Design for Internet of Things
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Lecture - 13
Energy Harvesting - 01

The movement of semiconductor technologies towards low power has gone so well that it has become enabling to harvest energy from the ambient and then start driving them. When you say ambient what occurs to you is the most obvious is solar. But you know solar rays very good it is a very mature source. And it is something that is available seasonal of course and the intensity of solar depends on the season.

And anyway, it is diurnal cycle, so you do not have the ability to harvest 24 hours. So, that is one thing then you could combine it with maybe some other source of harvesting which will allow you to make the node you know sort of perennially powered or you may want to store the energy from solar and store it in a battery and use that battery energy in a judicious manner. That is another possibility.

All these things have you know come up in the last one decade or so and there is so much of technology out there you have to catch up to understand what is realistic? What can you do? And what is it that you still have to you know understand in terms of its limitations, energy harvesting and its limitations. So, let us take the positive part first let us understand how this technology is evolved.

And then we will look at other systems where you could argument harvesting with batteries and so on which will allow you to give you 24-hour perennial monitoring and control requirements for using IoT devices. So, before we go into any obviously this module again, we will have some demonstrations. Because there is no point in just talking but we have to show things. But I want you to draw your attention to a basic current document which I sort of prepared to give you a feel for this area.

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Low power Devices

Introduction and use cases – The Internet of Things (IoT) is estimated to grow into a network of 21 billion interconnected devices by the year 2020. Seamless operation of these networks can be ensured when lifetimes of the interconnected devices are enhanced. Advances in low power hardware and software technologies indicate that lifetime expectancy of battery powered sensor nodes can be extended over 10 years. For example, the remote keyless entry systems installed in cars and other vehicles work for greater than 4 years (perhaps even 7 to 8 years!) without the need to change the battery.

Embedded IoT devices with coin cell operation has become a reality. Also, device low power consumption has made application of energy harvesting technologies a viable option. For instance, Renesas Electronic Corporation has developed a proprietary SOTBTM process technology and have demonstrated that the SOTBTM embedded controller can be powered using energy harvested from vibrations, light and thermoelectric module. A node that harvests energy from its ambience, i.e., Energy Harvesting Sensor (EHS) node can essentially function forever and thus eliminates the daunting task of battery replacement.

And here is where you could essentially focus on. Now I was following this area of low power devices for quite some time. And the initial paragraph is talking about billions of devices being connected to the internet. So, these are quite a few devices out there 20 to 50 billion is what they are saying and 20 is already out here in the year 2020. We are already in 2021 and many more that are coming up.

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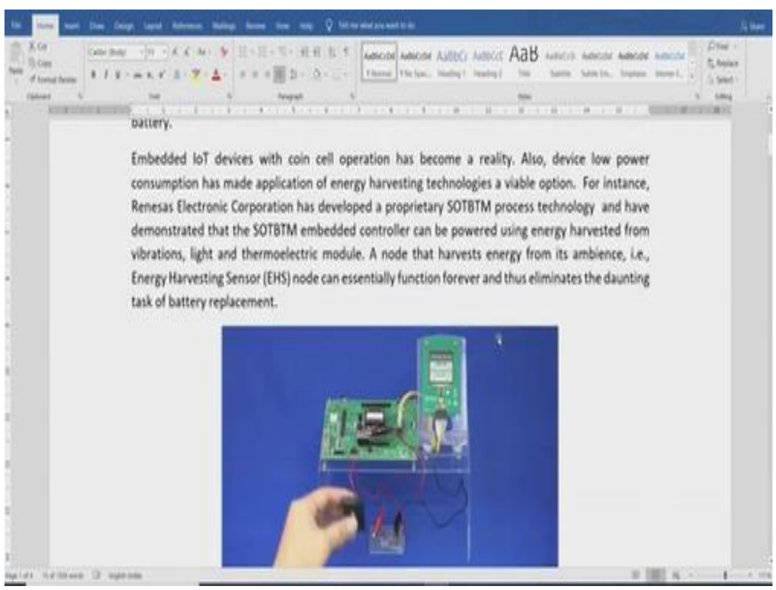
battery.

Embedded IoT devices with coin cell operation has become a reality. Also, device low power consumption has made application of energy harvesting technologies a viable option. For instance, Renesas Electronic Corporation has developed a proprietary SOTBTM process technology and have demonstrated that the SOTBTM embedded controller can be powered using energy harvested from vibrations, light and thermoelectric module. A node that harvests energy from its ambience, i.e., Energy Harvesting Sensor (EHS) node can essentially function forever and thus eliminates the daunting task of battery replacement.

Now if you look at this picture you will see something very interesting. This picture is from a company called Renesys and they made this kit. This kit has an interesting ability it is a full development kit which you can buy. What you see in the person's hand is some device which is holding which is actually a harvesting device. If this device is vibrated moved from left to right or right to left, in this plane you sort of shake it, this controller will power and not only power but will also power up the display.

That means this complete sensing system sense, powering and display all of it will work as long as this person is shaking this device. This is a harvesting device, and he is actually shaking it in a manner that it is able to generate some amount of power which is conditioned by this system, down below you see some conditioning circuit. After that you get some DC voltage DC power. The DC voltage is fed to this controller boots, controller run some code, controller is also having a display system and the display is actually also powering up.

As long as this is vibrating as long as this is shaking, I would say, you will still get energy here. This is a vibration energy harvesting of one type. This is a one type of vibration energy harvesting because in energy harvesting, vibration harvesting you have piezo electric, then piezo resistive and so on. So, many variations are there for energy harvesting using vibrations but broadly this is a vibration harvesting circuit.

Do look up Renesys, it uses this technology called SOTBTM technology from Renesys. And this is a very popular advertisement or rather a popular video which you can find on the YouTube and so on.

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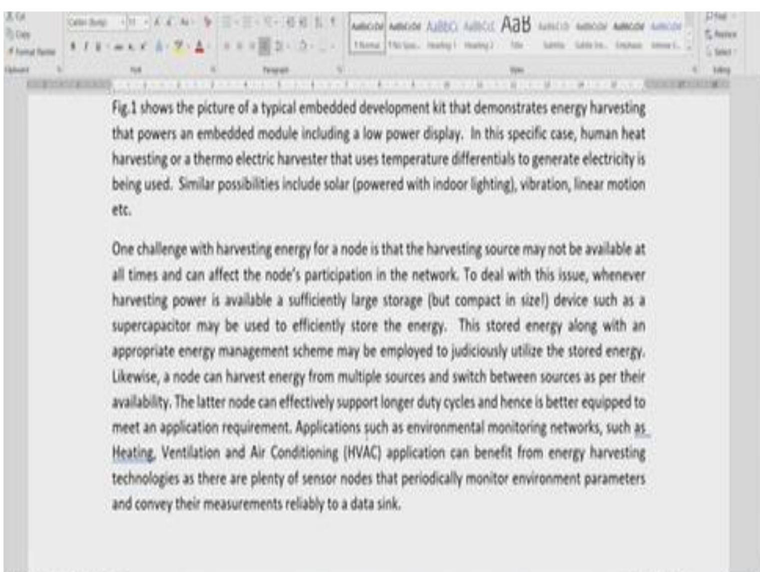

Fig.1 shows the picture of a typical embedded development kit that demonstrates energy harvesting that powers an embedded module including a low power display. In this specific case, human heat harvesting or a thermo electric harvester that uses temperature differentials to generate electricity is being used. Similar possibilities include solar (powered with indoor lighting), vibration, linear motion etc.

One challenge with harvesting energy for a node is that the harvesting source may not be available at all times and can affect the node's participation in the network. To deal with this issue, whenever harvesting power is available a sufficiently large storage (but compact in size!) device such as a supercapacitor may be used to efficiently store the energy. This stored energy along with an appropriate energy management scheme may be employed to judiciously utilize the stored energy. Likewise, a node can harvest energy from multiple sources and switch between sources as per their availability. The latter node can effectively support longer duty cycles and hence is better equipped to meet an application requirement. Applications such as environmental monitoring networks, such as Heating, Ventilation and Air Conditioning (HVAC) application can benefit from energy harvesting technologies as there are plenty of sensor nodes that periodically monitor environment parameters and convey their measurements reliably to a data sink.

If you go a little forward the trouble with harvesting, what is it that you have? Before you go, you actually see that vibration is just one part. You can also generate energy from temperature differentials. Essentially you have TEGs as they are called Thermo Electric Generators or TEGs. I will write it here TEG.

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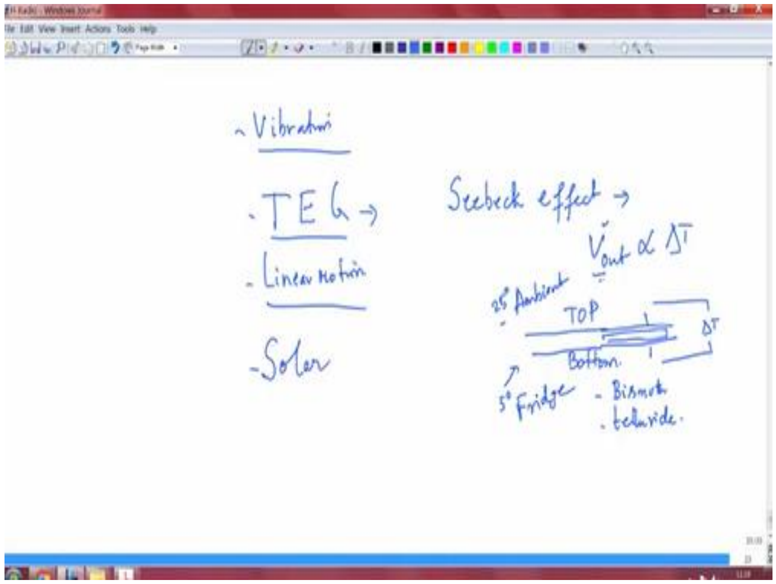

This is essentially that which follows the basic principles of Seebeck effect. That means you will get a voltage Vout, which is proportional to difference in temperatures. Basically, what is delta T you will have a device like this, there will be two surfaces and as long as there is a temperature difference between these two surfaces this, I will call is top and this is bottom. As long as there is a difference in temperature between the two surfaces you will keep getting an output voltage. Higher the difference in voltage, higher will be the output voltage.

So, this is something that is also you can use with TEGs. And some rare materials elements are actually used to make these TEGs, Bismuth is one of them, Bismuth then Telluride and so on. So, some materials some elements like this are used in the manufacture of these Seebeck effect thermoelectric generators. You can think of the lower side connected to let us say a refrigerator and the top side connected to ambient.

This will be around 25 degrees or so I am referring inside homes. And this may be if you have set it to let us say anywhere between 0 and let us say I will just say for example 5 degrees. So, you have a good differential of about 20 delta T is about 20 and for 20 you will get some output voltage. So, this is something that you can actually use harvest from. So, you have vibration which I showed you as an example.

And you also have thermoelectric generation which is another possibility. Of course, the well-known is solar I did not write that, you can also have linear motion and I will show you a demonstration of the linear motion. This is not in action but what we actually have with us. What we have is this device?

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This is a 3D printed device. You can see this is a 3D printed device. What you see is some sort of panel here, this is a solar panel, trick is not there the trick is inside. I will show you what is inside. Look here this is what is inside. This is you press this; you see that action happening there when you once you press this some amount of voltage is generated. That voltage you can take condition it, store it, consume it and be done that is the beauty.

Suppose you want to keep it sustained only one action how do I keep that node sustained? Well, if you have seen that I have put a solar panel on top. In case you want to fuse two different harvesting sources this is one way to fuse the harvesting source, you have a solar panel on top and you have a switch inside. That essentially what I mentioned by what I wrote here which is from motion.

So, you can do from vibration, you can do from TEGs you can also do from motion and of course you can do from solar. But what I showed you in solar is actually what is done from indoor, not actually this is not kept outside, this is indoor solar. And this panel is the same, but harvesting is from indoor light. Indoor light you do not have all the frequencies of the electromagnetic spectrum in the white light.

Because these are artificial sources, these are all artificial sources of light. Nevertheless, you will get a sufficiently good amount of energy which sort of matches that technology which has allowed us to do all these things that is the key point. Now one part is to know what energy source and what is its harvesting opportunity this is on the one side of the part of the story. The other part of the story is this an IoT course we have an IoT device. How much energy?

How do I quantify the energy requirement of the controller, microcontroller? How do I quantify the energy of let us say a display system and so on? You need to also know what is the energy breakup? What is the parameter to look for to see the energy breakup? So, then you know this is my harvesting source and the available opportunities so much this is my load equivalent where microcontrollers, sensor, display and so on are there.

And then you balance you see what should be the size of the harvesting source, such that it matches the requirement of the equal end load which is nothing but our IoT device. So, I will show you a few parameters which will allow you to think about those that balance that I was referring to. Let us go back to this basic document which I wrote up here. I will show you the chart first and then you will look up.

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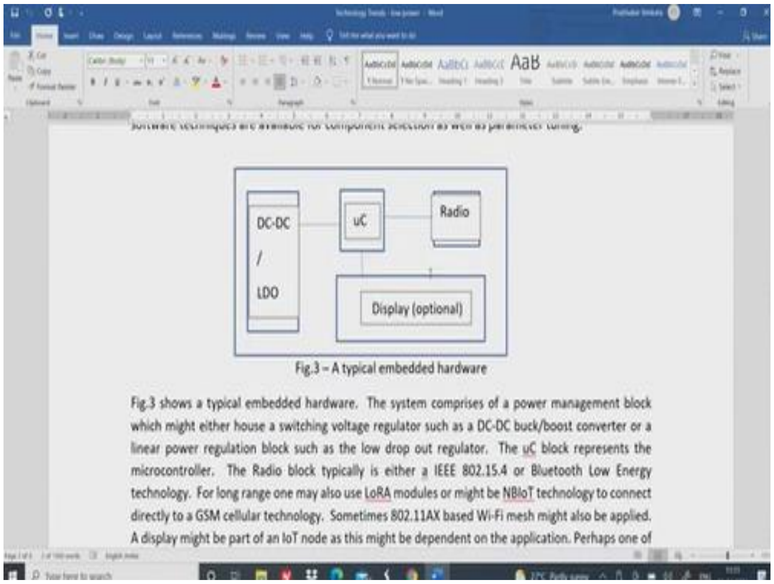

So, these are the different devices that are there. In the initial discussion where we mentioned about a IoT node having either DC-DC or LDO. This itself will determine one of the points in the right side of the balance. Load requirement, harvesting opportunity I mentioned is balanced between the two. If you choose DC-DC, the requirement is lower if you choose LDO the requirement is higher.

Choose then why not choose all the time DC-DC? No, you cannot because I mentioned about switching noise and how it affects the sensing systems and so on. So, that you can do then you have to choose LDO In that case. So, the energy goes up again. Then we mentioned about frequency of operation of the controller. That is another tie I mean energy guzzling component. Then the display part how much is the energy consumption of the display.

All these are very connected, and you may have experienced these things on your everyday life as well. The mobile phone you will see that if you are not talking and you are kept it turned off you know not using it for let us say a few seconds the display switches off. The reason is displays the highest power consuming device in any embedded node or any embedded device. So, if you want to have a display it is you will take an energy beating.

But these are changing. There are ultra-low power devices, display devices which have come memory in pixel, MIP display as they are called. These are very low power devices. And what you saw here is essentially a MIP display. This is a MIP display. This display that you see is a MIP display, memory in pixel this is called memory in pixel. Now the other so here you have the different components then you have controller then you have radio.

Radio again, if you are receiving radio, you will have reception current if you are transmitting at from minus 20 dBm to let us say plus 10 dBm currents can vary a little bit. And then there is power consumption due to the radio then there is display which is actually optional in several embedded devices. Because these are sort of nodes which on which you do not have a display.
But you cannot exclude that because there can be several applications where you may want to read off a value right there.

Because it may not have a communication unit anymore, it is impossible for you to set up a communication unit for just one single IoT node which is you know giving you some value. It could be let us say going to the field and looking at on the spot soil moisture value right in the field. Let us say you do not have internet connection you want to see it there. So, you press a button the display value will come up and it will show you the value of the soil moisture in that field.

So, many applications actually require a display in fact, if you have a display, you have more advantages. So, that is a very important thing.

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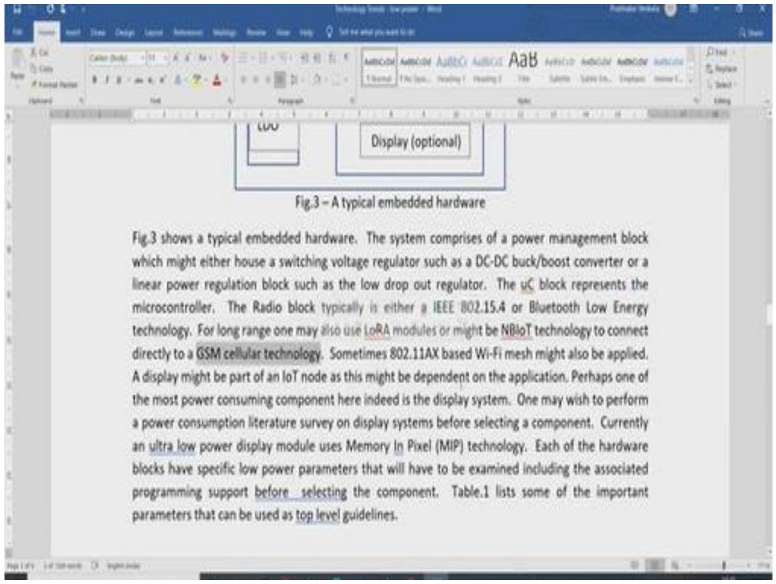

So, then radio again you can have different technologies taking different energy consumptions. You can be talking about low power radios like 15.4 or Bluetooth Low Energy or wide area radios like LoRa modules or NBIoT modules and so on also GSM cellular technologies. If all these are insufficient for your requirements you may even want to go in for a Wi Fi mesh system which is essentially classified as 802.11AX and so on.

I did mention to you about the memory in pixel option, which is an extremely low power display module, ultra-low power module. We will try we will try and see if we can do a demonstration of that as well for you. Let us now, I mentioned to you about this picture which essentially captured the different components which are part of a typical embedded hardware.

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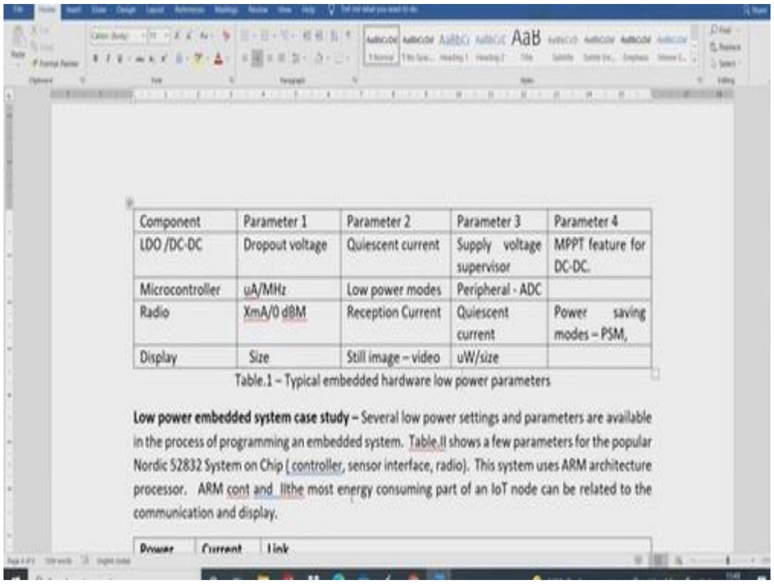

Component	Parameter 1	Parameter 2	Parameter 3	Parameter 4
LDO /DC-DC	Dropout voltage	Quiescent current	Supply voltage supervisor	MPPT feature for DC-DC.
Microcontroller	uA/MHz	Low power modes	Peripheral - ADC	
Radio	XmA/0 dBM	Reception Current	Quiescent current	Power saving modes – PSM,
Display	Size	Still image – video	uW/size	

Table.1 – Typical embedded hardware low power parameters

Low power embedded system case study – Several low power settings and parameters are available in the process of programming an embedded system. Table.II shows a few parameters for the popular Nordic 52832 System on Chip (controller, sensor interface, radio). This system uses ARM architecture processor. ARM cont and lIthe most energy consuming part of an IoT node can be related to the communication and display.

Power	Current	Link

If you start looking at the parameters with respect to the LDO or DC-DC control DC-DC power management block which is inside the controller.

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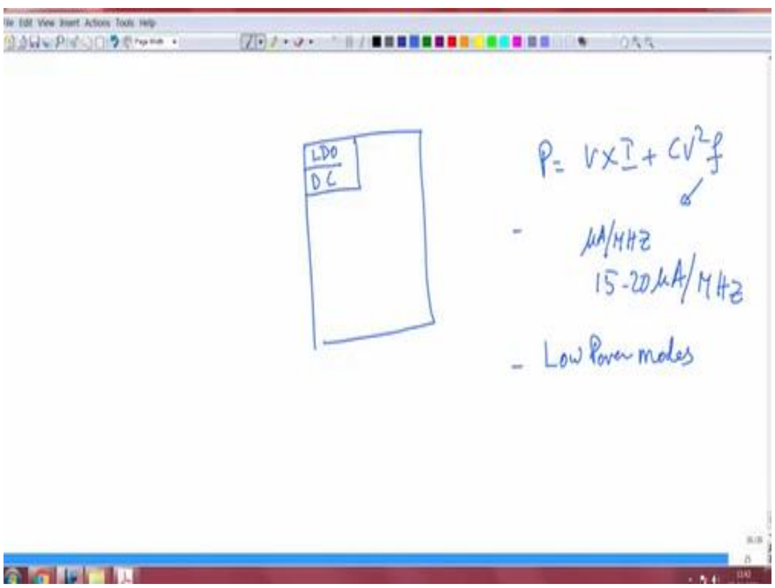

You can choose between either one of them we said this already. The parameter of interest if you are looking at LDO is the dropout voltage. And you can see here I have written about the dropout voltage. The second parameter of interest is the quiescent current. And this quiescent current is even when the chip is on not giving you any output voltage. The chip itself requires a certain amount of current to run.

So, that current will have to be factored into your system when you are harvesting energy. So, the very important, so these are all the places where you should look for when you do your budgeting energy budgeting. So, that your balance between the two occurs in a proper way. Then supply voltage supervisor is something that most components offer you. You can use this for brownout conditions that is if the voltage is sagging below a certain value, and you know your systems become unstable.

You can use the SVS, supply voltage supervisor to trigger the system to go into a low power mode. MPPT feature for DC-DC is something that is a very important aspect. So, that you extract maximum from the harvesting sources. So, this is a very important parameter. So, maximum extraction from harvesting sources happens through this. Microcontroller, if you look at microcontroller you are talking about typically micro amps per megahertz.

We did talk about the power expression which we gave here which is V cross I plus C V square f, f has a direct impact on the power consumption. And therefore, you will see that microcontroller typically you choose a microcontroller based on its micro amps per megahertz. Choose this as an important parameter. And today we are talking about anywhere between 15 to 20 micro amps per megahertz. So, this is another important parameter.

Then the low power modes if you talk about low power modes microcontrollers support several low power modes. And what you should notice let me give you an example of Nordic processor which we know quite well.

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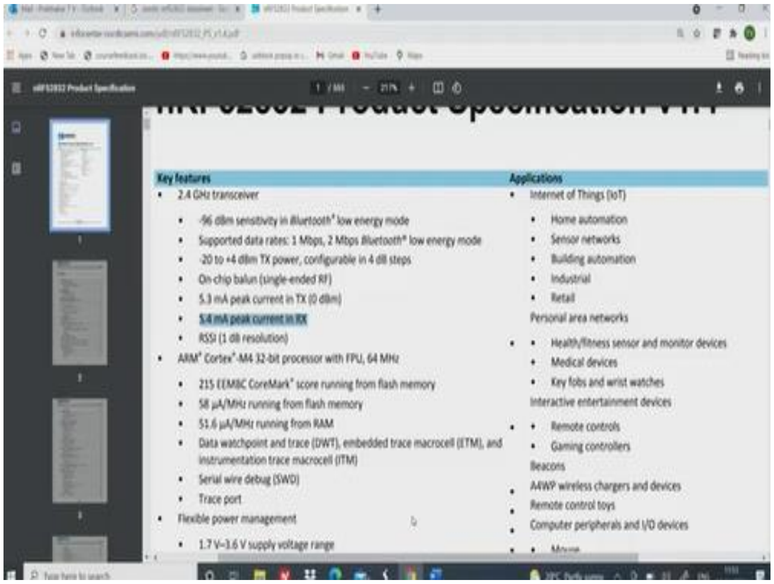

And you will see that some numbers are here. Look at this beautiful numbers that are mentioned here you have radio which is integrated into the system. It gives you 5.3 milli amperes for zero dBm make a note of this number because we are going to revisit this very soon. 5.3 milli amperes of peak current in the RX mod and it takes 58 micro amps per megahertz running from flash memory the processor itself, 51.6 micrograms per megahertz if it is running from ram.

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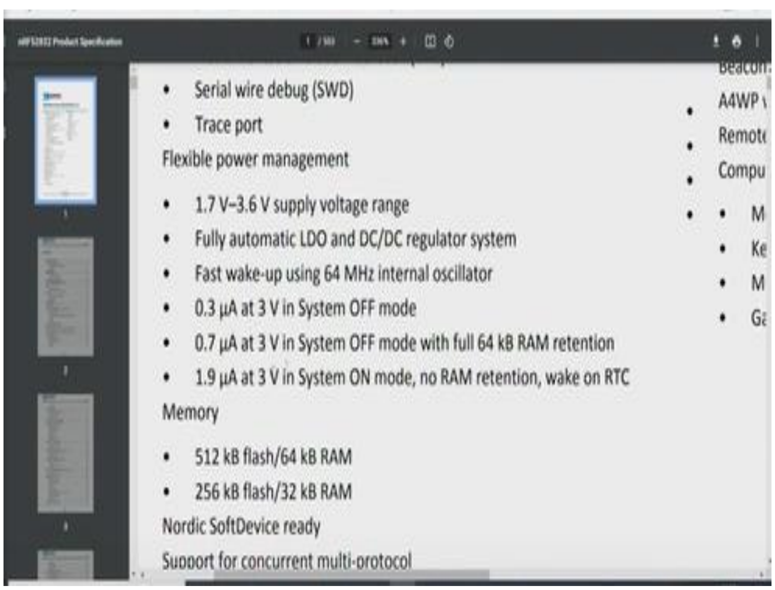

Then it runs on different voltage levels, 0.3 micro amperes at 3 volts in system off mode, 0.7 system off with full 64 kB returned ram retention, 1.9 micro amps at 3 volts when system is on no ram retention wake on RTC. These parameters become very crucial for you for designing the size of your harvester. So, this is an important parameter. So, let us go back and look up this chart again.

I already mentioned to you radio so many x milli amperes per 0 dBm, reception current, quiescent current and again power saving modes. All of them are indicated here go back to this Nordic, you will quickly connect to see the x milli amperes per 0 dBm is mentioned here. And that is what I was referring to when we were talking about the 5.3 milli amperes peak current at 0 dBm.

And continuously when you are receiving data you will also consume 5.3 milli amperes. These are the taps; these are the points where power will be required for your operation. You cannot design the size of the harvester if you do not know these numbers. You have to use these numbers to basically design the size of the harvester. Now one is the size of the harvester, and the other aspect is before we move on let us see if there is anything else, then there is display.

Display is to be in terms of a size, the size of the display. You have still images, and you have video and one parameter of interest which you must look for is the micro watts per size. This is as essentially based on the size it consumes certain amount of microwatts. And I gave you memory in pixel is a very good ultra-low power display device for your systems. So, this is about this chart.

Now I mentioned to you on the one side you have this issue of power consumption of the typical SoC. On the other side you also need to know the harvesting opportunities that are available, the size of the harvester that you should choose and so on. For that let us turn our attention to see where is it that you can scavenge from and how much actually is available. Let us go and look up this chart.

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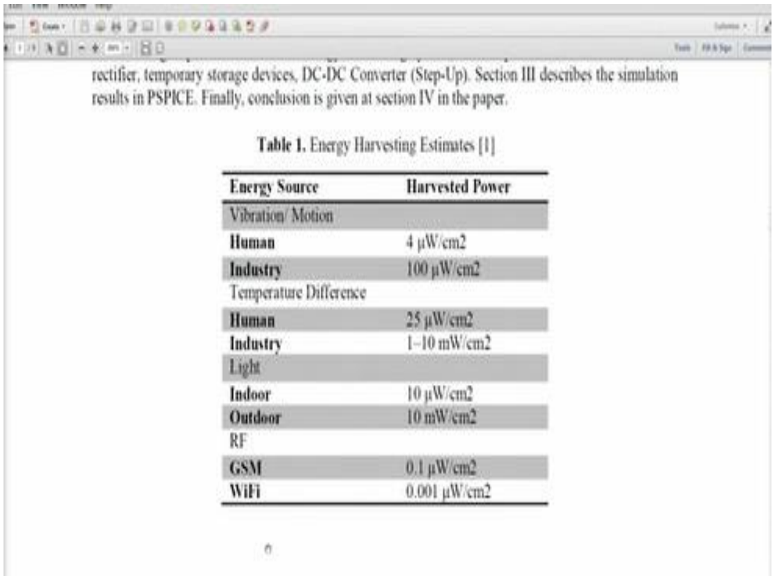

rectifier, temporary storage devices, DC-DC Converter (Step-Up). Section III describes the simulation results in PSPICE. Finally, conclusion is given at section IV in the paper.

Table 1. Energy Harvesting Estimates [1]

Energy Source	Harvested Power
Vibration/ Motion	
Human	4 μW/cm2
Industry	100 μW/cm2
Temperature Difference	
Human	25 μW/cm2
Industry	1–10 mW/cm2
Light	
Indoor	10 μW/cm2
Outdoor	10 mW/cm2
RF	
GSM	0.1 μW/cm2
WiFi	0.001 μW/cm2

You see this beautiful chart here. You get you have the energy source on the left the harvested power on the right. Look at what is actually happening, human walk, human vibration slash motion, if you take human walking which is essentially leading to vibration or motion you get 4 microwatts per square centimetres. In industry environment, you can get up to 100 micro watts per square centimetres.

If you take temperature differentials, human is 25 micro watt per centimetre square, industry is 1 to 10 milli watts per square centimetre. If you take solar, light, indoor is 10 micro watts per centimetre square and outdoor is 10 milli watts per centimetre square. Clearly you can see the differences which are mentioned here. And if you look at GSM you get point one micro per centimetre square and Wi Fi that gives you point 0.001 micro watt per centimetre square.

See this chart is okay, but this chart has hidden several things, it has hidden several things from you. One of the things actually this chart is from this paper which you can actually download.

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So, please look up this paper which you should be able to find designing a battery less Piezo electric based energy harvesting interface circuit with 300 millivolt start-up voltage please look it up you will see this chart out here. This chart is actually not telling you many things. One of the things it is not telling you is you take this temperature difference. Human 25 micro watt, industries 1 to 10 milli watts per centimetre square.

What is the temperature difference? What is the delta T? That has not been told. Similarly light indoor what is the Lux value? That you do not know. You are saying 10 micro watts but what is the input condition under which you get 10 micro watt, is it maximum? What is it? What is this number? I suppose this must be the maximum that you are actually getting. So, anything that you design will have to be lower than this actually in practice will be much lower than these things.

So, what I thought is, it is good for us to know the source of how much is the energy that is coming in and what is it that you are actually harvesting. In a way you should be able to calculate the efficiency of conversion, input and output. What do you see on this side here, this chart is actually only the output? What is the actual input? How much was the input that had come in? That is not clear here.

And also, the condition under which a harvested power is coming is not clear. In a way you do not know the input. So, that is a black box, and it is not a very good thing to do. Let us shift to this article. This article is interesting because again you can download this by the way, this is from Mouser. You see the link here; the link here is clearly visible. And you can download the article from here.

And this is written by one person by named John Donovan. He has written a good article talking about this aspect of energy harvesting here. One of the first things he says is that look at this chart he says. It is the same thing that you saw previously, but you actually know the source power. If you take indoor you are getting 0.1 milli watts you are getting you are getting 0.1 milli watts per square centimetre and you are harvesting only 10 micro watts.

And similarly outdoor is 100 milli watt per square centimetre and you are getting only you are able to harvest about 10 milli watts per square centimetre. Now you know what is the efficiency of conversion here? It is very, very clear. I do not want to do this simple thing. But you actually know that in this case how much is it? It is about 10% that is all it is saying. So, you can start calculating.

Similarly, vibration motion, human 0.5 meters at one hertz and one meter per second square at 50 hertz, this is the acceleration at 50 hertz. You are getting 4 microwatts per square centimetre, machine 1 meter at 5 hertz the acceleration is 10 meter per second square at 1 kilo hertz. So, you get 400 for about 100 micro watts per square centimetre. Similarly, you can look at thermal 20 milli watts per square centimetre are coming down to 30 micro watts per square centimetre, machine is giving you 100 milli watts per square centimetre.

You can get anywhere between 1 and 10 milli watts per square centimetre and so on. Similarly, from RF particularly from base stations. You might have seen by five base stations you might have seen GSM base stations and so on. The GSM base station is typically this is the kind of source power you are getting, and you are able to convert from 0.3 microwatts per square centimetre as an input to about 0.1 micro watts per square centimetre.

So, he goes on this way and then talks also about thermoelectric harvesters. Essentially thermoelectric generators use this Seebeck effect which I mentioned, these are thermocouples connected in series. And essentially you are able to harvest from the temperature differentials and they are typically used into power wireless sensor nodes in high temperature environments such as industrial heating and all that.

I gave you example of ambient and refrigerator. So, it is quite similar you can see in homes it can be ambient and refrigerator. In industrial settings it can be high temperature environments you know one side being a high temperature environment. Typically, that exists in industrial environments. A TEG mounted between a power transmitter, and it heatsink in can recycle some of the energy that would otherwise be lost as heat, this is interesting because a power transistor is actually dissipating a lot of heat power in terms of heat and that you can recycle that heat.

It is not that you are creating perpetual machines, but you can actually recycle some part of the heat that is being given out to the ambient. Then he talks about companies like Micro pelt and so on. These are other companies. Then he goes on to vibration. In vibration he shows a beautiful picture and I thought this is the picture that we should actually capitalize on and try and see if we can build a demo around this. What does he say?

He says that these are Piezo electric transducers generate electricity when stressed. This is Piezo electric type; this is important. That means what are the other types? So, that brings us to another interesting thing. How do we understand the ambient energy harvesting sources? So, we should stop here and go and look at this chart. Now this current chart is actually showing several nice things.

For example, ambient energy source and energy harvesting system you can have electromagnetic energy harvesting, you can have Piezo energy harvesting, you can have electrostatic energy harvesting, you can have thermo electric harvesting and you can have solar energy harvesting. These are all the sources that he has shown. Now let us look at electromagnetic energy harvesting.

You can be talking about waste energy generators and then you can be talking about converters that follow from there. Then you have Piezo electric, waste mechanical energy is a source. PZT are essentially the materials which are used for generating sources for energy by straining, deforming and vibrations of Piezo electric materials you actually get energy. Here, if you look at electrostatic these are capacitive based energy harvesting devices.

Initially charged varactor, variable capacitor is the kind of device that is used for converting from one domain of energy to another domain. Here, it is electrostatic to electrical where vibration separate, Varactor's plates. You can see that thermo electric is talking about thermal gradients. You have thermo piles which are essentially n and p type, temperature differentials between opposite segments.

Materials joined at high temperature junction establish a voltage difference between the base electrodes and it generates useful energy for working. Similarly, photons, solar energy harvesting. You have photo voltaic cells then you have cells consisting of reverse bias p-n junction essentially. This is the source of energy then light interfaces with heavily doped the narrow n plus region accumulates electrons and holes in the n plus and p regions.

This is how the electricity is actually generated; this is the reason why electricity is generated. And then you have interfacing energy harvesting circuit and storage and so on. So, essentially this chart is telling some nice things about the ambient energy source and energy harvesting systems which gives you a complete story. Let us just look at Piezo energy harvesting which is here this is here.

Let us look at this and then we will connect this picture to further demonstrations and so on. So, that you and you appreciate the actual way by which energy is being harvested. So, let us now shift to this screen. What does it say? This is piece of electric. We know that Piezo electric is looking at the waste mechanical energy that is coming in. This is your device which is generating which is your source is a PZT material base system, waste mechanical energy is coming onto this device and it starts vibrating.

These are all waste energies those are vibrating, and you get an AC signal. So, you need to have a bridge rectifier circuit and you do some basic you know little bit of filtering, accumulation of charge on this capacitor and then you make that available as an input to a chip. This chip has the ability to take very low voltages and increase the voltage to a higher range which is essentially means this is a DC-DC converter.

And this is actually a boost converter it will give you some reasonable output here typically 1.8 or 2.2 or 3.3 and so on. It may give you a slightly higher voltages. But on this side at the input at the Vin side you will not get very high input voltages. There will be maybe 200 millivolts or something like that. And this 200 millivolts taken and then amplified to the output side or boosted to the output side to give you voltages which are reasonable to be to drive microcontroller sensors and transmission units and so on.

So, Vin to Vout is actually difference in boosting above the voltage. You can see that these systems are available already. And Mide is a company which essentially makes these piezo of electric harvesting devices. And we will try to see if we can look up a demonstration around that. Similarly, there is RF then you can also harvest from RF and then use this energy for driving the embedded electronics.

And that is about this article, you kindly look up this article. It has many more harvesting modalities as well and gives you a nice idea of the harvesting energy, harvesting for embedded systems. Now let us shift to the demonstration part. We will see a small demonstration and then continue our discussion on energy harvesting. Thank you very much.

(Video Ends: 36:59)