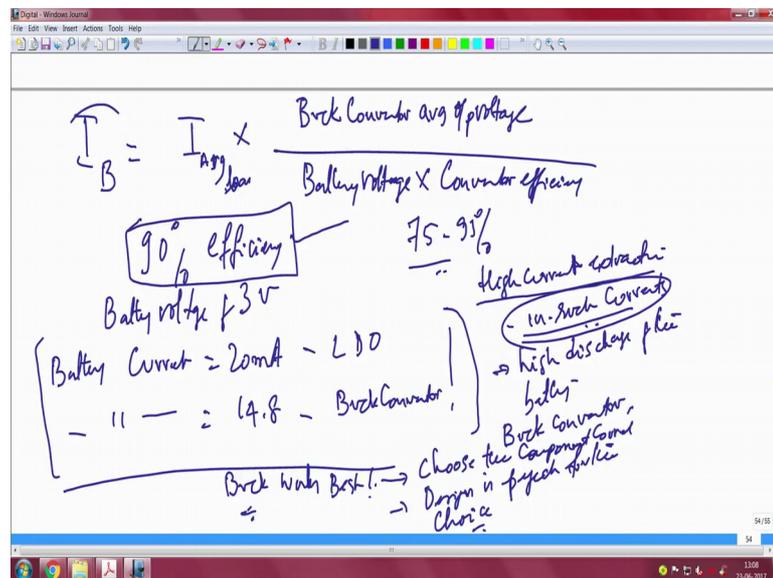


Design for Internet of Things
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Lecture - 12
Designing with LDO's, switching regulators and case studies Part II

So, what we should do is this- we mentioned about this Buck works best, right.

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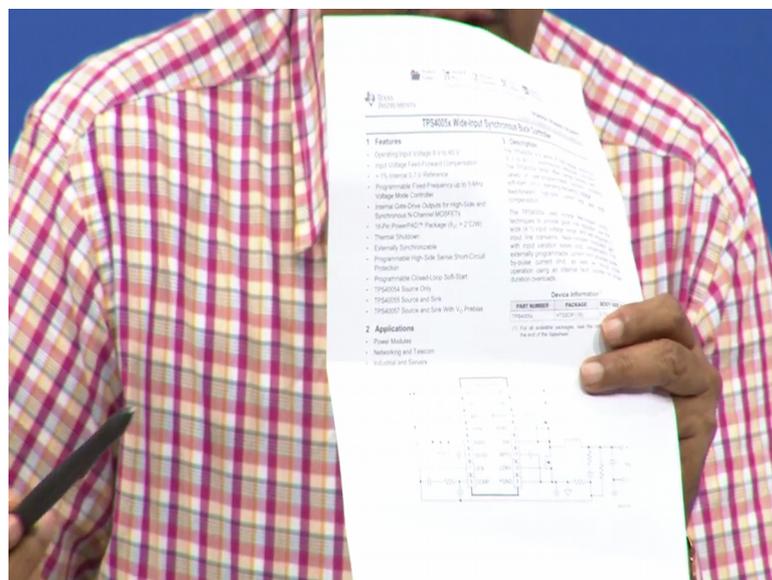
Scenarios where you know sometimes this scenario is that you do not want you can also have problems of inefficiency of this; you can also have inefficiencies of these Buck converters. And therefore, understanding the data sheet becomes important.

can operate from 8 volts to about 40 volts. So, it is a wide range and it has fixed frequency of switching it is fixed frequency, but it is programmable. That means, you can program the switching frequency up to 1 megahertz you can, but it is programmable.

So, I suppose you know what I mean you can set the frequency actually it is setting you can set the frequency and leave it, but once it is set it is at fixed frequency it is switching at fixed frequency that is what it means then internal get drive outputs for high side and synchronous n channel n channel MOSFETS. See, there is the usual thing that they seem to use n channel MOSFETS at least this particular one seem to use n channel MOSFETS for high sight and thermal shutdown is another thing thermal shutdown you must look out for this specification.

So, this is one such Buck controller wide input synchronous Buck cont controller I pick this TPS 4005 any of them in that series you could look up and these are the main important specification I would say features of that I see. So, if you look carefully into this data sheet here which I would like to show on this camera this data sheet it is not very clear, but let me try.

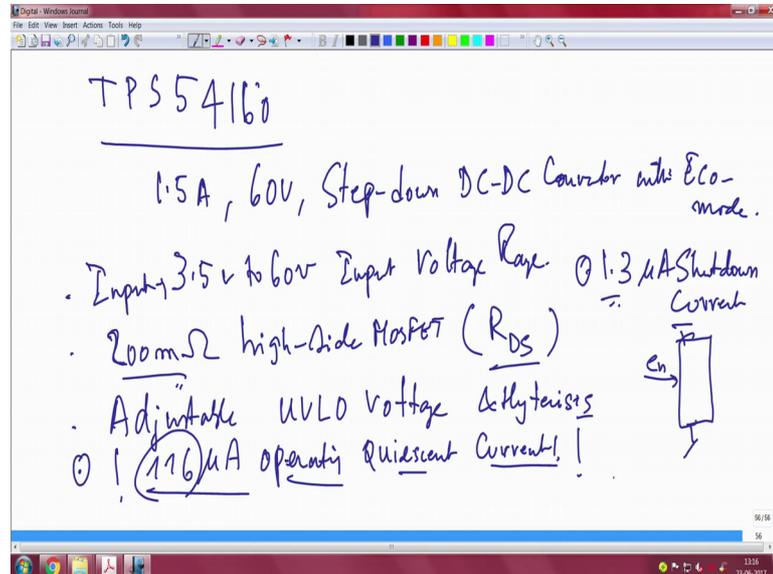
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You see this data sheet that you see here now let us see if it is own enough yes fantastic. So, its slowly getting zoomed you will see that this inductor is the usual inductor the output inductor whose value is most critical, because that is the place where that is the component in which the energy storage occurs after switching. I will not redraw the

circuit the details of it, but please do go through this specification what is interesting is you can see when you read this data sheets you will also come across.

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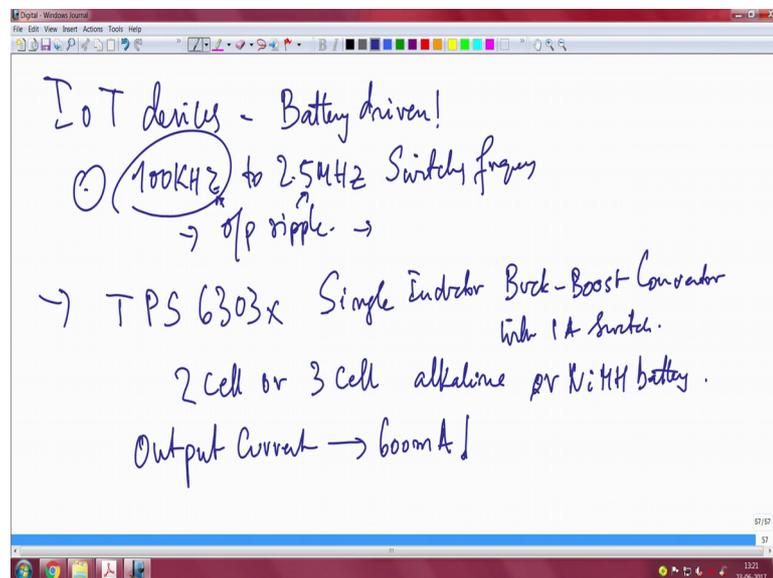
Another one; I will just take another sample to you know sort of complete the discussion on this continue the discussion on this; this is TPS 54160; 160 this is no biased to any specific vendor, but just that I pick this 1.5 amps 60 volts step down step down DC; DC converter with some eco mode has we call it they call it.

Here you will see that again it is the same standard diagram the block diagram simplified schematic block diagram they give you can have input coming from. So, input 3.5 volts to 60 volts input voltage range right then second spec 200 milliohms high side MOSFET. See, how nicely they talk about this RDS the lower the RDS the dissipation across the whole chip is low.

And therefore, aiming to go lower and lower in the RDS is a good idea right this is the resistance between the drain and the source and the lower this is the better further system. So, this is TPS 5154160 then there is another specification which you which this chip offers its says is this adjustable under voltage load protection UVLO voltage under voltage protection and hysteresis this is another specification perhaps one critical specification they give is a 116 micro amps operating quiescent: q u i e s c e n t - quiescent current.

This is a very important specification I will show you the context and you will perhaps appreciate this quite a bit and 1.3 another specification 1.3 micro amps shutdown current which means there is an enable pin there is an enable pin and if you disable this if you do not enable it is; obviously, it is an disable condition and its essentially in shutdown and in shutdown it is a drawing 1.3 micro amps in shutdown in essentially it is in that you have a situation where if nothing is connected no output is drawn from the Buck converter it is in that the Buck convertor is not drawing any current it is indeed drawing current when it is on it is drawing 116 microamperes of quiescent current and when it is shut down it is drawing 1.3 micro amperes of current.

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Why these numbers are important because every most of your IoT device most of your IoT devices are likely to be battery driven.

They are going to be battery driven and unless you look out for these specifications it is I mean you can end up with a sub optimal power for power supply requirement for the system. So, that is a very critical. So, also again coming back because this is a switching regulator the switching frequency there is specify is 100 kilohertz; 100 kilohertz to 2.5 megahertz switching frequency remember the output ripple right is the is the almost related to the switching frequency of course, there are switching losses if you go auto higher frequencies, but then that is why the design really comes into picture what is the desired switching frequency you will choose such that the ripple is well under your

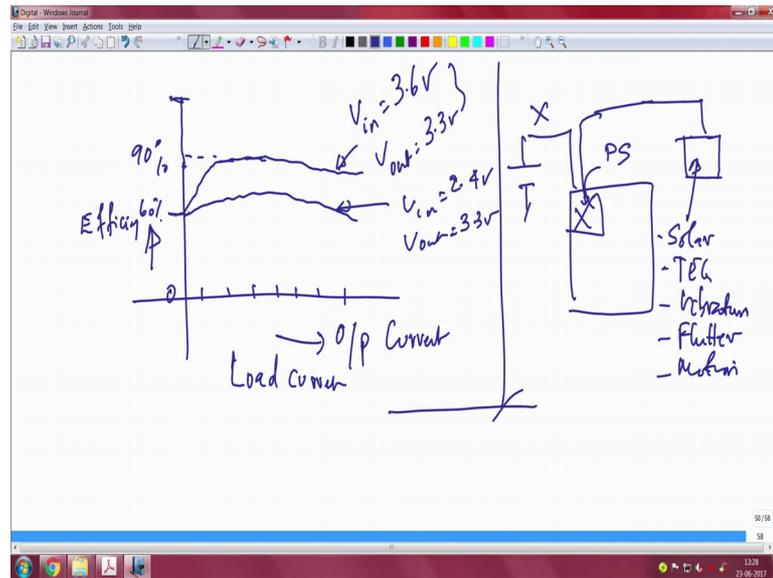
control yet dissipation is you know is also minimal and therefore, that that kind of regulator is the one that we will allow you to optimize your design. So, I show you an example of how a researchers have struggled with that and that we will perhaps I can I do not have a magic formula for you.

But definitely I can expose you to those in literature case studies in literature which actually emphasize the need for you to decide to choose between several of these Buck converters. So, it is very important do not just go and buy something in the market from the market and just put it because it gives you the required output voltage that is not the way you have to look at these parameters like these ones which I listed out like switching frequency and quiescent current the operating current and so on. So, these are this is another one. So, like this we can look at other regulator as well there is one more before we move on this one more which is quite populate it is called the TPS 6303 x high efficiency single inductor single inductor Buck boost it can do both Buck boost converter with one amp switch is.

So, you can see that it is quite a chip which by which you can actually you know draw sufficient you can regulate you can regulate your power and you have draw significant amount of power. So, this is a for products powered by either 2 cell or 3 cell alkaline nickel cadmium which people do not use anymore you should be using them. So, I will actually remove it from this list nickel metal hydride metal hydride battery this is for doing something like using it along with batteries output currents can be as high as you can get output current has high as current I will say output current let me write it as one spec. So, that of about 600 milli amperes is a sure possibility and so if this is quite some chip.

So, what I thought was; so, instead of; so, one important parameter before I go on move on with this particular one see here they give you a specification of efficiency.

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Again this is only an example, but you must look out for the efficiency curves of these switching regulators here you will have the output current here you will have efficiency their plot efficiency and of course, you can start with 0 and go up to 100 percent if you express it in percentages. And you expect a sort of a flat performance in spite of drawing higher and higher current you expect it to sort of be quiet little bit of flat, but I will show you how it would pan out you could get like this also right. So, let me re draw is the log graph normally they plot it in log.

So, but just for understanding I plotted it know I think I need to redraw both. So, that in gives you some field of sort of like a cap. So, like this it is very easy now for you to find out why. So, this is let us say 60 percent and this is going to let us say ninety percent. So, I remove this I will. In fact, remove this as well I will remove this line I will just extend this appear and show this at ninety percent.

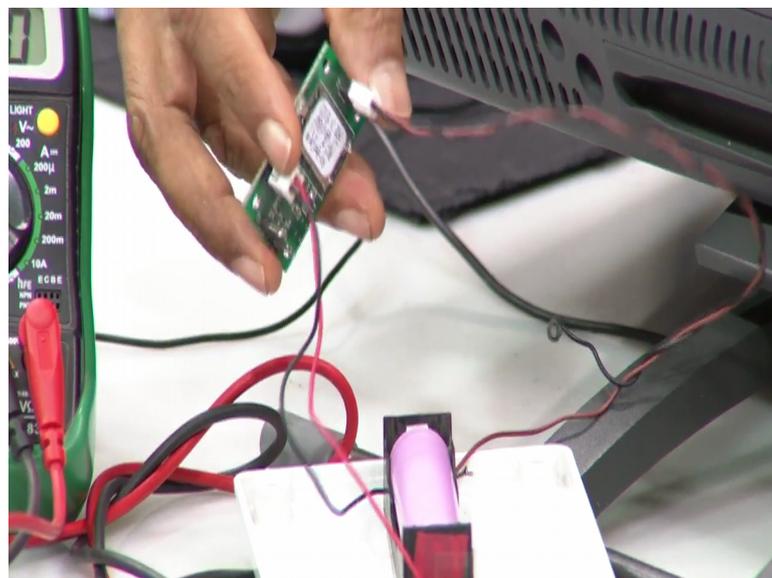
This is right this is obvious right. So, it is quite easy forget to guess in spite of the load current this is the load current in spite of the load current increasing you continue to maintain this graph you maintain continue to maintain significantly good amount of efficiency. In fact, it can go even like this you say a significantly high efficiency only because the V_{in} is in this case 3.6 and V_{out} is 3.3, whereas if you take this right v in here is 2.4 volts and V_{out} is again the same number which is 3.3 volts. So, what is the big story that you can come out with you see that the drop across the l d the Buck

converter is. So, small that efficiencies; obviously, right the efficiency increases let see in practice whether we can build the circuit and whether there is any measurement that we can do so that we can complete the story on these Buck converters. So, here is a very small circuit I built in the lab a few of my lab staff I have built in the lab.

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So, let me show you this let me show you this nice circuit nothing is a very simple one you can see that it is simple one that essentially has some input here coming from this battery this battery at taken as an input and I am just taken this as an output I have to be

careful that these 2 wires do not short. So, that you know because this I c can go back if there is no short circuit protection. So, anyway this is a circuit, but what I wanted to your attention is not. So, much on this PCB, but just to show you that we were experimenting to use super capacitors this is a best cap this is a company called best cap a v x best cap and this is actually a super capacitor.

Let me read this: this one it is a 15 millifarad capacitor at 5.5 up to 5.5 millifarad please note this is a 15 millifarad capacitor small little one which can be mounted directly on the PCB and I am using it for other applications one thing that occurred to me is that we can use this a capacitor to store harvested energy. Supposing you are embedded system which you have in mind and you build their embedded system with power supply and this time the power supply is not through battery , but not battery, but you want to use harvested energy, right.

So, I will let me just quickly put this. So, that it is in a convenient place this is your power supply block and to this your actually connecting a battery, but you do not want this you actually want to connect through to the harvested energy maybe you want to use solar right this is a solar panel or you want to use let us say if you do not they I mean I have just rubbing it because I am these you can replace it with. So, I will just put it like a block diagram it could be either. So, here it can either be solar it could be a thermoelectric generation it could be vibration as an in as in input source it can be aero elastic flutter right it can be electromagnetic switch or let us call it motion. Motion any one of them and that you want to store on to this capacitor which I have shown here we will take this discussion forward at a later stage, but just to tell you that these are all the possibilities.

So, now let us do this experiment and see a how nicely this Buck converter is actually working. So, what I will do is I will connect the input I will show you the input of this Buck converter which essentially should measure 3.78. So, let us focus on this multi meter now the input battery supply you can see is 3.78 this is a lithium battery and that I am using just for the lab demo purpose and now let me show you. So, this is the battery. So, I have connected across this and you can see that you got that output voltage input voltage now I will connect the output.

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And let us focus on the multi meter let us just focus on the multi meter and see what actually happens there you are you get 3.3, right.

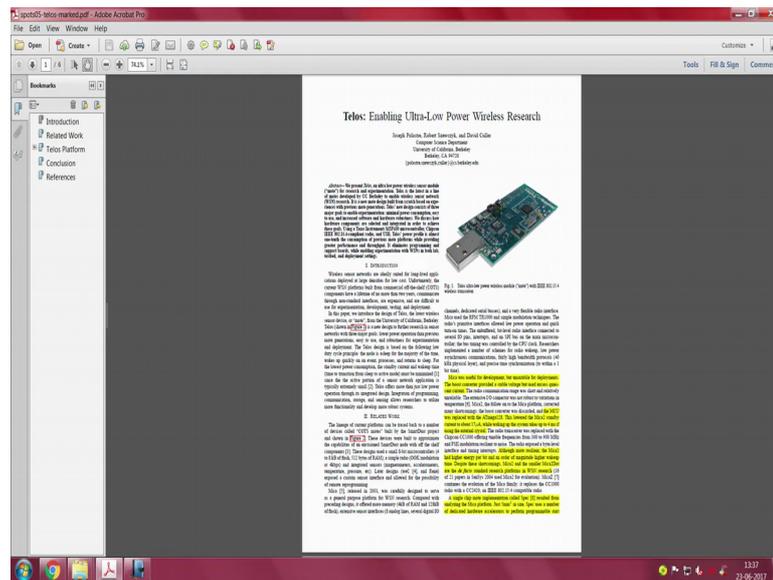
So, that is essentially what you we did with this switching regulator you can see that you have you have actually used this switching regulator to give you this out required output voltage which you could have also got through the LDO right here you are now at cross roads why should I use why should I use an LDO and why should I not use this where I can actually, also because the difference the voltage difference between the input and the output is about 0.4 volts and for 0.4 volts and 100 milli amperes of current the power dissipation is not very high right. And therefore, I might have all actually chosen an LDO and completed this complete circuit design. So, I live it to you now to actually infer now that you have a nice story of LDO and you know switching regulator this situation you take and now you realize; what should I do in this situation.

So, this is an open question hopefully not for you because you have gone through this module and you have understood this difference between the LDO and the Buck boost converter parameters that you should look at. And therefore, you I let you decide what would be a perfect choice for your IoT embedded device what we have not covered is a nice story how researchers how people have actually you know invested so much of time and energy in just making this one single choice.

Let us now turn our attention to a classic paper which was published more than 10 years ago and in that space people have actually made redesign of their embedded hardware just because they could not find the right component. So, let us focus on that paper and that paper is essentially I will go and open that paper for you which should is here, right.

So, this paper is called Telos enabling ultra low power research wireless research enabling ultra low power wireless research you see this embedded system here.

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It is no different from this embedded system that you see here it is no different from an IoT device or an IoT product that you might actually be building. So, a classic example this Telos is a very popular platform which is used by many researchers in many universities and also in several companies if you want to prototype something it is a very ideal thing for you to actually start and then put it into good amount of usage, but let us read this paper not the whole paper, but the key points here about this paper.

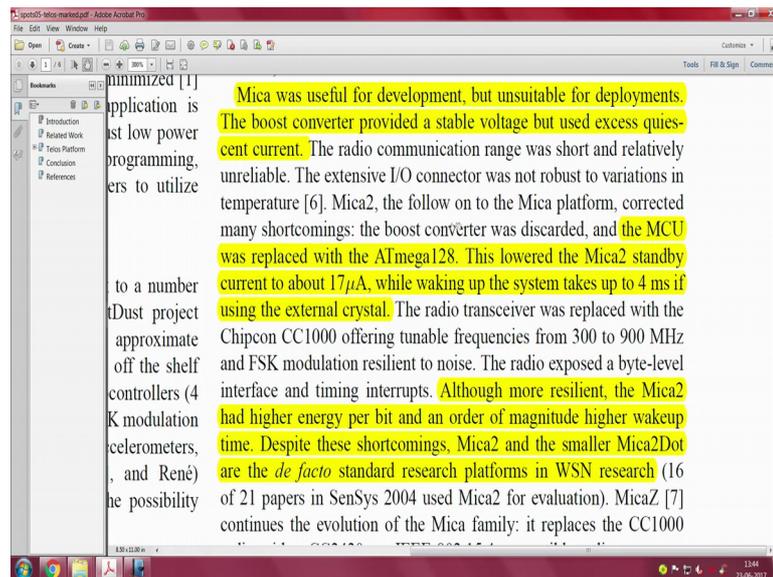
Now, this paper itself is talking about this as I mention to you about Telos, right; Telos is the platform which there trying to describe why did they write this paper because they wrote they built a previous version of this board which was not called Telos, but it was called mica. So, mica was its previous version they learnt a lot of things from mica and after experimenting for quite a few months they decided that mica is no good let us move on and build this new platform embedded platform and land.

Let us see what reactions and what exactly the researchers are trying to convey to us in this paper in one place they write here mica was not useful for development, but sorry mica was useful for development, but unsuitable for deployments very good to do in the lab very good in your drawing boards up on or drawing boards very good for quick experimentation which one mica.

But unsuitable for deployments really you cannot use its not practical there are some issues with respect to you know using mica for any deployment purpose and the line that follows this is interesting the boost converter provided a stable voltage, but used excessive quiescent current excess quiescent current. So, you see now this is already brought out very clearly by researchers when they were when they built mica they said no use no use in using mica because it is consuming quite a bit of quiescent current. So, any battery driven system with this kind of quiescent current can be an issue for the lifetime of the IoT products. So, that is the big lesson that we have then let us move on because there are so many things connected to the battery.

So, many items related to lifetime of the system the second one: they say is the mica was replaced with the at mega 128 this lowered mica stand by current to about seventeen micro amps while waking up the system takes up to 4 milliseconds if using external crystal. So, you see the controller of mica was also replaced and that was important they replaced it with 80 mega 128 and they moved on, but before that they wrote a few more things. So, let us read this a little more carefully the radio come in. So, I will start the sent reading the sentence so that everything falls in place to us quite well.

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Mica the researchers said this mica was useful for development, but unsuitable for deployments the boost converter provided a stable voltage, but used excessive quiescent current.

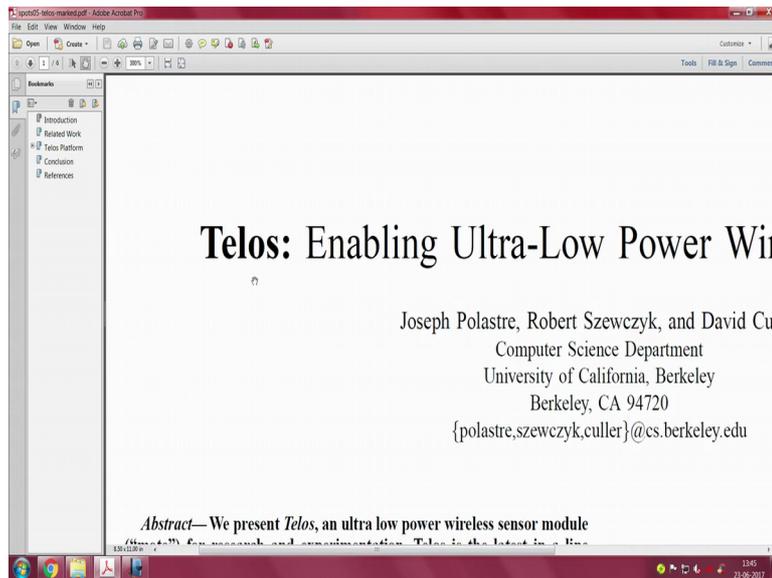
So, you see this is already a parameter which we said that is important when we looked at the data sheets the radio communication range was short and relatively unreliable also a problem with the mica system the radio communication, the extensive I o connector was not robust to variations in temperature. So, you see the extensive I o connector was not robust to variations in temperature unbelievable how the I o connector has a connection to the temperature you are doing an outdoor deployment you are going to have temperature fluctuations the connector that was chosen was not suitable for this kind of temperature fluctuations variations that were happening nights perhaps is colder.

The day is are hotter and the day as lot of sun out there the ambient temperature is very high and then the connector is faulty is not able to take that temperature cycling and therefore, they criticize the I think that the I o connector was not robust to variations in temperature mica to the follow up of mica platform corrected many short comings mica to and then Telos, we are actually talking about this is actually from the paper on Telos, but they are giving you the history of mica and then Mica2 .

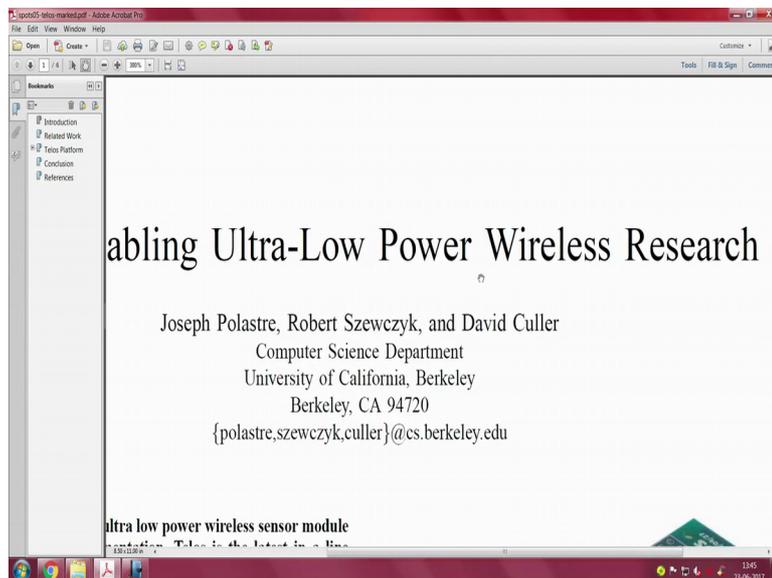
So, Mica2 the follow on mica platform corrected many shortcomings and what do they do let us zoom in again here to see what they did the in the Mica2 I think it is a little too

much let keep it like this the mica follow up on mica corrected many shortcomings the boost converter was discarded and the m c u was replaced with at mega 128 this lowered the Mica2 stand by current to 17 microamperes while waking up the system takes up to 4 milliseconds if using the external crystal.

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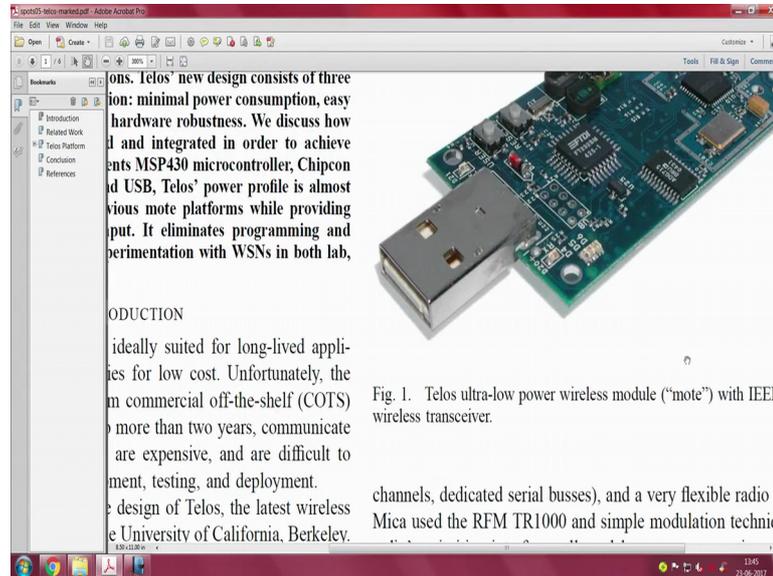
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So, we can see before they could come and do anything with Telos anything with respect to Telos anything with respect to Telos to further titrations were done enabling as you can

see this is there paper and 2 iterations said to be done before they can actually build this embedded system.

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ons. Telos' new design consists of three ion: minimal power consumption, easy hardware robustness. We discuss how and integrated in order to achieve ents MSP430 microcontroller; Chipcon d USB. Telos' power profile is almost vious mote platforms while providing put. It eliminates programming and perimentation with WSNs in both lab,

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ideally suited for long-lived applie for low cost. Unfortunately, the m commercial off-the-shelf (COTS) o more than two years, communicate are expensive, and are difficult to ment, testing, and deployment.

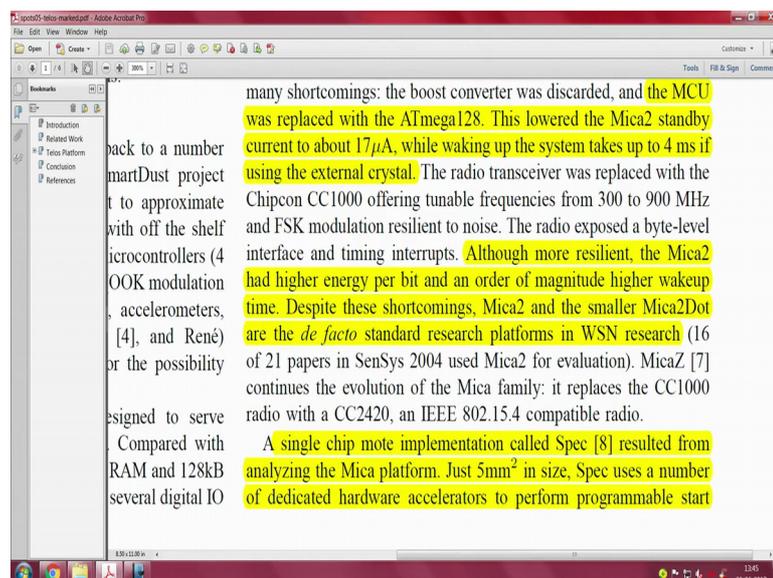
e design of Telos, the latest wireless e University of California, Berkeley.

Fig. 1. Telos ultra-low power wireless module ("mote") with IEEE wireless transceiver.

channels, dedicated serial busses), and a very flexible radio Mica used the RFM TR1000 and simple modulation technic

So, big takeaway power supply section of your embedded system is very critical that is all you can say at this stage.

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many shortcomings: the boost converter was discarded, and the MCU was replaced with the ATmega128. This lowered the Mica2 standby current to about 17µA, while waking up the system takes up to 4 ms if using the external crystal. The radio transceiver was replaced with the Chipcon CC1000 offering tunable frequencies from 300 to 900 MHz and FSK modulation resilient to noise. The radio exposed a byte-level interface and timing interrupts. Although more resilient, the Mica2 had higher energy per bit and an order of magnitude higher wakeup time. Despite these shortcomings, Mica2 and the smaller Mica2Dot are the de facto standard research platforms in WSN research (16 of 21 papers in SenSys 2004 used Mica2 for evaluation). MicaZ [7] continues the evolution of the Mica family: it replaces the CC1000 radio with a CC2420, an IEEE 802.15.4 compatible radio.

A single chip mote implementation called Spec [8] resulted from analyzing the Mica platform. Just 5mm² in size, Spec uses a number of dedicated hardware accelerators to perform programmable start

So, then look at further things the radio transceiver was replaced with the Chipcon CC1000 offering tunable frequencies from 300 to 900 megahertz and FSK modulation was resilient to noise the radio exposed a byte level interface and tang timing interrupts

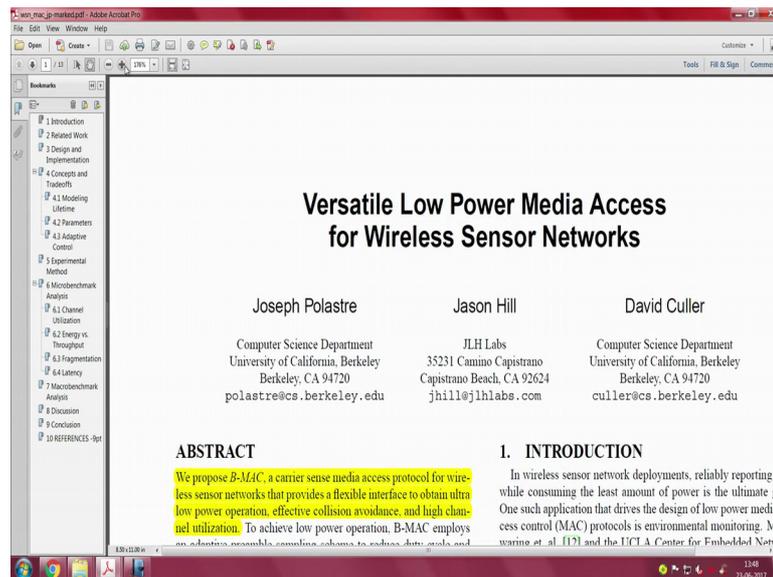
all the more resilient mica to had higher energy per bit and an order of magnitude higher wake up time see this if the wake up time increases the wake up time in sorry the wakeup time increases it went to 4; 4 millisecond while waking up the system takes up to 4 milliseconds waking up requires more current right.

So, if you are waking up at a time takes a lot of time then the power consumption increases and therefore, you must take care of this it is unclear at the moment I know this we will handle this in another paper which talks about this particular aspect of why this wake up time of the system is important we will handle that separately, but we will move on and read this paper at least sections of this paper which will allow you to understand the importance of the hardware here.

All the more resilient mica to had higher energy per bit and an order of magnitude higher wake up time despite the shortcomings Mica2 and smaller Mica2 dot are the de facto standard research platforms in WSN research many many papers were published many deployments were done mica z continues the evolution of mica family I replaces the CC1000 radio which with CC2420 radio and so on right single chip mote implementation called spec. Let us go down and see resulted from analyzing the mica platform just 5 mm square in size spec uses a number of dedicated hardware accelerators to perform programmable start and so on. So, really this paper goes into other details which essentially is you know further detailing of this paper which at this moment is not relevant for us.

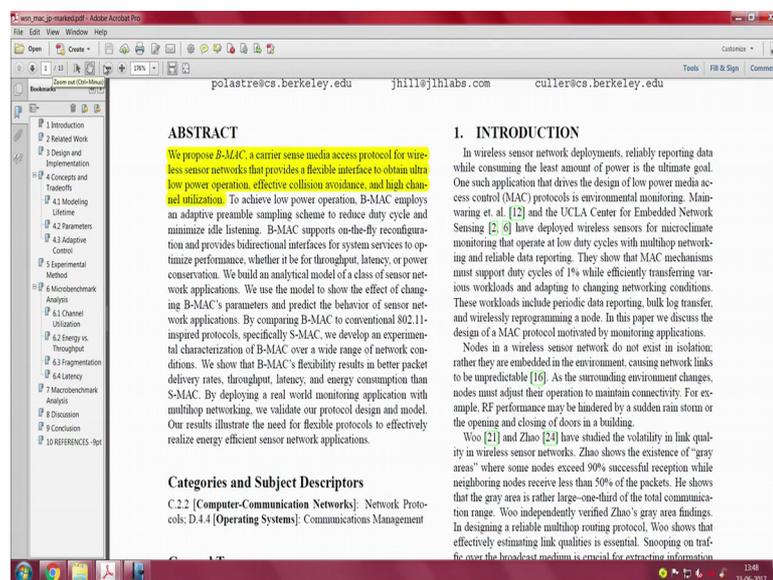
So, we will see one part which I did not mentioned handle with you is we did not is look at that wake up time right.

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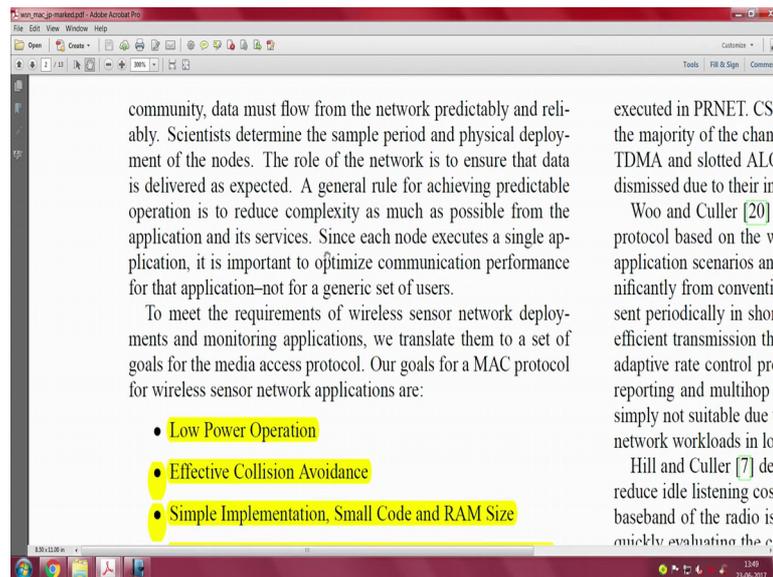
So, for that let me open another file which is called this one this paper is called this paper is called versatile low power media access for wireless sensor networks again from Berkeley.

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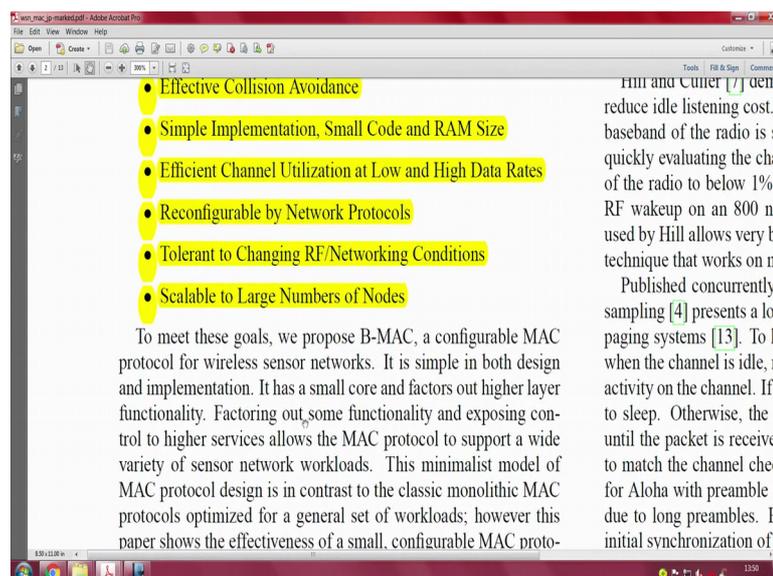
This is about a Mac protocol which details several parts. So, let me see if I can. So, this can perhaps help us if I expand a little bit more yes. So, let me see I marked a section for you to for you to explain this particular aspect.

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So, you see this to meet to meet the requirements I write it they write it here to me it is also looking at a software platform for a given hardware platform the hardware platform was given they looking at the software which is actually a media access control protocol called B Mac this. So, this paper is about that to meet the requirements of wireless sensor network deployments and monitoring applications we translate them to a set of goals for Mac protocol.

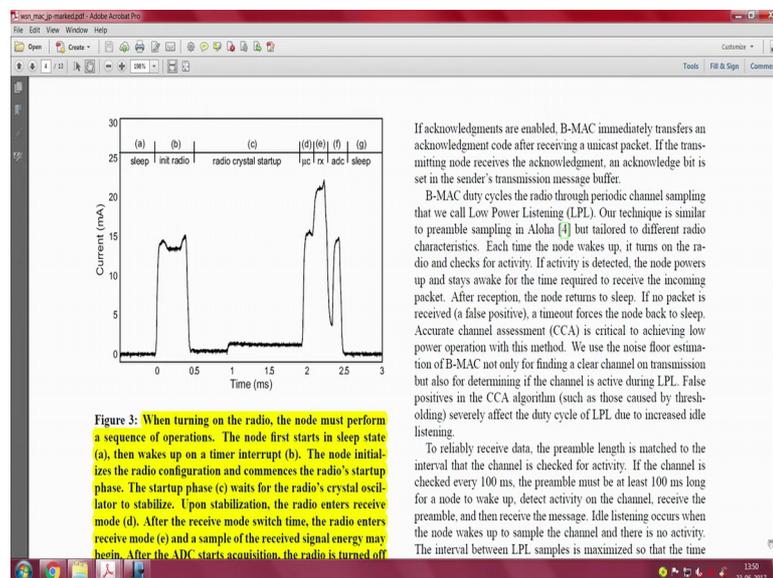
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Our goals for the Mac protocol for wireless sensor network applications are first important point low power operation effective collision avoidance simple implementation code size small codes and ram size efficient channel utilization reconfigurable by network protocols tolerant to changing RF conditions scalable to large number of numbers of nodes and so on.

So, really these are all the kind of goals that they have set for themselves in order to come up with this high performance proposed Mac protocol again this does not really go into the detail of what I started off by saying about the wake up time why is this important why is this connected to the energy consumption.

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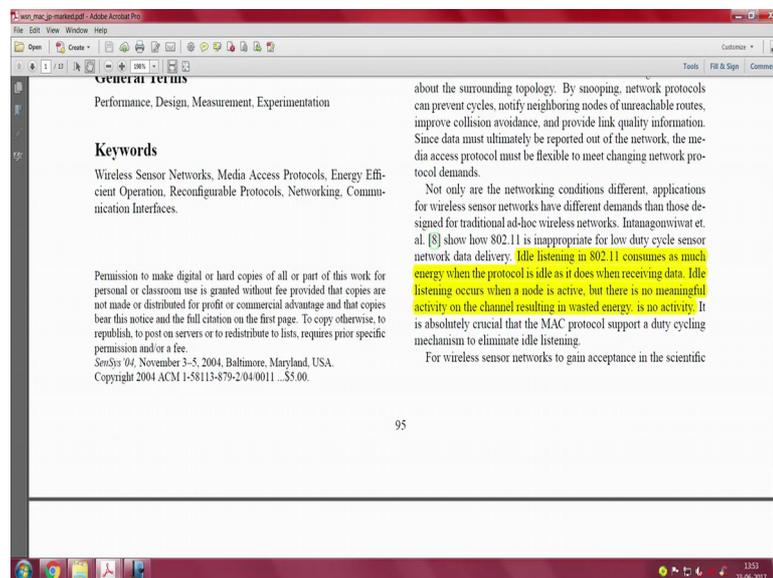


So, I want to show you this see this is the most important this is how you connect from different papers in literature look here what he says this is time on the x axis and current in the y axis x axis is time and current is in the y axis. So, you can see that when turning on the radio when turning on the radio the node must perform a sequence of operations the node first starts in sleep you can see this is the sleep section the section here is sleep as we marks it here let me expand a little bit more. So, that its much much more clearer for you this is the sleep this is the initialization of the radio this is the radio crystal startup time this is the microcontroller switching on this is reception this is performing analogue to data conversion and then this is going back to sleep.

See this pikes here this is one initial important point here this is another crystal startup time is this is the crystal startup time it still consuming some amount of energy here, some amount of current here. You can see this should be as small as possible. If you could get it down to here this point or maybe this point would have been better this whole part right side part would have shifted here perhaps. And then you actually compress this whole thing, but that is not the case indeed it takes a finite amount of time. And this is what that other paper was talking about that the startup was quite high.

In fact, this is what is for me a real eye opener when you start designing an embedded system for your applications and IoT application which you are trying to do an IoT product that you are trying to build an IoT system that you are trying to build an embedded system that you are trying to build we will have all these components and I strongly urge that these 2 papers particularly the Telos paper and this paper which is the versatile low power media access for wireless control wireless sensor networks be read to maximum amount of to the maximum detail.

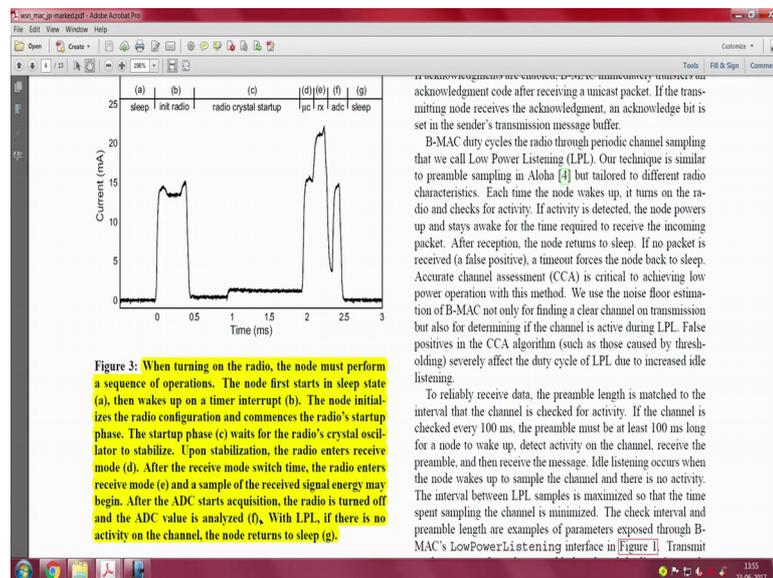
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Several aspects of this paper we will highlight why energy consumption becomes important look at what he says in respect to some other protocol particularly the 802.11 protocol which is the also popularly called the Wi-Fi land systems when the Wi-Fi land radio wireless radio is in idle listening mode it consumes as much energy when the protocol is idle as it does when receiving data.

So, you are reception time data 100 bytes at your receiving. Let us say the time to receive or the time to the time that you are idling both of them consume the same amount of energy idle listening occurs when a node is active, but there is no meaningful activity on the channel resulting in wasted energy that is there is no activity at all and, but there is an energy consumption. So, unless you keep these things in mind a effectively we will not be able to design a products IoT products in these space trying to run them from battery based systems.

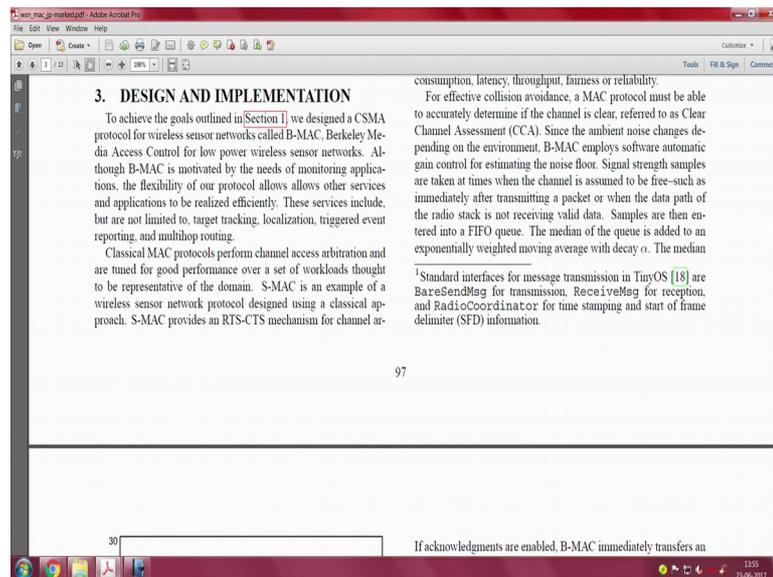
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For complete less the sake that may read this particular thing down here from this figure 3 which they call from this paper when turning on the radio the node must perform a sequence of operations the node first starts in sleep state a then wakes up on a timer interrupt b the node initializes the radio configuration and commences the radios start up phase the start up phase c.

The start up phase c the waits for the radio crystals oscillators to stabilize upon stabilization the radio enters receive mode d after the receive modes which time the radio enters receive mode e and a sample of received signal energy may begin after the ADC starts acquisition the radio is turned off. And the ADC value is analyzed which is f with LPL low power listening mode if there is no activity on the channel the node returns to sleep g all of this we will have to be done.

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And therefore, designing an IoT system with battery based system with a microcontroller with a communication interface like a ultra low power radio this particular picture becomes very very critical for you to understand the new wants us that are associated when you chose components for putting a system in place.

I would like to stop here.