamperes. So, the pressure on the battery is reduced significantly if you use DC-DC. If you want to use the refresh mode you need the schematic for DC-DC. If you do not care about energy efficiency as much and you want a cheaper smaller board, go for LDO as it saves you two components.

The whole decision is hanging around. You do not want energy efficiency; you want to throw that out of the window.

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Go ahead, no problem, use LDO and be done. But if you want you are careful you are looking at 10 year lifetime designs then you may want to choose between LDO and DC-DC switch between them by putting it into the refresh mode. What a powerful way of doing it internally. Choose

LDO when you are using the radio because from 6 it comes down to 4. That is what he is saying and it can be done so dynamically.

Now why all this magic happens? I will take you to another example of how I am trying to connect the story for you.

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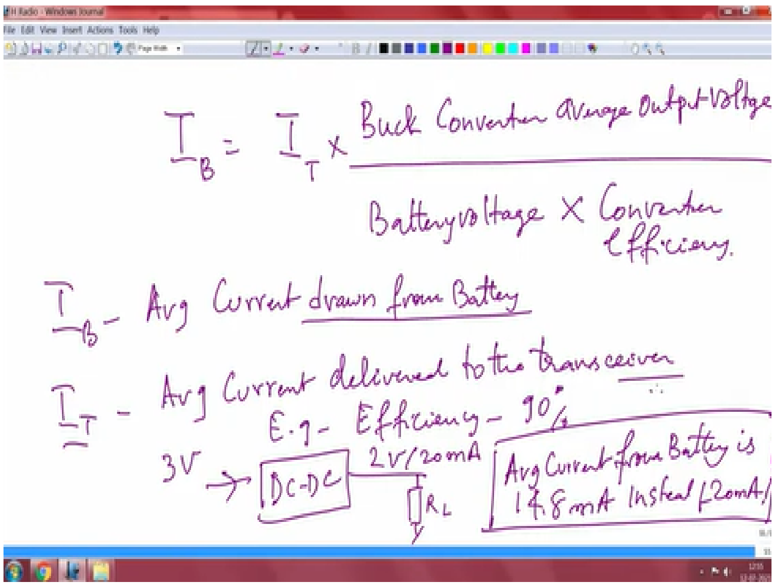

And for that I want to show you this slide and what I wrote here. I B is the average current run from the battery, I T is the average current delivered to the transceiver. This is your expression of interest. Keep this in your mind. I T times buck converter average output voltage divided by battery voltage into converter efficiency. Put some numbers here. If this is your expression put some numbers.

Supposing you have 3 volts going to a DC-DC converter and your load current is 20 milliamperes your DC-DC converter is bucking it by 1 volt. That means 3 volt in comes to 2 volts at the output. 1 volt is the drop, 20 milliamperes is the current being drawn. If you apply these numbers into this, what will you get? You will get 14.8 milliamperes instead of 20. This is the average current drawn from the battery folks. This is why all the discussion I did boils down to this number.

It says that the choice of LDO or buck converter is one part of the story. How to ensure that you design for high efficiency, high battery life is another part of the story. Now you see if you have an LDO or DC-DC inside a SoC, you can exploit the SoC as effectively as what I already showed you here.

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And this is true even for a chip like Nordic NRF52 because you see it is going in line with what I wrote here. If you use the radio, you will have high current draws using the LDO you would consume 6 milliampere when transmitting 0 dBm. If you use the internal DC-DC you would use about 4 milliamperes.

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This same story connects that so well to this picture. Your 20 has become 14.8 which means that much less current is being actually drawn from the battery and therefore lifetime improves. So, keep all these things into your mind when you are working with LDO and buck converters. And writing energy efficient software means exploit the UVLO, exploit the oscillators, exploit the low power mode, and exploit the frequency of operation and so on. Thank you very much.