Design for Internet of Things
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Lecture - 18
Battery less power supply and battery life calculation for embedded devices II

Ok. So, now what I am going to show you is a demonstration setup from our lab colleagues, Miss Madhuri has been working on this. So, what I have here is RF DC electronics this is the RF DC board, this is the RF DC board RF DC energy, you take RF energy converted into DC and store in this capacitor ok.

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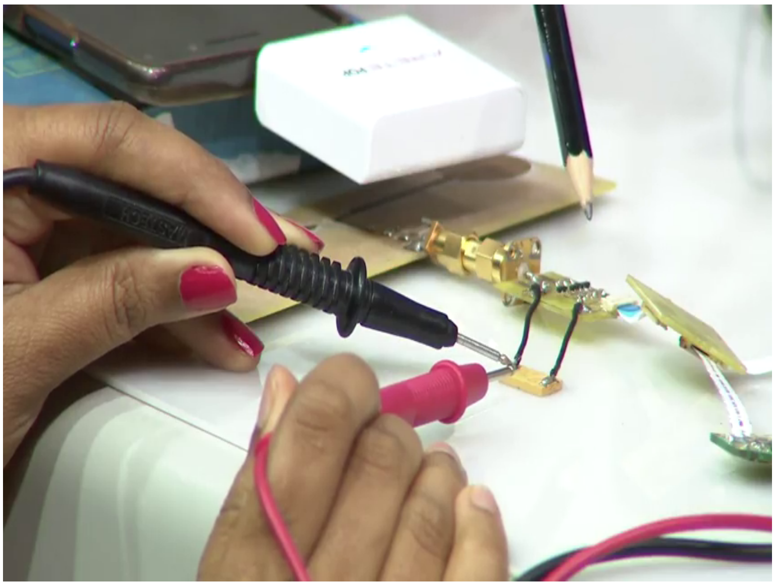

You store in this capacitor and how are you throwing RF energy on this, how are you powering this, how are you feeding RF power you are feeding the RF power through this antenna, the antenna is here you can see and which is the RF source well the RF source is right here, this is an RFID reader. This RFID reader is a handheld reader it is a portable reader and this reader is actually connected to this mobile phone through the audio port this is called arête POP, POP e m reader and it is throwing 20 plus 25 dBm of transmission power, as you can see the rangers very very short, you still have to apply the path loss the for this distance and then calculate the received power we can do that at a later time.

But you can already use the (Refer Time: 01:43) equation to find out what is the actual received power here. This antenna is tuned for the sub 1 gigahertz a 900 and 850 megahertz because 850 is indeed the RFID frequency, and you can also see that this board has a little piece of electronics here small circuitry here which is essentially the impedance matching right. We did discuss about the maximum power point tracking which would be required in order to maximize the amount of energy for improving the efficiency of the system.

Therefore, you do have the impedance matching circuit and once the importance is matched, it is fed to this board and this indeed is the RF DC board. And at the end you get DC which is here and what do you do with this DC well once you get sufficient amount of DC, you actually power this little board this board I will perhaps twist and show you this is essentially a microcontroller board, this is a small microcontroller board which is connected through this gateway device here ok.

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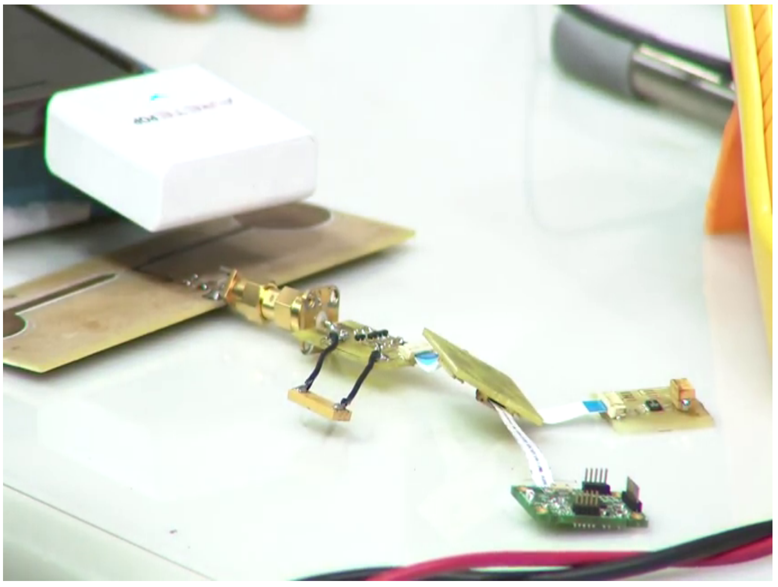

Let us see how good this system is doing. So, I will ask Madhuri to hold against the capacitor and let us know focus on the multi meter, you can see now that the multi meter is reading 3.66 and slowly you will see that it will increase to 3.67.

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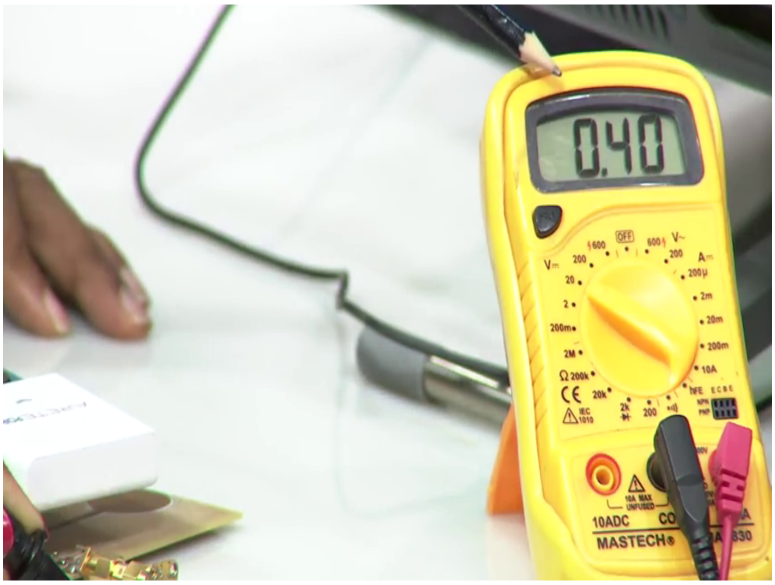

So, let me not load the capacitor and we will only make intermittent and measurement so that we can actually show you that it is building. So, what should happen? Soon as it builds to a little over 4 volts, you will see a data packet on this mobile phone. So, that is another important thing right now you can see that there is no data packet, there is nothing here it is blank and so, we need to ensure that now let us see how much is the voltage it is 3.74.

So, we will have to wait a little longer all right very good. So, what is important is, it should be in this scanning mode if you press that it will stop scanning. So, it is continuing to scan this is a simple android app given by the manufacturer of this device, which allows you which actually tells you that it has received a data packet. Now the communication from this controller board is a Bluetooth low energy, this is the Nordic NRF board, which essentially or is an SOC which has the BLE radio built inside the system, and you should be able to power the board and we can see that it has built significantly well and you can see the success here that we have we do have a data packet which you see here, this is indeed the data packet which has come.

So, what is the summary of this experiment? The summary is that if you have a sensor node which is connected to the which is which essentially has RFID, essentially which has a sensor connected to this board and it does not have any battery, you want to come and let us say come with a handheld reader like this, and you want to power this sensor node let me now that the demo is over you want to power this just the lab demonstration setup, which makes things a little more modular that is why we have a passive board which connects there. So, you could essentially come this is let us say you are electronics and with the sensor, you come periodically and try and see if you want to read the sensor value through that, you just come close to this and then you get the sensor value right.

Many such applications are possible where you want to sense through you know on the fly you want to sense some amount of without a battery. This is a basically a battery less system which allows you to gives you the flexibility to read a sensor value without battery and an on demand. Whenever you want you go there you know take the system power it with the you basically power it with the RFID reader, and basically power the system here power the system with the reader and then you essentially read of the sensor value. How did this work can you build this all by yourself, what is the magic behind this powering and transmission, I will show you that in a moment.

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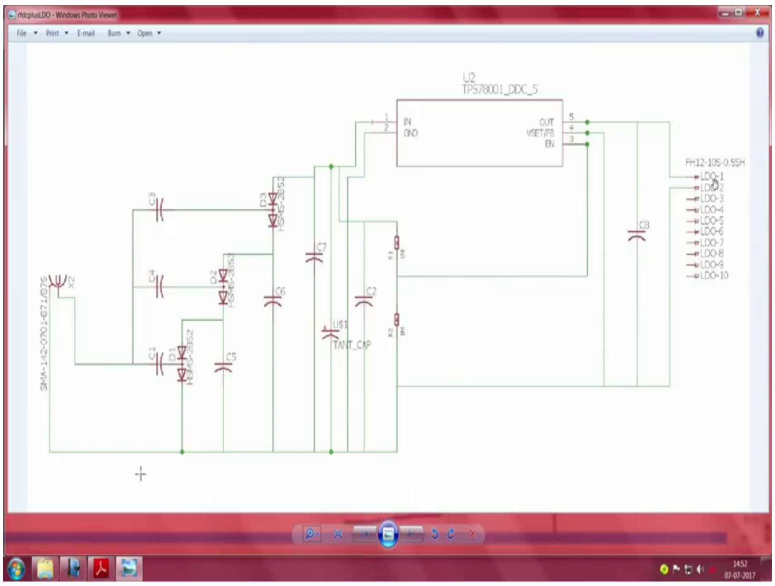

Essentially what we have here is this circuit, you can see that this is the antenna that is nothing, but this antenna this antenna right, this is the antenna here essentially this is the antenna here, and this is a Dickson charge pump. This is nothing a Dickson charge pump remember we discussed this disc Dickson charge pump multistage; 1 2 3 stages of Dickson charge pump, all the energy coming from the RF is multiplied voltage multiplier here Dickson voltage multiplier circuit and stores that energy in this tantalum capacitor.

Now, this is an LDO TPS 678001 LDO from t I another one sum vendor and one vendor from where we could get this regulator LDO, and the output is essentially giving you a certain fixed value right. As you can see if you use an LDO, you will have to put the stability capacitors this is the C 8 which is a stability capacitor, and this is the input capacitor, this is the capacitor on which the there is a storage and you can easily build this multistage voltage Dickson voltage multiplier. I will give you some details of this voltage multiplier, where you can buy this I C where should you buy it and how you can actually use it. So, let us go back to this part here where you can actually source.

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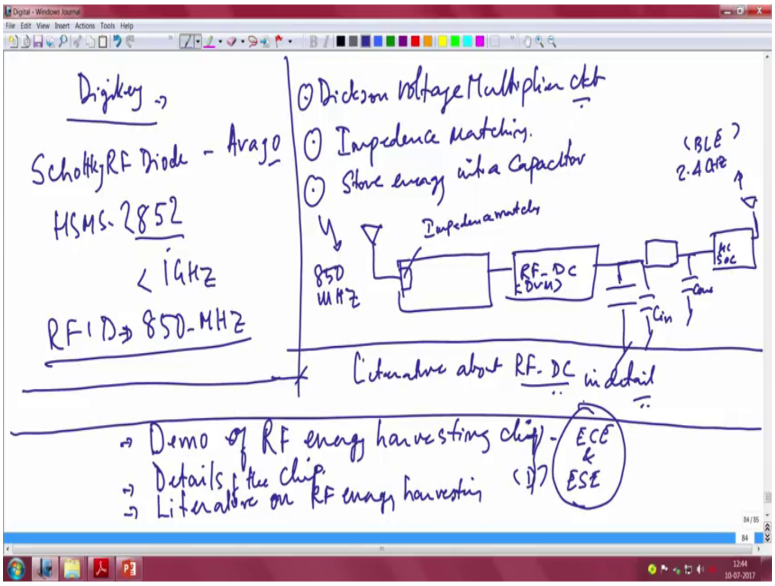

This from digikey easily, you can easily source this component from digikey, this is RF diodes it is an RF diode nothing, but a Schottky; it is a Schottky, Schottky RF diode these are also called detector diodes; this is from a company called Avago ok.

The diode that I have used in our lab is HSMS 2852, most suitable for the sub gigahertz frequencies because we used the RFID frequency of 850 megahertz, this is the RFID frequency and therefore, these diodes are quite suitable for application. Build your voltage divider circuit voltage sorry voltage multiplier circuit, Dickson charge pump voltage multiplier Dickson voltage multiplier circuit and then connected and essentially you have to build this. So, let us take a very practical circuit and see if we can actually rig up this circuit and show you this voltage doubler output ok.

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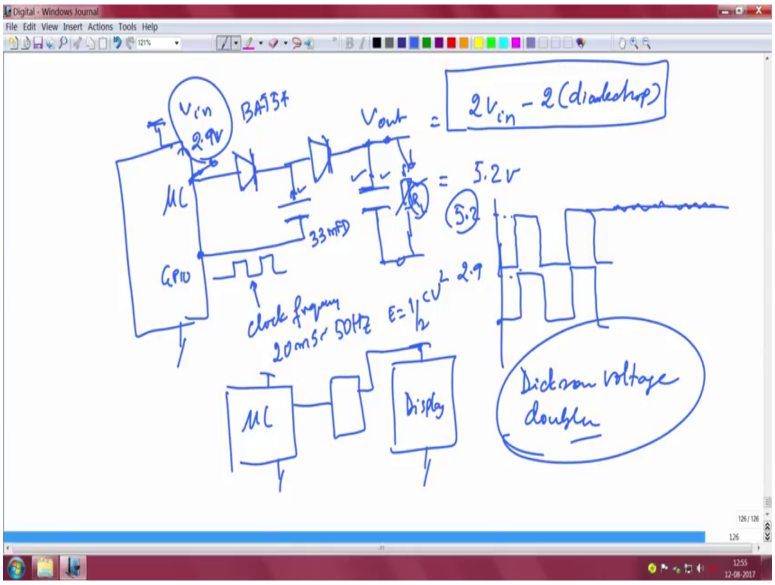

For this let me put back this picture to you I just quickly read drew that you have a microcontroller, and there is a GPIO pin on the microcontroller, and to this microcontroller what I will do is I will connect to one of the pins, I will connect the Schottky diodes these are basically Schottky diodes.

You can look up bat 54 diodes, which are essentially Schottky diodes and this is the arrangement you have a diode here and you have a capacitor here, and you generate a clock here right a basically small clock circuit generate here, this clock frequency is a critical thing. So, what should be the clock frequency is another story, we will come to that in a moment and I will tell you the design requirement for that. Then you are essentially trying to get an output voltage here.

So, this is the output voltage V out is here, and for that what you do is, you have this arrangement and the output capacitors connected here, the second the stage of the diode the actual doubler circuit part comprise of this circuit, and the load RL is connected here. Now if you look at the if you draw a if I draw your attention to what I have shown here, you have 2.9 volts connected to this input, where that is a essentially what is being fed to this diode, and it is charging this capacitor it is a DC that is being fed to the to the capacitor and there is a clock.

Right now the clock frequency that has been set for this demonstration is 20 milliseconds; that means, it is a 50 hertz clock, and so, it is just shocking and what is appearing across this capacitor here is appearing doubled across this capacitor, that is all that is happening and why is that happening? Because of the doubling action 0 is here, 2.9 volts is here and then automatically 5.2 volts we will appear here, it is the reason why it is not really ideally it should be double, but it is not in the practical it is not because of these 2 diode drops and the equation for that is here very simple equation 2 times V in is what you expect V in is here V out should be this is V out. So, let me read write it carefully here this is V out, V out should be 2 times V in minus 2 diode drops which occur here which is roughly 5.2 volts.

Now, the value of this capacitor we will largely depend on the current that you want to draw right the power that you want to draw through the road load resistor. So, it should be able to give you whatever energy that is there, which is half c v square right. It should be able to source that for whatever duration of time that current is required, it should be able to the power that is required we will have to be a source through the value of that capacitor.

So, the capacitor value we will be determined based on the power requirement of this r l; also the clock frequencies critical because a every time the power is drawn the voltage across the capacitor is going to fall and then again going to rise when the power is reduced right. If you want to reduce this ripple and make it even more shorter let us say, a smaller ripple then you obviously, have to increase the frequency switching frequency that is the key here.

So, the choice of switching frequency we will largely depend on what is the kind of ripple that your system can tolerate. So, so keep these 2 points in mind, and let us now move on to see our actual demonstration, which Miss Madhuri and Miss Anuja have said together. We will actually show you through a multi meter the values at this point; you will see an input of 2.9 which they will show you, and they will show you and output which will give me which will be close to 5.2 volts. And for that what I have done is I have taken a standard microcontroller board, and that microcontroller board is being powered through some u s b system, but what actually is available on this pin is actual 2.9 volts. So, let us now go to the demonstration and see whether we are able to set up this circuit.

The value of the capacitor that they have chosen is 33 microfarad, 33 microfarad for both the stages for this, at this value as well as this value as a set the value of the capacitor we will largely depend on the power requirement of your output load. And these are bad 54 diodes, you can connect any potentiometer that is required at the output keep wearing this potentiometer to understand across variable loads what kind of current you can actually draw from the system and see whether it matches the load requirement.

So, as simple as this can easily be built these essential it say Dickson voltage doubler, that you might is that you have that we will be putting together. Many many situations we will come where there will be a microcontroller, there will be some other peripheral something like a display unit, and this display unit we will require a higher voltage as compared to what is available on the board. So, that is the time when you actually connect this voltage doubler, and connected to and connected to the required peripheral. So, these are the typical applications.

Now let us switch to the demonstration and move on from there. What we have here is small is a microcontroller board, and we have taken a general purpose board Madhuri has taken a general purpose board here.

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You see these 2 devices here these are essentially capacitors diodes are not so, clearly visible, but never mind you may want to look at the multi meter in order to see what is the input and the output voltage. First step what she will do is she will show you the input voltage. So, just look up this multi meter. So, what you read there is 2.8 84 right 85 let us say 2.85. So, we measure 2.9 at that stage, but now it seems to give you 2.9 it is all right never mind. So, accordingly output we will be a little over. So, that is 5.2 good 2 point. So, it is 5.21 all right very good excellent.

So, you can see that by magic what you will measure at the output, indeed is 5.2 volts and you can simply rig up this circuit and try to drive your peripheral which requires higher voltage. You have to do impedance matching, you have to impedance match and then you should be able to store energy into a capacitor and use that energy. So, let me draw the picture for you block diagram, you have the antenna, this is the and receiver antenna there is an impedance matching, then you feeding it directly to RF DC, this is the Dickson charge pump Dickson voltage multiplier, I will simply call it DVM, you get output voltage this is the RF harvested voltage, use this to drive either through a LDO or directly your load it is useful to put an LDO all the time because you will do we will be able to do load isolation.

So, let me put to smaller picture, this is the C in which you know very well and this is the C out and this in turn is connected to the microcontroller S o C. So, this is harvesting in the 850 megahertz, this is what I should you demonstration is BLE Bluetooth low energy transmission in the 2.4 gigahertz right. So, these are some of the experiments we did with respect to the RFDC, it is important now to know literature about RF DC in detail all right. So, what we will do is stories never incomplete if we do not understand everything about the RF harvesting in it is completeness right. So, what are the elements of. So, we showed a we saw a demonstration of an RFID reader, which is working in the sub 1 gigahertz frequency powering, a RF DC system which uses a voltage doubler configuration and ultimately you are able to send out a PLE a transmission packet right.

So, we saw the demonstration and we also saw the circuit topology that goes behind, but if you want to really build a complete system with RF energy harvesting, there are so many parameters people actually talk you and lot of literature, which actually talks about efficiency of such a system right this is a big thing in the RF harvesting domain. So, we have to understand all those aspects correctly. For that what we will do is we will go through one recently published article, and run through that article completely which is a very good eye opener on all aspects of RF harvesting in the domain related to RF energy harvesting. But before that I also thought I should show you another demonstration which essentially is a RF energy harvesting chip which we did in the lab, which we built in the lab of course, chip was you know basically designed in the lab and given out to a foundry process so, that you acquired the bear die and from there you package the die and then you get the package dies.

So, the chip fabrication did not happen in the lab because that is a different process and different equipment you know factory requirements which fabrication requirements which are there, but the chip was designed here right simulated and designed here. So, we will under I will show you a short clip what we did? And going to the detail of that chip and explain to you how you can actually go from a discrete component solution where we use Avago diodes, multistage Avago diodes and then build a system, down to a very small compact small chip which can also do the same functionality, but at a much reduced much at lower input power level also you can also do it at a smaller size ok.

So, let us see that little demo, for that I would before I show you the demo what I want to actually discuss is I will show you a demo the right. First things demo of a RF energy harvesting chip this is the first part, this chip was built in our department it was done in joint collaboration with the ECE department ECE and ESE, D ESE actually department of electronic systems engineering together, built this chip along with students right our own IASEM tech students Bharat Hegde and Syed Younus actually build this design this chip. So, I will show you a demonstration of that, after I demonstrate that chip the functioning and working of that chip I will then go into the details of the chip the internal details of the chip, and then I will then go and we look up the literature on r d energy harvesting. These are the three things that we should try and see if you can complete very good.

So, fast is to run through the chip. So, let me open the chip and then we will yeah. So, this is the. So, let us play this clip this is one more (Refer Time: 27:03) we are using the p c board plus antenna which is also.

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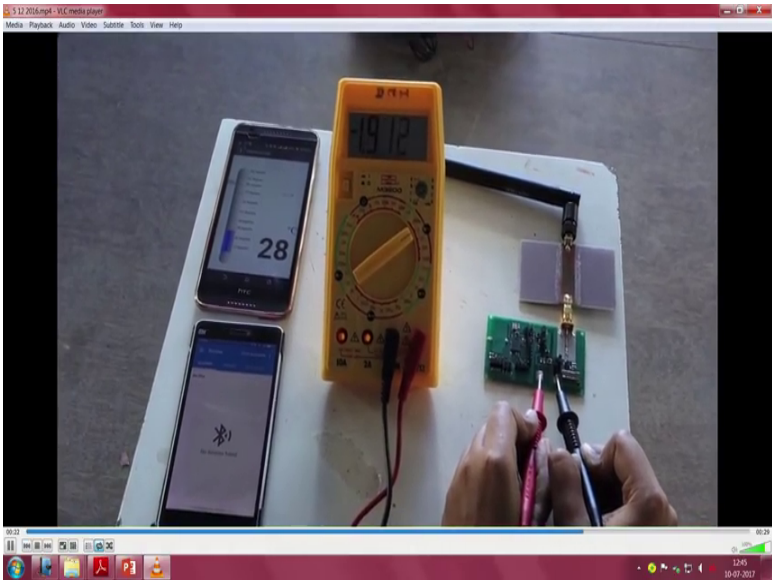

So, first let me. So, let me start this video. So, first is to. So, let me let me restart this video. So, here is a RFID reader that you see here which is throwing energy RF power on this antenna, this is a quarter wave match antenna impedance matching system, and the chip is right here you see the voltage being red there right you see nothing here now you will quickly see something yeah there you see you get some value, the value of the temperature also has changed.

So, let me go slowly and re show this demonstration again to you, will see that the voltage is slowly building up; it builds to 1.95 at the instant when it builds to 1.95 you will get a data transmission. So, 1.6, 1.7 there you go slowly builds then for a moment you will see that 1.95 and then you will see a packet here right. So, which is clearly what it is doing is it is harvesting RF power, and you can see it is a quite a distance from the antenna here and other quarter wave impedance matching, then the chip here and the complete application here very good. So, this chip what does it contain inside it, what should be how should be designed this chip and all that I will try and show you a little bit on that front.

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So, to begin with this chip essentially is design was designed by 2 of my students; Syed Younus and Bharat Hegde as you can see a guided by ECE faculty professor K J Vinoy and also myself.

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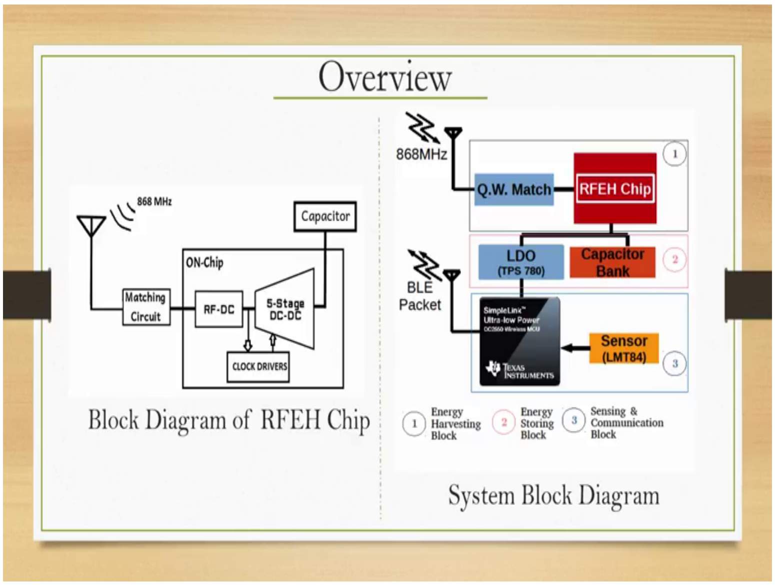

So, this is an RF energy harvesting chip based system; the there is one part which is the chip the other is indeed the complete system that they built. Inside the ship you will see that quarter wave match which we discussed is here, the impedance matching circuit is here and then what is inside the chip is an RF DC, usual Dickson charge pump that we looked at in the previous times is already here, then there is a 5 stage DC-DC. It is a boost converter; this is a 5 stage boost converter.

And then there is a storage of the energy that is harvested through this there is a capacitor we are in, it is in a nutshell this is what it contains inside getting into detail here the quarter wave match which is a which was actually the small PCB which was attached to the antenna is here, the RF energy harvesting chip is there, then there is a an LDO which is doing actually it is sort of isolating the load recall I keep telling you that it is important not just look at and I d o from the fact that it is providing your stable rail it is utility can be many many types, in this case we are actually using this LDO for a nice purpose.

The purposes is that if you recall the demo, the voltage was building right once it reached a critical of 9 point; 1.95 and little over 9 point 1.95 volts, you had a packet transmission, then you drop to 1.6 volts recall the demo all right. You did not make it go to 0, we have no draining it to 0 which clearly indicated this LDO was turning on at a given voltage and power in this complete system down here. This little c p u this SOC which had a BLE interface and then there was a sensor and the sensor we used was LMT 84 which is basically a temperature sensor. So, the function of the LDO is to turn on the system the turn on the system at a given voltage, and turn off also when the voltage drops to a certain critical voltage.

This essentially means you are taking care of a certain hysteresis that the we are exploiting not taking care. You are exploiting the hysteresis which is associated with the LDO turn on enable and disabled. Because you do not want to discharge this capacitor completely, you do not want to discharge it to 0. You want to do a packet transmission and then you want to use that energy for packet transmission and then you want to replenish the energy and therefore, keep sending our packet transmissions at regular intervals right.

So, you can see that that is possible because we are actually exploiting, the LDOs hysteresis associated with the a LDO, and in fact, the such LDos are available. So, when you talk about design for IoT is, when you talk about system design, when you look at the power supply section, look at the novelty by which you can use this LDO, you can use it as a switch with hysteresis turns on it some voltage, turns off at some other voltage, turns on again at some voltage, turns off at another volt again at the same voltage back.

This way you can harvest communicate compute sense whatever and then a you know replenish the energy by turning it off and then again do the same operation all over again. So, that is really the fund the actual story behind this chip. RFDC nothing, but a voltage divide a voltage doubler ok.

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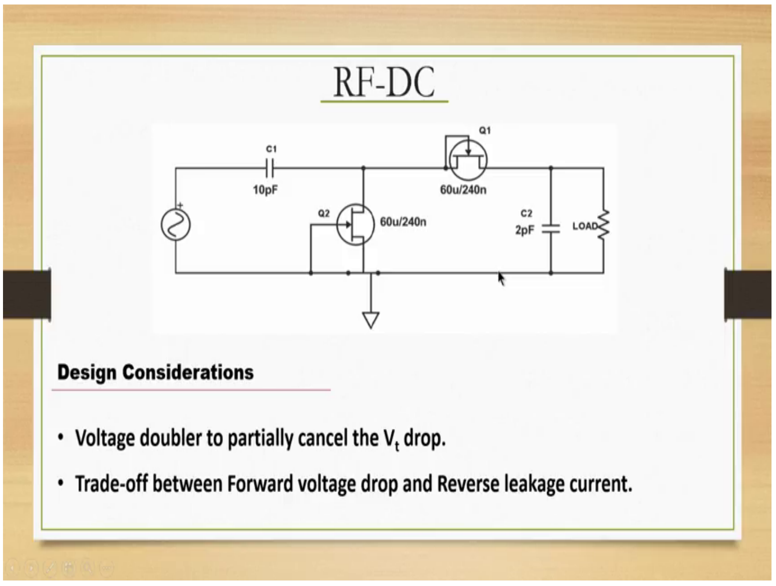

And essentially we are trying to exploit in silicon the fact that you can construct diodes from them these are all the w by l ratios, you do not have to worry so much about it. The fact that we are we have optimize the RF DC for a given frequency, this is very critical. When you say you are talking about RF DC, RF DC for what input frequency becomes important; so all these optimizations inside in silicon or for a given frequency.

So, the first parameter of anything when you do with RF energy harvesting is, that you should know that you are optimizing for a particular frequency. You are optimizing for a particular efficiency, you are optimizing for a given load, and these things we will keep recurring back to you recall what I said in the introduction. You optimize for an application, you optimize for a specific goal these things are falling in place already when you look at this fact that you will design and RF DC for a given a particular frequency.

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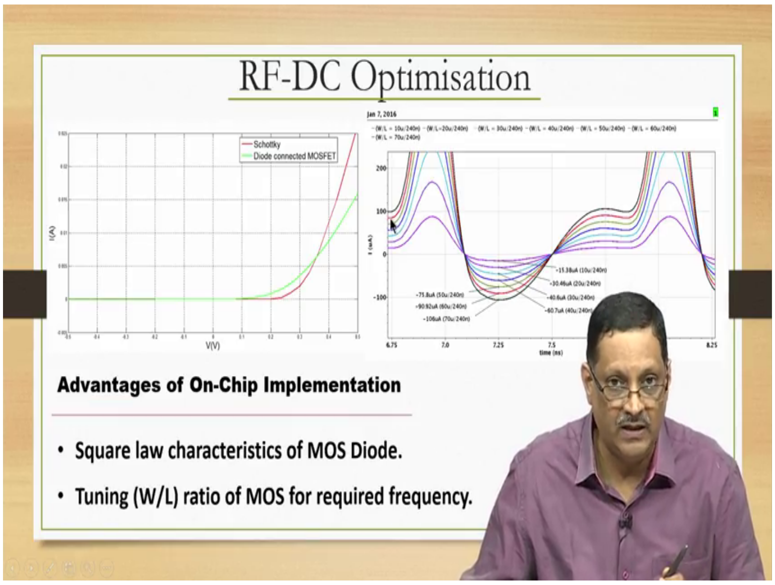

In this case it is the sub 1 gigahertz and again this is not a very important slide because it gets into detailing on simulations that you have to do. So, basically use some eda tools like (Refer Time: 34:08) mentor graphics and so on and actually simulate them and see it is performance before you actually tape it out right.

So, these are all some optimizations, but I want to point out that if you really use diode connected MOSFET, which is shown in this picture here, it actually cuts in much earlier than the regular Schottky diode that you can actually buy. So, which means at low powers at very low input RF input powers, you are you are able to already start using it very effectively you are able to rectify very effectively at very low RF inputs already.

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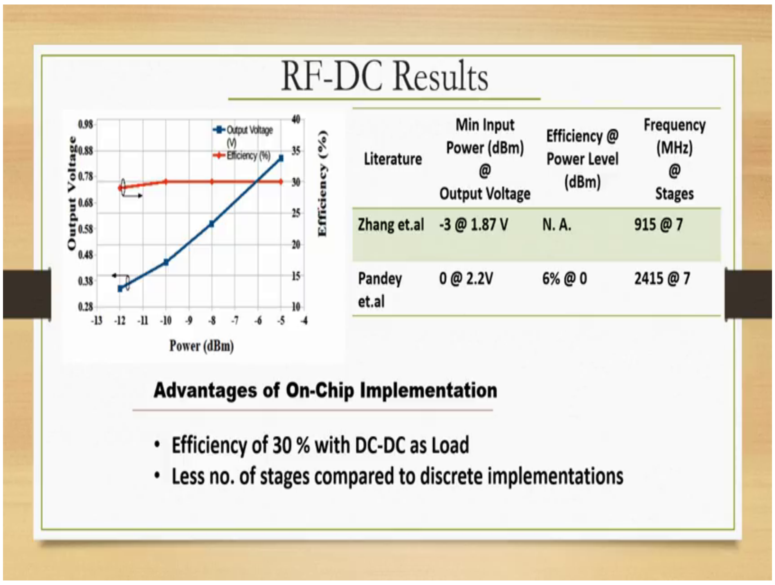

So, essentially it just conveying that meaning, but what is important is this nice picture here on the left side, which is a clear indicator to say that you will see efficiency which is roughly 30 percentage all through and through it starting with something close to 30 percentage, and it is trying to maintain the same efficiency over a large range of input powers. The x axis here you can see is the input power RF input power, power in dBm right you can see that you can feed as low as minus 12 dBm input power, which the antenna can take and provide you RF DC very important note here RFDC efficiency is not the complete system efficiency, I want to stress this it is not the complete efficiency it is the RF DC efficiency, the efficiency is close to about 30 percent.

Output voltage that you get is also shown here it is quite a natural thing, as the input power increases RF input power increases the voltage that is developed at the output of RFDC, the DC output voltage that is developed also starts increasing which is quite natural right, Which is bringing us to a very important point in the right side of the picture. What is the voltage that I can develop for a given RF input power is already a matter of discussion in the RF energy harvesting world. Many many papers that you say that you read and follow you will actually understand that they say I can give you this voltage at this input RF power they all they keep saying this all right. So, many papers claim what is the output voltage that I can develop for a given input RF power.

So, please note efficiency is one part, the second part is what is the output voltage that they can give you for a given RF input power; this brings us back to the same picture here on the right side, which says you can see that it is giving you my 1.87 volts at minus 3 dBm, at 0 dBm I get 2.2 volts, then they say frequency is 915 megahertz and number of stages which are which they are talking about the DC-DC stages, DC-DC converter stage is 7. The another paper says I will give you 2.2 at 0 dBm, I will give you efficiency of RF DC efficiency of 6 percent at 0 dBm and that is the highest efficiency there able to achieve and the frequencies now in the 2.4 gigahertz and number of stages is 7.

Clearly there are advantages of doing on chip implementation of both RF DC as well as DC-DC. What should go in RF input we will go in with a matching circuit, in the demonstration I showed it is a quarter wave match you have RFDC RF antenna with a certain gain of course, antenna we will have a certain small gain and then you have the quarter wave matching circuit which feeds directly to this chip and then output you get certain DC output voltage.

And now you measure the input to the output when you say you meant you would look at the input the output DC voltage to the input a you take power for instance you take output power that you can deliver that you get and the input power and you take the ratio and you get the efficiency power efficiency ratio. These things are done I will we will when we go through that paper we will discuss that in detail, but at the moment this is what you have as a nice picture.

Now what is it that went inside the chip? Let me detail this very important for those of you are interested in building, RF energy harvesting chips you may want to look at different topologies. Recall I drew a very simple diagram of a voltage doubler and the fact that you need multiple clocks, for each stage you need a clock. Without detailing too much into that you must need an importantly you need a clock generator and you need these non overlapping clocks to clock each one of the RF DC stages right and therefore, clock is a very important requirement.

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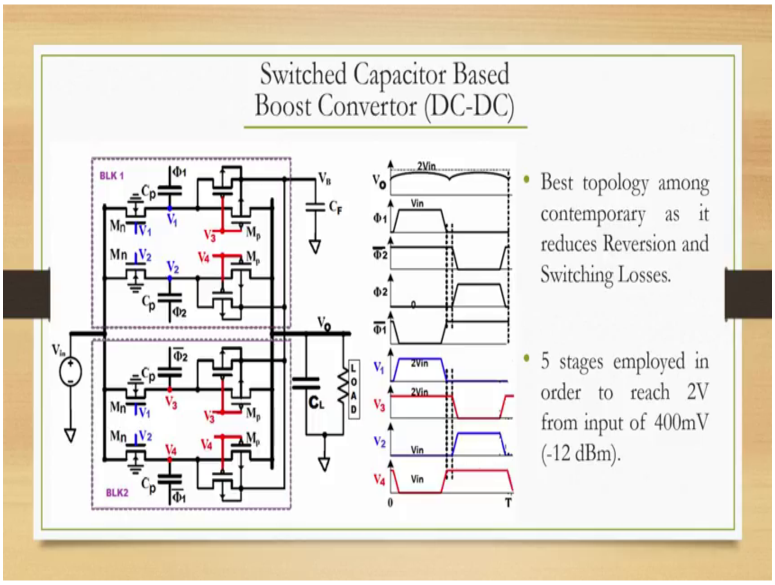

But what is also important is the fact that the best known topology for building a DC-DC is indeed this point that there is written here, which is the switched capacitor based boost converter. They say from literature that this is indeed is one of the best possible topologies you can think of when you want to build DC-DC converters on silicon. The other best way would be the ones that we know very well from the previous discussions that we did was if you take buck converters, we actually put inductors right these an outputs where inductor at the output and we also spoke about the inductor current the picture that I showed there. That is one way of doing it you can also have inductors on chip, but then they are a lot more harder to achieve, but it is possible it is not that you cannot do without inductor you can build you can do inductors on chip as well.

But from what we see this is possible that switched capacitors are definitely very high performance circuits and they essentially are able to provide very high they are supposed to be the best in topology. This is the key this is the key here and we have reached they required 1.95 volt which I mentioned to you by using these 5 stages of you know DC-DC converter. So, you can see that 2 volts from an input of 400 millivolts. Minus 12 dBm is the RF input power, you do DC you do RF DC you get 400 millivolt you take that 400 millivolt pass it through voltage doubler circuit you will get 2 volts roughly that is what we also saw one point a little over 1.95 volts we started doing the transmission all right.

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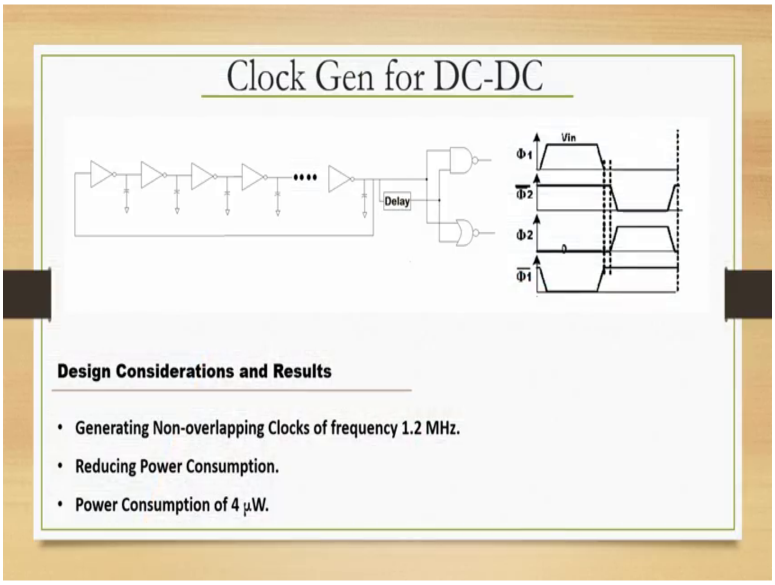

So, going back to the next slide here is the clock generator for DC-DC, I will not going to the detail here and these are essentially the right side picture.

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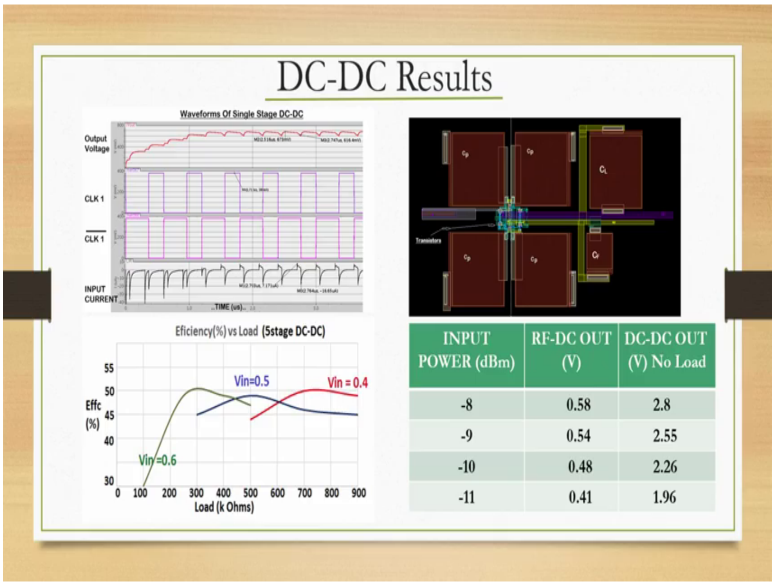

That one that you see on top is essentially the amount of area used in silicon for building this chip, but I want to draw your attention to the one on the right side here, where there is input power of minus 8, minus 12, minus 10 and minus 11 dBm, you will see that the second column is simply the RF DC out; that means, after just passing through RF DC you get roughly 0.58 volts for 580 millivolt for an RF input of minus 8, dBm and down to about minus about 410 millivolt for minus 11 d B m.

This is showing you the DC-DC out for different RF inputs; you can see that is builds as close as 2.8 volts as highest 2.8 volts. Now you can connect everything well to say that I got 1.6 right which means the demonstration I showed you was for an RF input of minus 11 dBm, I gave minus 11 dBm and no not I did not transmitted minus 11 dBm I trans I do not actually care too much about what my transmission power is, what is important is that received power. The input power at the antenna was minus 11 dBm it develop 1.96 volts at the output and DC-DC output, which was sufficient to drive the micro control and that intern provided me the required a power to do a BLE transmission.

So, this is the key of the whole demonstration which says that you can also build switched capacitor based DC-DC converters, multistage get reasonable power voltage outputs and use that voltage output for a given application the application we had in mind was to monitor the ambient temperature and we had actually interface a temperature sensor to our microcontroller.

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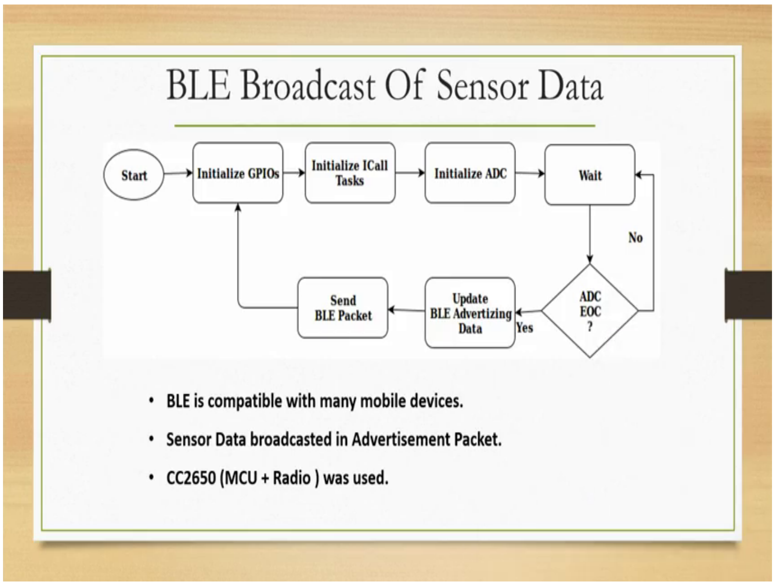

So, these are the die micrograph and all that, but let us not worry too much about it. Look at what we did we use this chip called C 2650, which is essentially and MCU plus radio and we were actually transmitting BLE broadcast of the sensor data as that is what I had shown you on the second mobile phone, which actually read the temperature and a transmission was possible.

Quite a simple with this little state machine here a simple flowchart here, start if the power is available after harvesting the MCU boots, and when the MCU microcontroller unit boots what does it do? It initializes the GPIOs, initializes the call initializes the tasks, initializes the a DC, because temperatures the temperature sensor is connected to the a DC, and it will wait for reading the a DC end of conversion if it happens, you take that put it into a BLE pocket and then do a BLE transmission.

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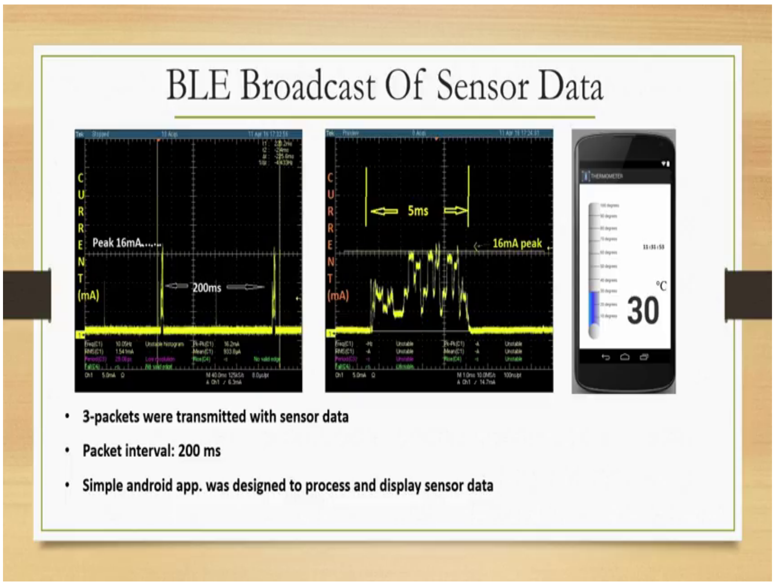

All of this is what was actually happening. Fantastic; and again I want to draw your attention to the regular thing that you must be looking at what is the amount of energy that the system is actually utilizing. So, you must know that so, far that again we do a current you put a current probe and actually measure the current that it that the system utilizes. Look at the picture on the left side, you will see that the peak is 16 milliamperes and a transmission of three packets is happening at regular intervals of 200 milliseconds. The right side simply shows an expanded view of this little peak that you see here, this peak actually last 5 milliseconds and you can see that there are packets multiple pockets that are being transmitted, essentially one here, one here and one here right these three essentially are the three broadcast packets which are actually sent out, and there is an interval of 200 milliseconds happening.

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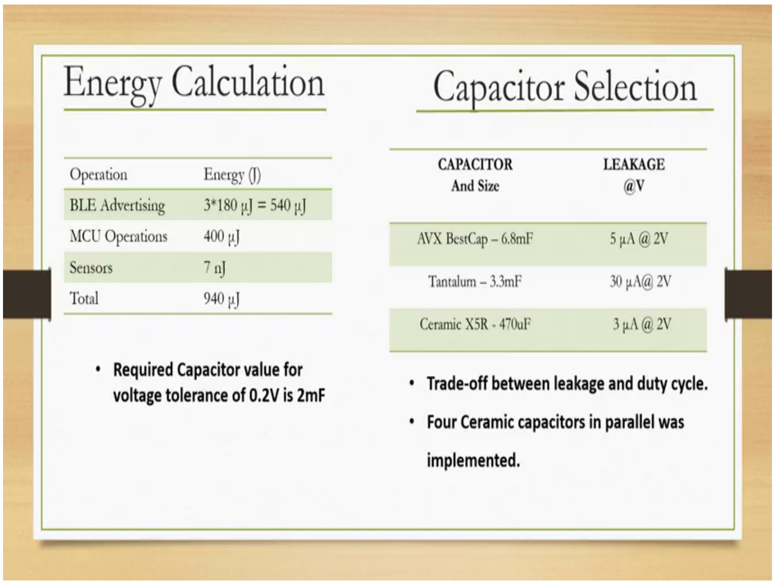

A simple android app you build you can actually measure the ambient temperature using RF energy harvesting right. So, what I have shown you is a complete system that you can build with RF energy harvesting for doing ambient temperature monitoring. Now you may ask; what is the amount of energy required for all these operations, well we did these energy calculations again; you see BLE advertising requires 540 micro joules, MCU operations required 400 micro joules.

Please note that this also includes the a DC sampling right you have to sample the a DC to get the temperature value, sensors need a very small amount of power it only requires 7 nano joules and you need 940 micro joules in order to it complete your operation. So, the required capacitor value for voltage tolerance of 0.2 volts is 2 millifarad, you need a 2 millifarad capacitor right. And we started looking at if I need a 2 millifarad capacitor, what are the types of capacitors are available? The first one is a super capacitor from AVX best cap 6.8 millifarad leakage is 5 microamps at 2 volts, tantalum capacitor which is a 3.3 millifarad capacitor it has 30 microamps at 2 volts the ones that we chose and then there is also, the ceramic capacitor which is 470 microfarad it has 3 microamps add 2 volts.

So, you must do lot of trade off between duty cycle and the leakage and try some combination. And the combination that seems to work very well for us was to try that to use this ceramic capacitors, put them in parallel and somehow get to very low leakage yet pull of the required application. So, 4 ceramic capacitors in parallel was actually implemented. So, this actually shows you the story a complete story, what you can see on the right side extreme right is the impedance matching post impedance match that is what we got here.

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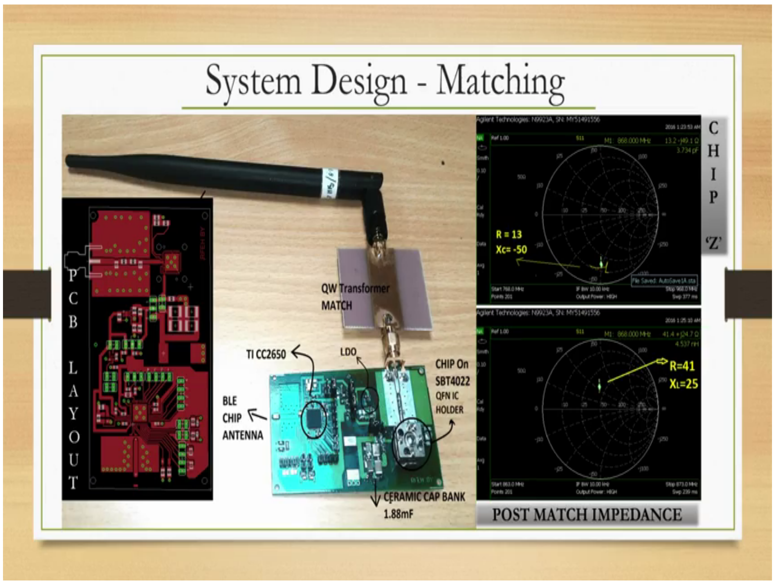

You can see this is the quarter wave match is a part and then this is the antenna receiving antenna the chip is here, embedded inside the microcontroller MCU unit is here, the BLE chip antenna is here, this is the PCB that we will we put together and you can see that quite nicely that is whole system seems to be working.

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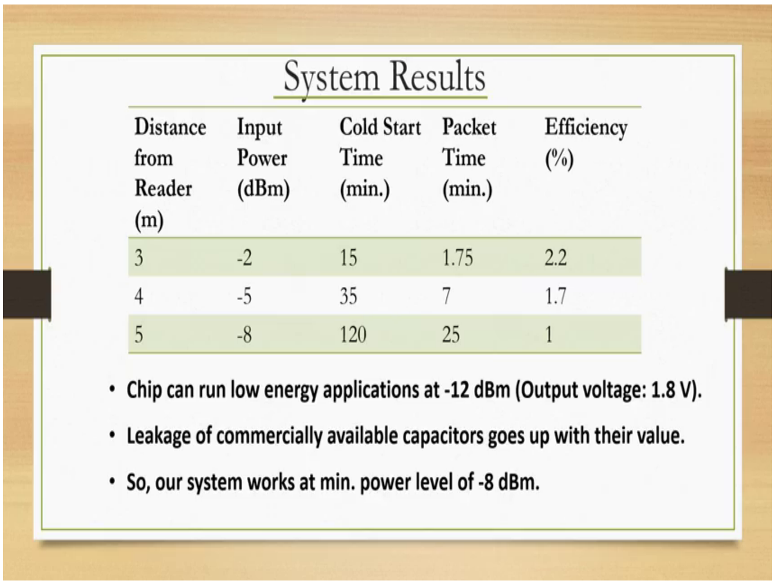

It is not that if we this is the nice story to tell you, but there are issues right it is not that everything is hunky dory here, there are issues what are the issues in this? Look at the third column, third column says you want to do all of this, I showed you a nice demonstration of a charge buildup from 1.6 to 1.95 and going down, because we were trying to exploit the hysteresis LDO which was in place, but if you want to start from 0 volts across the capacitor, the third column actually tells you a what is exactly the story here. It requires a minimum of 15 minutes, if the reader is placed at some distance roughly 3 meters it is not important, what is important is the second column which is minus 2 dBm, and if the me if the reader is kept at a distance of 5 meters from the from the system from the system that we built, the input power is down to minus 8 d B m.

Simple to calculate just based on prize equation one can calculate, all you can also use a u s b meter to actually characterized the required power, if time permits I will show you a demonstration of the u s b meter towards the end, and look at the third column. 15 minutes cold start; that means, from 0 volts across the capacitor, you keep building it requires up to about 15 minutes and if it is 4 meters away from the reader, you need 7 minutes and 25 minutes in the case, it is 5 meters source. RF source is 5 meters away from the reader and obviously, the efficiency is best when there is higher input RF power, you get 2.2 percent efficiency from the chip that we built. So, big summary big story I was the system that we showed you can work nicely at minus 8 dBm RF input power.

So, it can of course, the chip alone I can work at minus 12 dBm can give you 1.8 volts, but sometimes it is not useful to just say something about the chip, but it is always useful and important to say something about the system, and this is the key of the whole of the system building exercise on RF input RF harvesting circuits. So, that is about what I wanted to say about the chip which was built in 180 nanometer, and the RF harvesting that we did and all of the requirements and the study the literature and all that that would be required to build including a nice demonstration of the whole system.

Now let us spent time in understanding the actual way by which literature actually looks at all this; For this I will take a nice paper and run through that paper so that we complete the understanding of the complete system.

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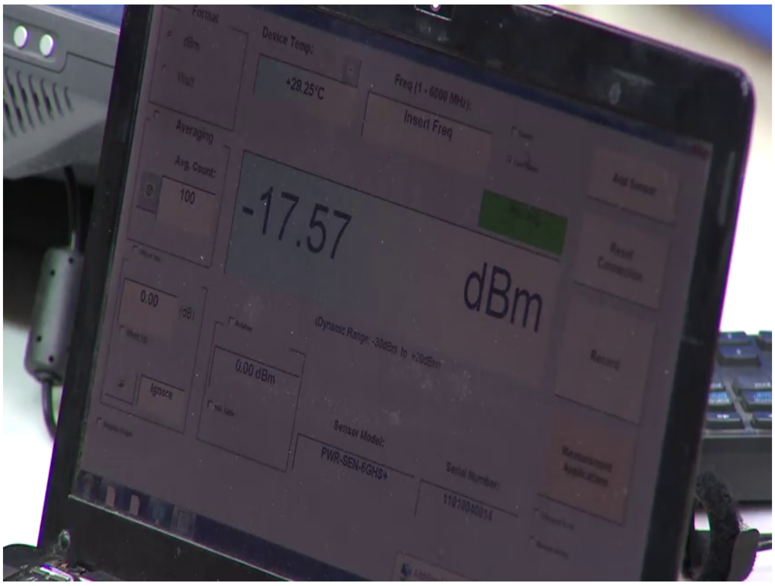

So, if you recall be showed you the transmission with a RFID reader and the RFID reader that we were using was this particular one, you can see this is a RF I reader.

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this is something that is throwing power at transmitting at 20 plus 25 dBm, and we said that for any RF energy harvesting you should know what is it is not important about what is the transmission power, but at what received power does all this harvesting actually start of. How efficiency, what is the efficiency of the RF DC conversion, what is the efficiency of DC-DC what is the combined efficiency of DC-DC as well as RF DC and so on right. So, for that what you should actually do is, use this u s b we have a very small a basically power meter and this is which can be connected to a u s b port, using the simple cable and then there is an antenna here.

So, what you can do perhaps is co-locate this set up along with the receiver electronics; and you can start measuring the received power. There is a very simple g u I which is as shown on this p c here you can see that this is essentially indicating the received power the received power as you can see is changing from minus it is going from minus sometimes minus 17 minus 12 and so on and it is a fluctuating. As you can see as you go lower as you go closer and closer antenna going closer and closer to the a transmitting antenna going closer and closer to the receiver, you will see that values can even go up to sometimes even up to plus right.

You can see that indeed it is also indicates a transmission power greater than 0 d B m. So, essentially with demonstration is to help you that help you to assist you to understand that such power meters are available, simple power meters are available in the market and you can use these power meters this is from mini circuits, you can use this power meter and make a measurement of the received power. And this is what ultimately we will drive several of the systems several circuits by making this measurement you will actually know what is the power at which the system is able to receive the system is able to basically at what at what received power the system is able to harvest, and convert that harvested energy into useful DC output for driving electronics.

So, that is the main goal and just pointing out that how do you calculate in theory the received power, well the thing is you can use simple price equation for calculating the received power.

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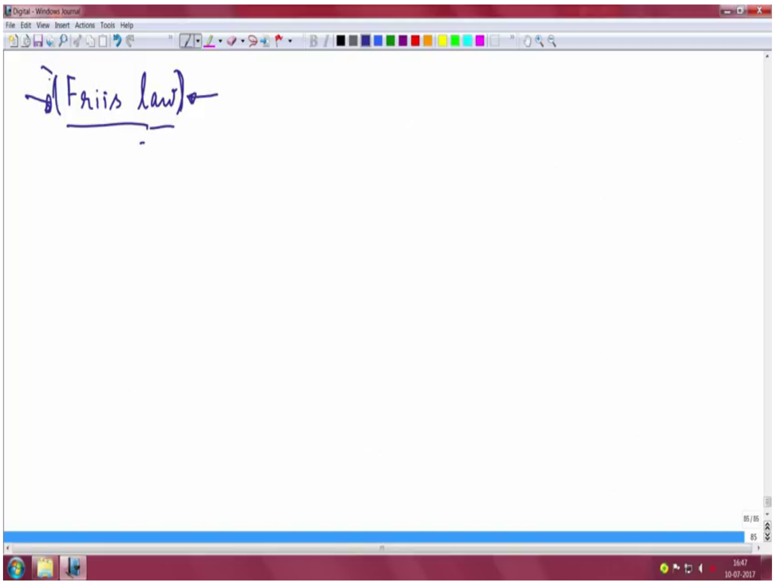

And therefore, that is a straight forward which you can look up, and already start using for all calculation paper calculations towards the received power. Now let us move to another important thing which essentially is on I mention to you that if you really want to you know sort of. So, let me pull out the paper that I wanted to share with you on the system here. So, it is here. So, supposing you. So, just to complete the story I also mentioned that it is important that we go through a full paper recently published paper, and which is sort of cap I mean summarizes several things which you must note when you are actually sort of working with this.

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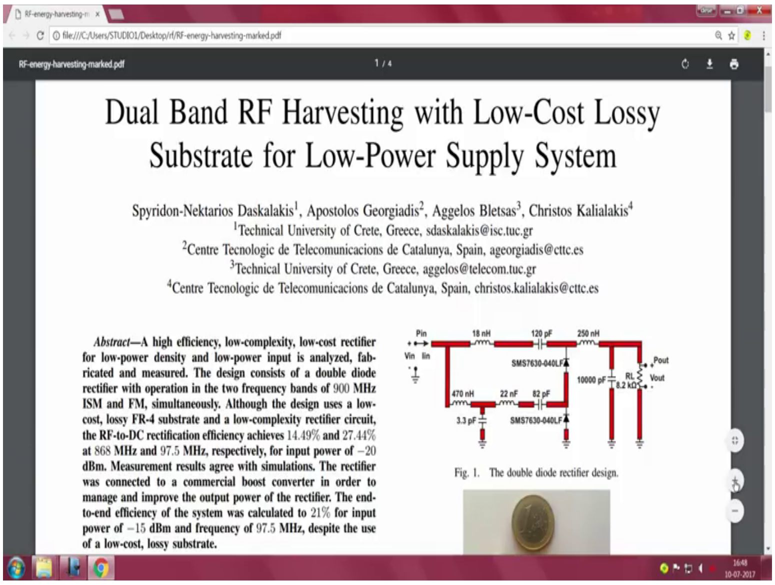

So, let me expand this completely so that it is clear to you as well. This paper is on RF energy harvesting with low cost lossy substrate for low power supply design. I will give you the overview, this actually uses f r 4, FR 4 is a fiber fire retardant level 4 glass epoxy coated substrate this is basically the PCB. The PCB on which this whole system is built as you know that PCB is use most popular PCB material, which for most low power low frequency operations use f r 4. F r simply stands for fire retardant 4, and different thicknesses is are available you have 1.6 mm; you have 0.8 laminate and so on right. Now on top of that is the copper; copper typically is a coating on top of this glass epoxy and rain forced substrate, which essentially we will have a thickness of roughly thirty 5 micron microns. Some people say 35 microns; some people write it has 35 micro meter and so on.

So, anyway that is the that is what the thickness of the copper which is on top of it. So, he is actually trying to tell us that we have made an RF energy harvesting using FR 4 for low power supply system. Now when you say dual band, what are the 2 bands of interest that they have looked at they have looked also at 900 megahertz which is write here, and they have also looked at f m. The normally what happens is in cities you have a number of FM stations which are transmitting quite a few kilowatts of power. So, they are looking at how to design a RF energy harvesting circuit using both these frequencies. 900 megahertz is also the frequency at which at least some of the operators seem to offer their g s m services some of them now earlier. In fact, it used to be mostly nine hundred, but people have the operators have moved away from nine hundred megahertz and are now using the 1800 megahertz range.

Ah, but nevertheless b s n l for instance in some of it is systems tower still use 900 megahertz for their transmission. So, these are the 2 frequencies which they are choosing for their dual band, they are mention some nice numbers here right I all study mentioned about a FR 4 substrate, you can leave that what there sing is RF DC a rectification achieve is 4 is achieved is 14.49.

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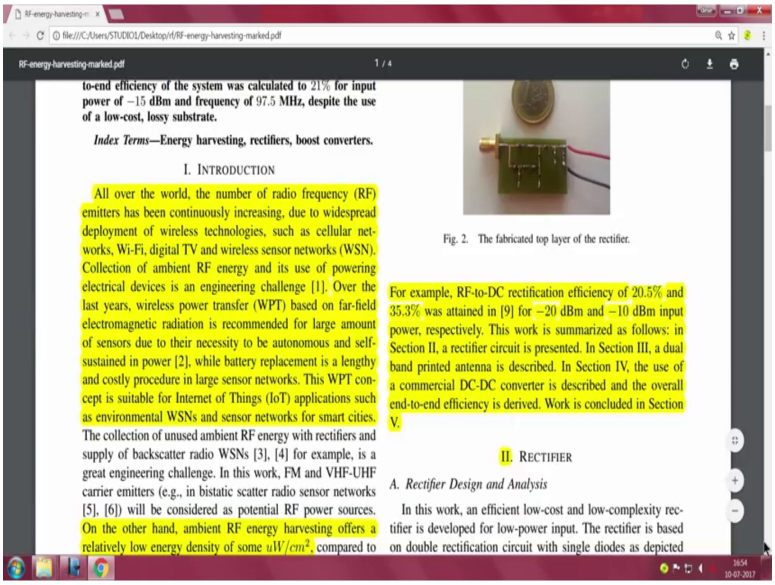

to-end efficiency of the system was calculated to 21% for input power of −15 dBm and frequency of 97.5 MHz, despite the use of a low-cost, lossy substrate.

Index Terms—Energy harvesting, rectifiers, boost converters.

I. INTRODUCTION

All over the world, the number of radio frequency (RF) emitters has been continuously increasing, due to widespread deployment of wireless technologies, such as cellular networks, Wi-Fi, digital TV and wireless sensor networks (WSN). Collection of ambient RF energy and its use of powering electrical devices is an engineering challenge [1]. Over the last years, wireless power transfer (WPT) based on far-field electromagnetic radiation is recommended for large amount of sensors due to their necessity to be autonomous and self-sustained in power [2], while battery replacement is a lengthy and costly procedure in large sensor networks. This WPT concept is suitable for Internet of Things (IoT) applications such as environmental WSNs and sensor networks for smart cities. The collection of unused ambient RF energy with rectifiers and supply of backscatter radio WSNs [3], [4] for example, is a great engineering challenge. In this work, FM and VHF-UHF carrier emitters (e.g., in bistatic scatter radio sensor networks [5], [6]) will be considered as potential RF power sources. On the other hand, ambient RF energy harvesting offers a relatively low energy density of some uW/cm^2, compared to

Fig. 2. The fabricated top layer of the rectifier.

For example, RF-to-DC rectification efficiency of 20.5% and 35.3% was attained in [9] for −20 dBm and −10 dBm input power, respectively. This work is summarized as follows: in Section II, a rectifier circuit is presented. In Section III, a dual band printed antenna is described. In Section IV, the use of a commercial DC-DC converter is described and the overall end-to-end efficiency is derived. Work is concluded in Section V.

II. RECTIFIER

A. Rectifier Design and Analysis

In this work, an efficient low-cost and low-complexity rectifier is developed for low-power input. The rectifier is based on double rectification circuit with single diodes as depicted

And 27.44 percent for 868 and 997.5 megahertz respectively that is for input power of minus 20 d B m. So, they feed minus 20 dBm here in this part they feed minus 20 dBm push nine hundred and ninety megahertz this 97, 98 to 107 right that is the FM frequency they push that they feed 88 to 107 megahertz as an input, 80 82 108 I think it is yeah it is 81 to 108 megahertz, as the input frequency here at minus 27 dBm is there is it is the input power.

Like typically like what I showed you with the RF meter that here that we just see saw if you get a number which is around minus 27 dBm, means that that is the RF input power sorry minus 20 dBm that is what the paper says. Minus 20dBm is the receive is the relieve P in is minus 20 dBm and they claim that there is a RF DC efficiency which is 27.44 percent 497 and 14 point roughly 15 percent, 14.5 percent for 826 megahertz, input frequency right. The rectifier was connected to a commercial boost converter what they have done is they have taken their RF DC output, and given it to a commercial commercially available boost converter.

Unlike the previous one where we actually convert you know connected to our own chip, which had multistage switched capacitor system, this indeed uses a commercial available chip which is from ti I think they use BQ2 double 5 0 4 we will see as we go along and then give you something at the output. The DC output the end to end efficiency of the system was calculated to 21 percent for input power of minus 15 dBm and frequency of 97.5 megahertz, despite the use of low cost lossy substrate. This is really the highlight of their measurement. The efficiency is 21 percent for an end to end system.

Please note end to end meaning RF DC plus DC-DC which can ultimately be used took either power a microcontroller and SOC and a sensor and so on. So, that is what they are getting around 21 percent for an input RF. That means, P in here is minus 15 dBm, this is for the FM frequencies. So, this really this big summary of their paper, but let us look at what this paper says as a exciting way of writing this paper, I like this because the way that has been written easy to understand, easy to follow and quite easy to connect to this world of RF energy harvesting. Where lot of results are shown lot of paper lot of literature a very active area of research, but this is what ultimately it matters you should be able to put up a system, from which you can harvest and you can actually drive a complete a sensor module or a embedded node or an embedded system or an IoT system, ultimately that is where the challenges.

So, the introduction is quite nice this talk about Wi-Fi digital TV and all kinds of RF signals that are available, and wireless power transfer based on far field electromagnetic radiation is recommended for large amount of sensors, due to their necessity to be autonomous and self sustained. See the nice thing that they write here again is interesting they say battery replacement is a lengthy and costly procedure in large sensor networks therefore, this WPT wireless power transfer concept is suitable for IoT application such as environmental WSNs and sensor networks for smart cities ok.

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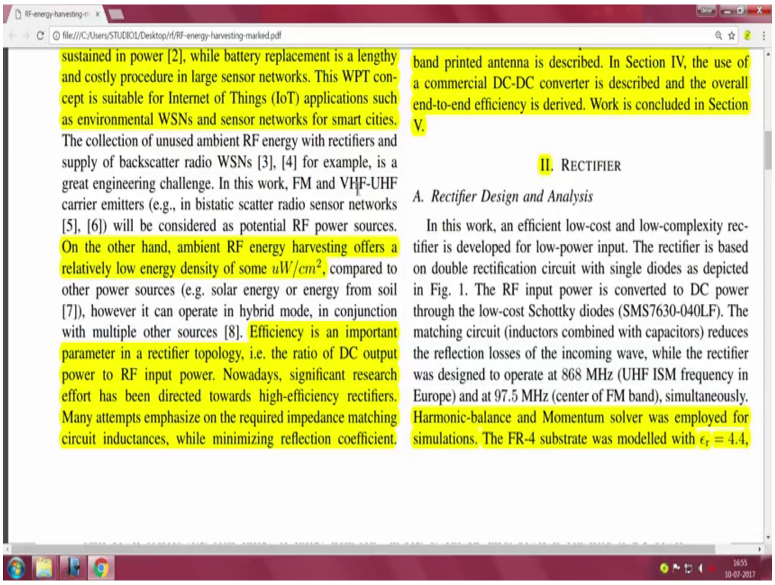
sustained in power [2], while battery replacement is a lengthy and costly procedure in large sensor networks. This WPT concept is suitable for Internet of Things (IoT) applications such as environmental WSNs and sensor networks for smart cities. The collection of unused ambient RF energy with rectifiers and supply of backscatter radio WSNs [3], [4] for example, is a great engineering challenge. In this work, FM and VHF-UHF carrier emitters (e.g., in bistatic scatter radio sensor networks [5], [6]) will be considered as potential RF power sources. On the other hand, ambient RF energy harvesting offers a relatively low energy density of some uW/cm^2, compared to other power sources (e.g. solar energy or energy from soil [7]), however it can operate in hybrid mode, in conjunction with multiple other sources [8]. Efficiency is an important parameter in a rectifier topology, i.e. the ratio of DC output power to RF input power. Nowadays, significant research effort has been directed towards high-efficiency rectifiers. Many attempts emphasize on the required impedance matching circuit inductances, while minimizing reflection coefficient.

band printed antenna is described. In Section IV, the use of a commercial DC-DC converter is described and the overall end-to-end efficiency is derived. Work is concluded in Section V.

II. RECTIFIER

A. Rectifier Design and Analysis

In this work, an efficient low-cost and low-complexity rectifier is developed for low-power input. The rectifier is based on double rectification circuit with single diodes as depicted in Fig. 1. The RF input power is converted to DC power through the low-cost Schottky diodes (SMS7630-040LF). The matching circuit (inductors combined with capacitors) reduces the reflection losses of the incoming wave, while the rectifier was designed to operate at 868 MHz (UHF ISM frequency in Europe) and at 97.5 MHz (center of FM band), simultaneously. Harmonic-balance and Momentum solver was employed for simulations. The FR-4 substrate was modelled with $\epsilon_r = 4.4$,

So, this what they claim; on the other hand ambient RF energy harvesting offers relatively low energy density of a few microwatts per square centimeter yeah this is a, as I said these numbers which are nice to put down in tables and charts, but actual measurements will actual harvested power we will depend on a number of parameters. It will depend on the gain of the antenna the type of antenna that you use, the environment in which you place the orientation of the antenna that you end up with which gives you a lot more power so many other related things.

So, I would say that you should take this carefully you should look at this carefully from system to system. Now this next sentence is important, efficiency is an is an important parameter in a rectifier topology, that is the ratio of DC output power to the RF input power finally, you take RF converter to RF DC give it to a DC-DC converter you get DC output rail feed for your sensor node, please find out what is the efficiency of the complete system that is what he says. This pay the author say nowadays significant research has been directed towards high efficiency rectifiers, the first stage is important the first stage rectifiers are important many attempts emphasize on the required impedance matching circuit impe inductances while minimizing reflection coefficient. I am sure you appreciate the s 11 requirements such that unless you have a good impedance matching, you will not be able to harvest sufficient amount of power at a given input RF power. At a given input RF power if they you have a claim that is not that would not work out if you do not do proper impedance matching this is very critical right.

So, he also saying the same thing and actually I showed you the quarter wave match that we did for our own chip and that turned out to be quite successful in trying to harvest at minus 12 dBm and so on. So, that is a very critical step, the point is you should note that just do not connect the antenna in say I am not able to harvest it would not work unless you do proper impedance matching. So, for example, going back and reading it further for example, RF DC rectification efficiency of 20.5 and 33, 35.3 respectively were observed for minus 20 dBm and minus 10 dBm input power respectively. So, he saying that there is this block of RF DC, has different efficiency is based on the input power; obviously, if you feed in minus 10 dBm much higher power the efficiency seems to be much better.

So, let us read it further and look at the whole thing; before we move on let me just describe the circuit for you also well written paper and also a good circuit you can see P in his here right this the P in clearly all of this that I have circled here is all that impedance matching part here. This is the diode these are the diodes here and then this is the essentially what you get at the output. There are also other components which are modeled in this particular diodes, they have also been accounted for ultimately P out comes here this is nothing, but RF DC P out when they say is just talking about the DC out after the I suppose he is talking about. So, we will see this, this is an interesting observation. So, RF input RF this is the impedance matching these are the diodes and then this is the output.

So, let us read this paper a little bit to see what exactly he connects as the load all right. So, he takes FR 4 substrate they try to use a simulation tool I am remember I mentioned to you about simulations as a very important step in all of this. A very popular tool for RF related impedance matching related activity is the ADS; ADS is I forget the name you can look up it is called advanced design simulator or a I think it is called advanced design simulator. ADS is a very popular simulator for impedance matching you can go to key sight technologies which earlier used to be called Agilent technologies, they have this tool which you can download request for a license in install a temporary license if you are a student or a university there is a nice licensing procedure. Download the tool

ADS download it install it and start looking at how to do impedance matching with a this software which I mentioned is ADS.

So, that is another important thing, here they used a different simulator they use harmonic balance and momentum solver which is for most of their simulation, the substrate they have chosen is FR 4 and the dielectric constant for FR 4 is 4.4 and this is important when they actually simulate.

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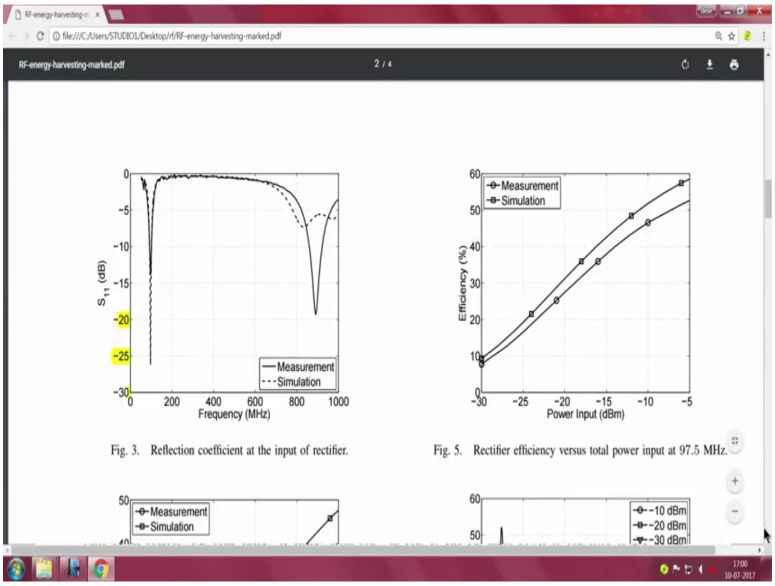

Now, this is the basically the reflection coefficient, what is the big take away from this? The dotted line indicates the simulation, the full connected line indicates the measurement, there are 2 dips the deeper the dip the better right this is 0, this is minus 30, this is the sweep across the 2 freq across frequency. So, basically they have showing 2 dips one dip is at the 90 sub 100 megahertz range, which is the frequency of interest in the FM this is the dip for the FM, and this is the dip for the sub giga 1 gigahertz in the 900 megahertz range.

So, these 2 dips are what they are claiming is what is the because of their good impedance match, they seem to claim that they get minus 20 less than minus 25 in the case of the FM frequency, and something like minus 18 or minus 19 dBm S11 for in the case of dBm I am sorry d b in the case of the sub the 900 megahertz. So, these are very important thing. So, you should do this, this is my step by step thing that you should really follow in order to when you are doing an RF energy harvesting system. Now the other result of interest is you see what happens here.

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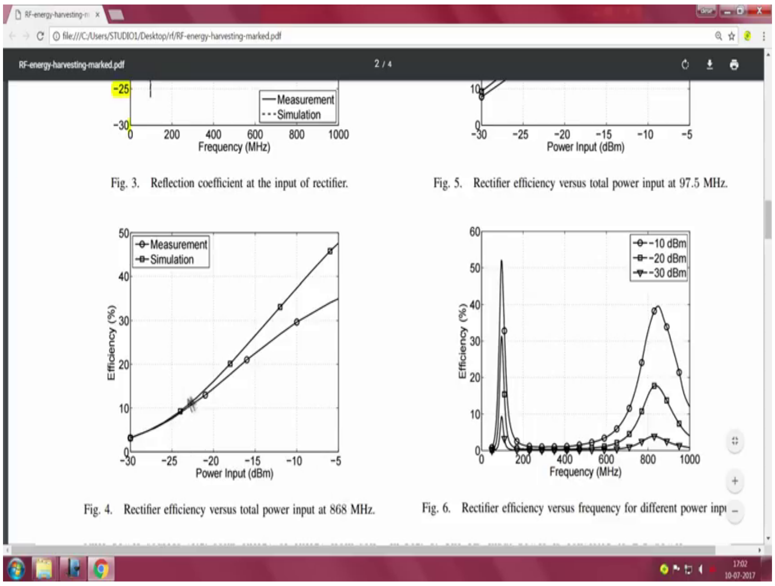

This is figure 4 this is a sweep of the input power which is starting from minus 30 dBm to minus 5 dBm, this is input this is P in from that circuit that you see this is for sub 1 gigahertz. This is for the 8 68 megahertz frequency, they show how as the input power keeps improving keeps increasing a basically your tending towards if you go from here forward you will go towards 0 dBm right as you go along this line, the say the efficiency keeps moving up higher and higher and they do show that their measurement is quite good you can see at minus 10 dBm they getting 30 percent efficiency, for the 900 megahertz this is figure 4.

Now, figure 5 let us move on to figure 5. So, this is the same result, but now the frequency input frequency is 97.5 megahertz, the sweep is input power P in as you can see is again starting from minus 30 to minus 5 dBm, as you go along you will get 0 on this direction and this is again the efficiency the measurement you can see their claim is quite high at minus 10 dBm it is roughly 45 or even close to 50 percent the their efficiencies. And the minimum efficiency that they seem to get is less than 10 percent at minus 30 dBm; you can see that it is directly related to the S11 because they have a very good S11 characteristic minus 25 dBm, they are able to get much better efficiency as well. I suppose you can connect it to the fact that their match at 97.5 megahertz is indeed excellent even better than that of the sub 1 gigahertz.

Anyway so that is an important useful observation to connect between the efficiency at 97.5 to the actual S11 that we have. Now this is the rectifier efficiency versus frequency for different input power. So, here what he is doing is he sweeping the frequency right this is from 0 to 1gigahertz is sweeping. And obviously, you are trying to look at the efficiency with respect to these frequencies. Clearly indicating that the system that they have design gives you the best efficiency at only 2 frequencies, and that is at that 97.5 and at the 900 megahertz range. This is for different input powers you can see that minus 10 is indicated minus 20 and minus 30 dBm is indicated.

So, you can look up these nice little charts that you have to make after you build your system, in order to actually arrive at something useful whether it is a useful power or whether this is really useful for building your IoT for powering your IoT using RF energy harvesting right.

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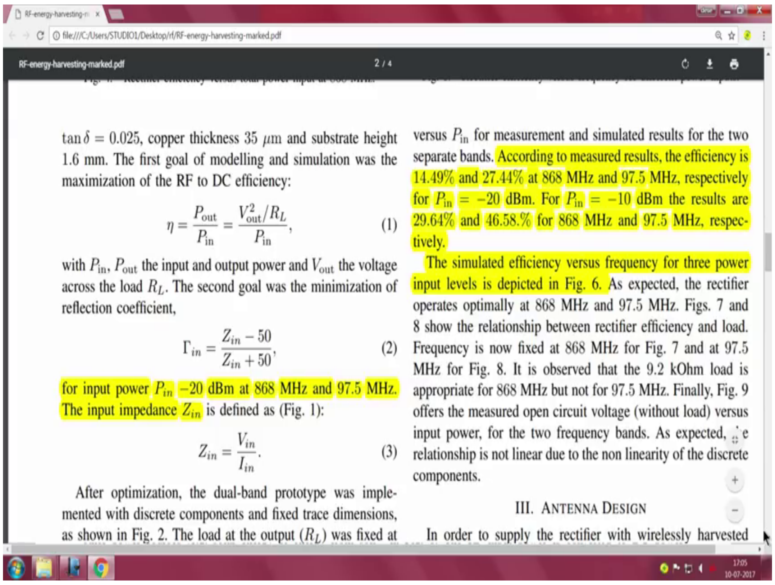
RF-energy-harvesting-marked.pdf 2 / 4

$\tan\delta = 0.025$, copper thickness 35 μm and substrate height 1.6 mm. The first goal of modelling and simulation was the maximization of the RF to DC efficiency:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{V_{out}^2/R_L}{P_{in}}, \quad (1)$$

with P_{in}, P_{out} the input and output power and V_{out} the voltage across the load R_L. The second goal was the minimization of reflection coefficient,

$$\Gamma_{in} = \frac{Z_{in} - 50}{Z_{in} + 50}, \quad (2)$$

for input power P_{in} −20 dBm at 868 MHz and 97.5 MHz. The input impedance Z_{in} is defined as (Fig. 1):

$$Z_{in} = \frac{V_{in}}{I_{in}}. \quad (3)$$

After optimization, the dual-band prototype was implemented with discrete components and fixed trace dimensions, as shown in Fig. 2. The load at the output (R_L) was fixed at

versus P_{in} for measurement and simulated results for the two separate bands. According to measured results, the efficiency is 14.49% and 27.44% at 868 MHz and 97.5 MHz, respectively for $P_{in} = -20$ dBm. For $P_{in} = -10$ dBm the results are 29.64% and 46.58.% for 868 MHz and 97.5 MHz, respectively.

The simulated efficiency versus frequency for three power input levels is depicted in Fig. 6. As expected, the rectifier operates optimally at 868 MHz and 97.5 MHz. Figs. 7 and 8 show the relationship between rectifier efficiency and load. Frequency is now fixed at 868 MHz for Fig. 7 and at 97.5 MHz for Fig. 8. It is observed that the 9.2 kOhm load is appropriate for 868 MHz but not for 97.5 MHz. Finally, Fig. 9 offers the measured open circuit voltage (without load) versus input power, for the two frequency bands. As expected, the relationship is not linear due to the non linearity of the discrete components.

III. ANTENNA DESIGN

In order to supply the rectifier with wirelessly harvested

Now, as coming to the simple steps that they try to go about in there in their characterization, the first goal of modeling and simulation was to maximization of RF DC. This is the RF DC P out by P in they just substitute the power that they are feeling in to the RL which is the load register here. So, I suppose when they mean RL they mean this system here. So, this is surely the efficiency of the RF DC system output of the RF

DC which is they connect here. So, this is another important thing keep note of this registered here, essentially when you do v I characterization of a solar panel or you do v I characterization that is voltage and current characterization of either a solar panel or that of a thermoelectric generator or that of a linear motion harvester and now that of a RF energy harvester often you have to do the you basically plot the v I characteristic right.

Quite like that this is also the same story here that you do you basically so far in. So, the point I am trying to say is for any of these characterizations, what they normally do is they connect an output resistor and they keep changing this register value they put a potentiometer put a potentiometer at the output here, and keep changing the potentiometer value till you obtain the maximum V and the maximum I and then you plot right this is a standard way of you know characterizing the panel by putting a potentiometer here. Quite like that this experiment is also done in the same way they have connected a register here a variable resistor here and potentiometer here and they keep modifying the changing the value to get the efficiency.

So, now RF DC efficiency is P out by P in this is the reflection coefficient which is also quite a straight forward, you have for input power of P in of minus 20 dBm at 868 and 97.5 megahertz the input impedance Z in is given by V in by I in, pretty straightforward set of equations which you can actually follow quite easily and how they do the match. So, according to.

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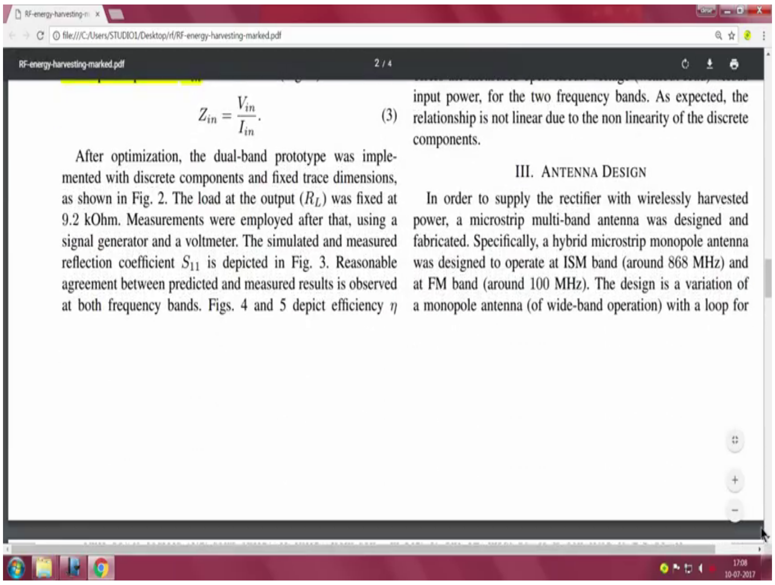

$$Z_{in} = \frac{V_{in}}{I_{in}}. \quad (3)$$

After optimization, the dual-band prototype was implemented with discrete components and fixed trace dimensions, as shown in Fig. 2. The load at the output (R_L) was fixed at 9.2 kOhm. Measurements were employed after that, using a signal generator and a voltmeter. The simulated and measured reflection coefficient S_{11} is depicted in Fig. 3. Reasonable agreement between predicted and measured results is observed at both frequency bands. Figs. 4 and 5 depict efficiency η

input power, for the two frequency bands. As expected, the relationship is not linear due to the non linearity of the discrete components.

III. ANTENNA DESIGN

In order to supply the rectifier with wirelessly harvested power, a microstrip multi-band antenna was designed and fabricated. Specifically, a hybrid microstrip monopole antenna was designed to operate at ISM band (around 868 MHz) and at FM band (around 100 MHz). The design is a variation of a monopole antenna (of wide-band operation) with a loop for

So, let us read that part which is very important thing here. So, you can say that the load at the output RL was fixed at 9.2 they show 8.2 there, but I suppose they have put a 9.2 k ohm as well as also tried it with 9.2. Measurements were employed after that using a signal generator and a voltmeter you can see these are simple equipment the simulated and measured reflection coefficient were shown in the S11 shown in figure, 3 reasonable agreement is there between the predicted and the measured results; figures 4 and 5 depict efficiency versus P in and all that. So, according to measured results the efficiency is 14.49 and 27.44 percent at 866 megahertz, and 97.5 megahertz respectively for P in of minus 20 d B m.

In other words what he saying is that if you feed P in of minus the input power is minus 20 dBm, you will see for about 15 14.5 percent and 27.5 percent at these 2 frequencies that is what the ultimate stories. So, you have to do these characterizations before you can actually use anything, what is the required input power to drive my system if you want to know, what is the duty cycle of the node you want to drive so that you have continuous monitoring if you want to know, unless you know what is the input power and what is the output power and what kind of efficiency is you get, you will not be able to actually build a successful perennially monitored RF energy harvesting node. So, that is the key thing. So, moving on for P in of minus 20 dBm, the results are x are 29.64 percent and 46.58 percent respectively. Again he claims about his the simulation results agreeing well with the measured results.

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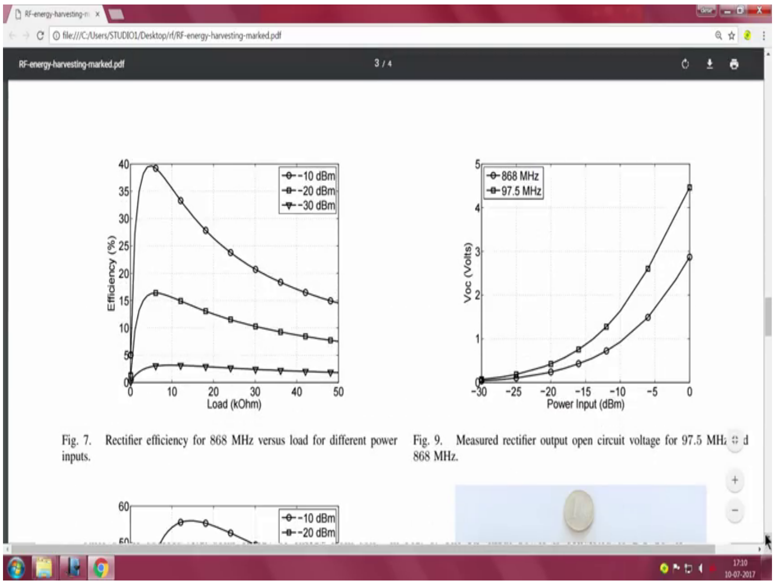

So, antenna designed well that is another story altogether, you must go through a proper tool in order to actually design your antenna for the application, and the vary this is basically the design is a variation of a monopole antenna with a loop and he is talking about the antenna loop which is write exactly like this. This antenna is the antenna which is working both for the 97.5 and the 9868 megahertz. In fact, they have chosen 868 these are the this is the antenna that they have actually design.

Now, there are further results to know in this paper. So, let us quickly spend time here, this is the rectifier efficiency for different output loads this is important I told you about the potentiometer, and all that before they arrived at anything useful in terms of what is the best value of the load that they can apply, they could not have found out if they had not had a potentiometer and varying the value of the potentiometer such that they get a peak right peak power is got exactly at one or at around a let us say a spot a resistor value how to get to that you have to do this what you do you start with 0 go on sweeping the load resistor.

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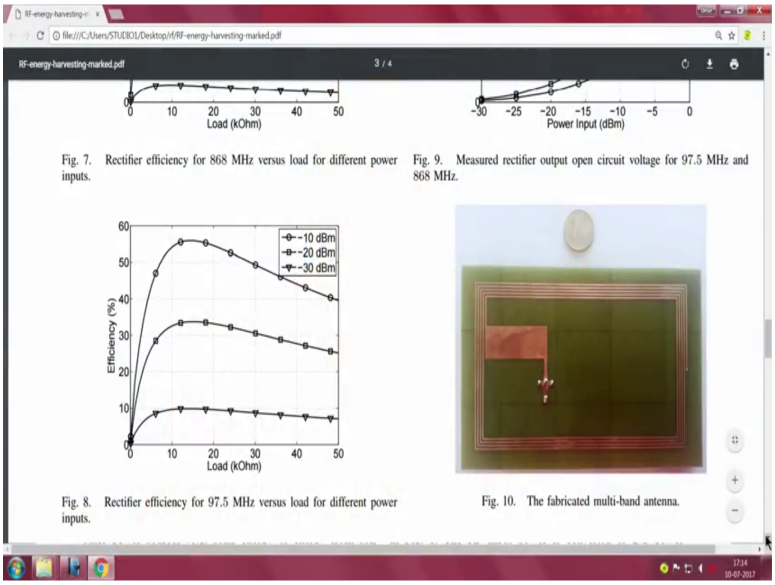

You can see 0 10 20 40 30 40 50 kilo ohms, you find out the efficiency go on plotting what you get for minus 10 dBm what you get for minus 20 the input power is minus 10 dBm what do you get, minus 20 minus 30 and so on and then you know that you are actually peaking around this less than 10 k around this value is what seem to work the best that knee point this knee point exactly the knee point here, will actually tell you that this is the best resistor value load value for getting the maximum efficiency of the system.

Now, coming to this is basically the RF DC please note this all RF DC part, now this is a figure 7 so let us do. It is structure and this is figure 8 I, you do the same by changing the input frequency to mine to the FM frequency 97.5. And again you find that it has shifted not so much right. It is around the same point here close to 10 k so that seems to be a nice thing that for both the frequencies they seem to get around at 10 k value which seems to be giving them the best or the maximum efficiency.

So, that is about figure 8 and figure 9 now. Figure 9 is another interesting thing what they do is they sweep the input power and what they do is they look at the rectifier output open circuit voltage for both the systems, they just say that what is the output voltage that I can get right and that appears that they sweep again the input frequency the input power, for the 2 frequencies and then they show that see this is what ultimately we will determine the usefulness of the system right at what is the V out that you should get from your rectifier, before you connected to any standard DC-DC converter, they are not even spoken about the DC-DC converter please note.

All the results and measurements the action, is how good is my RF DC full characterization of RF DC. All kinds of measurements with respect to sweep in sweeping the input power, sweeping the 2 frequencies connecting different load resistors trying to find out where is the best efficiency all of that is for the RF DC system. So, the next story we will really be around the DC-DC converter you can see.

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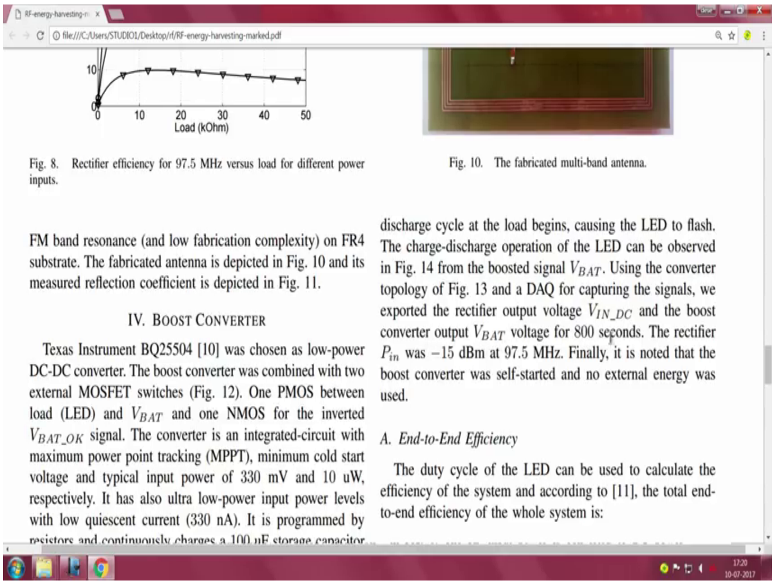

Now the boost converter comes into picture and say that we use BQ 2 double 5 0 4 which is the standard boost converter from t i, essentially it seems to be the one that they seem to have interfaced and ultimately they show that they have connected at the output of the boost converter, they have actually connected an LED. I will show you that result I will show you the circuit diagram.

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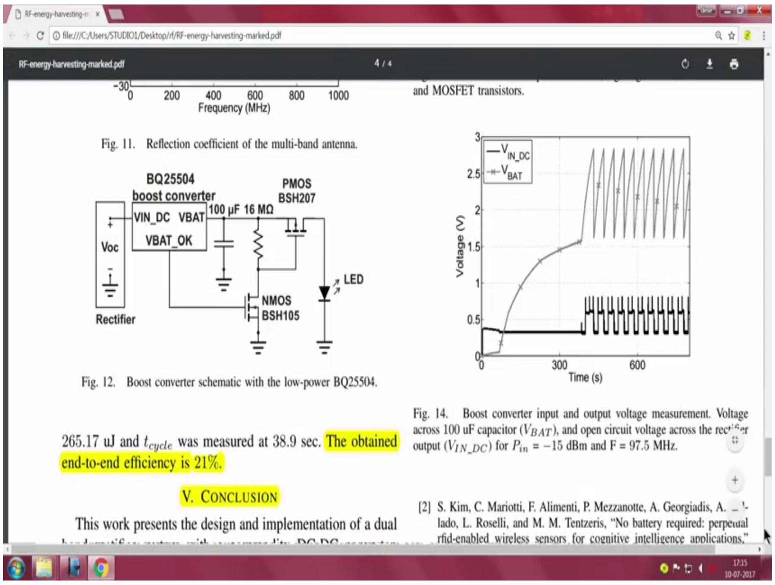

So, what they do is this is a circuit diagram here. So, what they do? They take the v open circuit voltage and they connected to this V in DC of the. So, this is the input voltage which is coming into the BQ2 double 5 0 4 it boost it charts charging this hundred microfarad at the output; and once the output rail is fine is at stable, this series pass transistor conducts this LED switched on, and it is switches off soon after the energy across this 100 microfarad lowers and then it is it this transistor simply shuts down. So, you will have a light on and you will have a light off, light on and a light off right essentially that is what there load is and they use 2 transistors here at the output one is the series pass which is a P channel MOSFET, and an n channel, NMOS, N channel MOSFET for providing the gate trigger.

So, this circuit you can try take these the RF DC which they have implemented connected directly to a commercial available BQ2 double 5 0 4, you should be able to essentially be able to harvest and drive this LED based on RF using the RF input power all right. So, the story really is if you look at the: so I think before we go on there let me show you the end to end efficiency that they have achieved. After having done this the RF DC they have to also finally, calculate the end to end efficiency this is the very simple expression you can see this is energy efficiency basically total n total e E DC is the energy DC.

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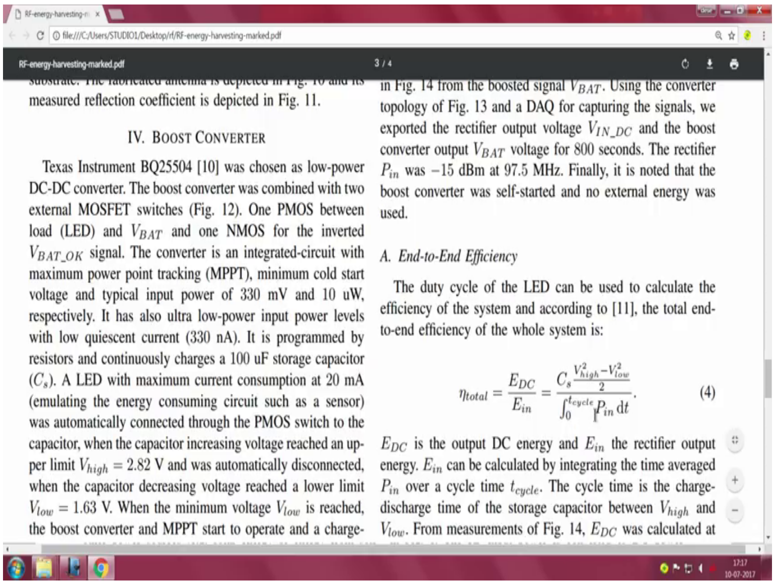
measured reflection coefficient is depicted in Fig. 11.

IV. BOOST CONVERTER

Texas Instrument BQ25504 [10] was chosen as low-power DC-DC converter. The boost converter was combined with two external MOSFET switches (Fig. 12). One PMOS between load (LED) and V_{BAT} and one NMOS for the inverted V_{BAT_OK} signal. The converter is an integrated-circuit with maximum power point tracking (MPPT), minimum cold start voltage and typical input power of 330 mV and 10 uW, respectively. It has also ultra low-power input power levels with low quiescent current (330 nA). It is programmed by resistors and continuously charges a 100 uF storage capacitor (C_s). A LED with maximum current consumption at 20 mA (emulating the energy consuming circuit such as a sensor) was automatically connected through the PMOS switch to the capacitor, when the capacitor increasing voltage reached an upper limit $V_{high} = 2.82$ V and was automatically disconnected, when the capacitor decreasing voltage reached a lower limit $V_{low} = 1.63$ V. When the minimum voltage V_{low} is reached, the boost converter and MPPT start to operate and a charge-

in Fig. 14 from the boosted signal V_{BAT}. Using the converter topology of Fig. 13 and a DAQ for capturing the signals, we exported the rectifier output voltage V_{IN_DC} and the boost converter output V_{BAT} voltage for 800 seconds. The rectifier P_{in} was -15 dBm at 97.5 MHz. Finally, it is noted that the boost converter was self-started and no external energy was used.

A. End-to-End Efficiency

The duty cycle of the LED can be used to calculate the efficiency of the system and according to [11], the total end-to-end efficiency of the whole system is:

$$\eta_{total} = \frac{E_{DC}}{E_{in}} = \frac{C_s \frac{V_{high}^2 - V_{low}^2}{2}}{\int_0^{t_{cycle}} P_{in}\,dt}. \quad (4)$$

E_{DC} is the output DC energy and E_{in} the rectifier output energy. E_{in} can be calculated by integrating the time averaged P_{in} over a cycle time t_{cycle}. The cycle time is the charge-discharge time of the storage capacitor between V_{high} and V_{low}. From measurements of Fig. 14, E_{DC} was calculated at

And there is the energy input here you are not looking at power, but you are looking at energy therefore, the denominator is simply to the on cycle 0 to the t cycle time over which the capacitor charges for the input power P in, which comes in the denominator and this is simply half C v square with start with a high voltage charge capacitor building up and then when the capacitor builds up, you switch on the series pass and then they LED switched on and after it the capacitor starts discharging you go to a lower voltage and the.

So, essentially if you do half C v 2 square minus V 1 square V h square or V square high minus V square low, you should get the output energy quite simple half C v square here and this is the time integral of input power from 0 to the time it takes to charge the capacitor. So, in a sense this is what the explanation here is. So, let us read this together and then summarize this nice RF energy harvesting circuit.

So, minimum cold start see this is another thing self starting cold starting all these are very critical in energy harvesting applications minimum cold start voltage and typical input power for BQ, this is now all the story is around what BQ requires as an input this is a three thirty millivolt and 10 micro watt respectively only if it gets this much power 10 micro watt of power it can actually not start it also has an ultra low power input power levels with low quiescent current three thirty nano amperes is minimum required .

So, this together essentially is. So, you program the resistors for the BQ it is a standard circuit which you can implement, and the LED that they are connect outside requires 20 milliamperes and the capacitors charges to a voltage high voltage of 2.82 and the low voltage is 1.63. So, you start with 2.82 you switch on the LED, if it goes the capacitor starts discharging goes to 1.63 switch off the LED the LED gets switched off because the transistors turn off and then the capacitors again charging from 1.63 to 2.82 and that charge discharge charge discharge keeps going periodically.

When the minimum voltage V low is reached the boost converter and m p p t start to operate, and charge the charge discharge at the load begins causing LED to flash the charge discharge operation of the LED can be observed in figure 14from the boosted volt signal V bat. Using the converter topology of figure 13 and DAQ for capturing the signals basically a piece of equipment, we exported the rectifier output voltage V in DC and the boost converter output V bat for 800 seconds.

Essentially it is a time trace for 800 teg seconds the rectifier P in was at minus 15 dBm at 97.5 megahertz. Finally, it is noted that the boost converter was self started with no external energy that was used. So, it goes back to what we discussed that energy harvesting any challenge in energy harvesting means, it should be really self starting. This is in summary the whole story of this paper which is quite well written in my opinion they also do the end to end efficiency calculation.

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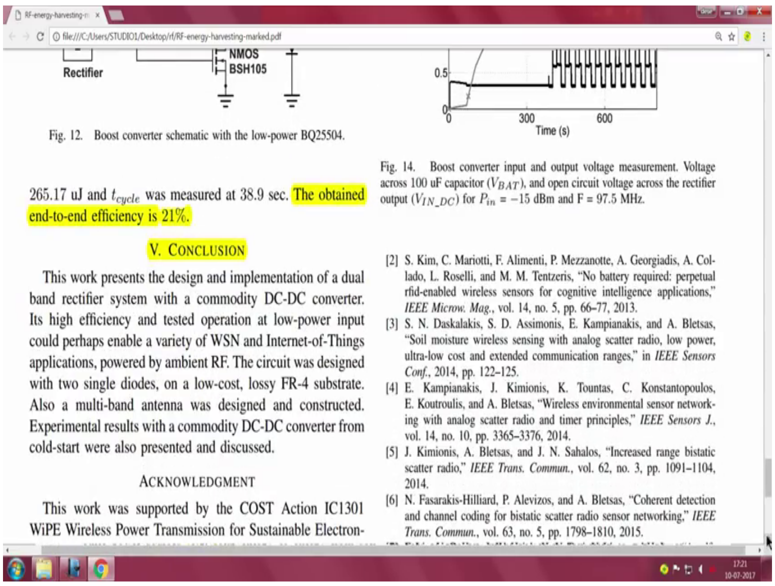

Fig. 12. Boost converter schematic with the low-power BQ25504.

Fig. 14. Boost converter input and output voltage measurement. Voltage across 100 uF capacitor (V_{BAT}), and open circuit voltage across the rectifier output (V_{IN_DC}) for P_{in} = −15 dBm and F = 97.5 MHz.

265.17 uJ and t_{cycle} was measured at 38.9 sec. The obtained end-to-end efficiency is 21%.

V. Conclusion

This work presents the design and implementation of a dual band rectifier system with a commodity DC-DC converter. Its high efficiency and tested operation at low-power input could perhaps enable a variety of WSN and Internet-of-Things applications, powered by ambient RF. The circuit was designed with two single diodes, on a low-cost, lossy FR-4 substrate. Also a multi-band antenna was designed and constructed. Experimental results with a commodity DC-DC converter from cold-start were also presented and discussed.

Acknowledgment

This work was supported by the COST Action IC1301 WiPE Wireless Power Transmission for Sustainable Electron-

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And they find that they get a 21 percent end to end efficiency that is both RF DC as well as DC-DC, because they use a commercially available boost converter like t i is BQ2 double 5 0 4. Big summary if you want to do RF DC you want to use RF as an input harvesting source, do proper characterization no what is the input power power in is important do proper impedance matching. How do you measure input power I showed you a demonstration that you must use a proper equipment, you must be able to measure the input power using a simple power meter.

There are cheaper ones available you can buy some good equipment cheap ones accurate ones for your simple applications use that for measuring input power do proper impedance matching characterize S11 right then use necessary diodes for rectification connect different loads, do V i characterization.

Find out the right kind of load that would be required to drive your system find out the open circuit voltage see what you can do with the open circuit voltage such that it can be fed to a boost converter you can use any commercial available boost converter like BQ2 double 5 0 4 or any of the magazine chips or any of the linear technology chips or any one of them. And see if you can build a simple nice circuit which can use the ambient RF around you this is the big story.

Thank you very much.