Low Power VLSI Circuits and Systems

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Lecture No #37

Battery-Driven System Design

Hello and welcome to today's lecture, on battery driven system design and here is the agenda of todays lecture.

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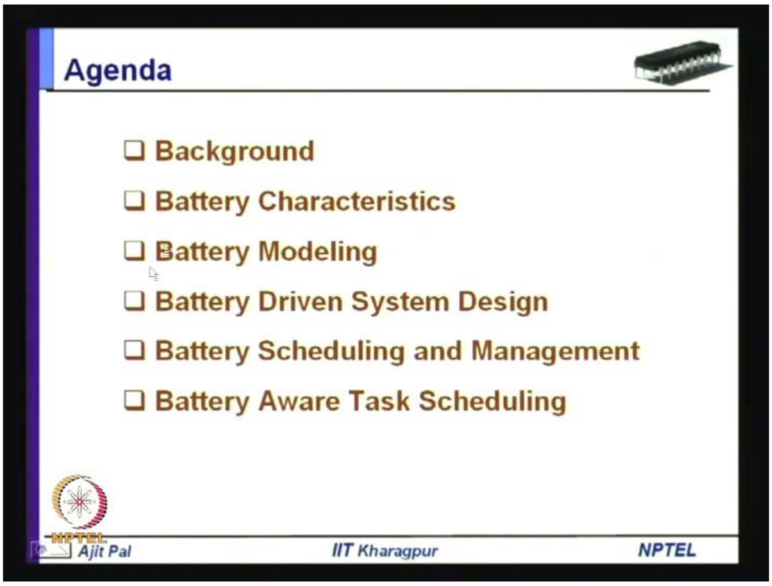

I shall give a brief background of this battery driven system design particularly we shall emphasize on why battery driven system design is necessary? Then we shall discuss characteristics of batteries which are commonly used in modern embedded systems. And then we shall consider, how the characteristics of these batteries can be modeled by using various techniques. Then, we shall focus on battery driven system design various approaches for this purpose and battery scheduling and management approach and battery aware task scheduling.

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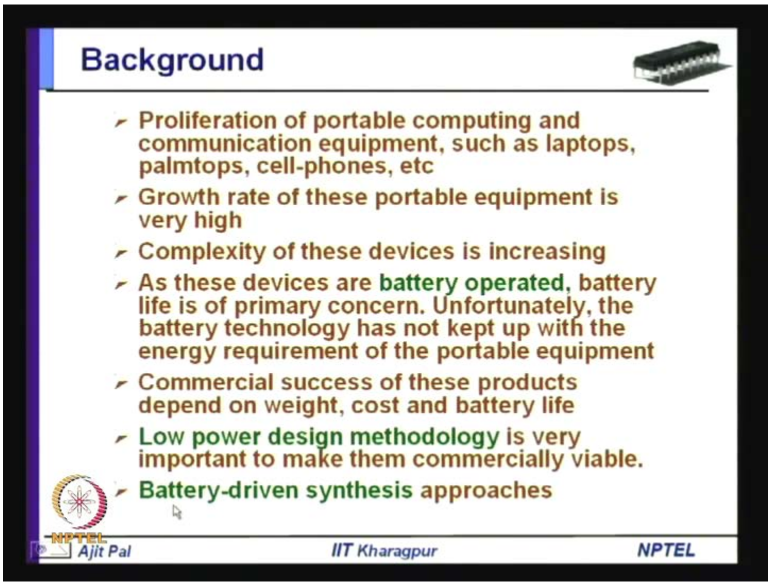

We have seen that there is strong proliferation of portable computing and communication equipment, such as laptops, palmtops, cell-phones in the centers. In the centers these battery operated portable systems are increasing, at a very large I mean rapid rate compared to servers. And other systems and this growth rate of this portable equipment is very high we have observed that. And one important characteristics of this battery is that, not only I mean of this system is that not only the number of such equipment is increasing battery driven systems are increasing their complexity is growing.

Let us focus on one of the most common portable equipment that is cell-phone. Initially cell-phone was developed primarily for voice communication now, we are using cell-phone not only for communication of voice, for sending SMS, for access internet, for receiving radio, fm radio, for capturing picture and so on. So, the number of functions is growing and as a consequence complexity of these devices is increasing, as a increasing with the use of with the rather increasing need for the users. And as these devices are battery operated battery life is of primary concern.

So, we find that battery is an integral part of the systems because the, if the battery fails, the system fail if the battery I mean battery power is reduced the capability of the system reduces. So, battery plays an very important role in these portable devices unfortunately, the battery technology has not kept up with the energy requirement of the portable equipment; that means, the energy requirement of these portable devices is increasing because of the increasing complexity of different applications. But the battery the energy that can be delivered by battery is not increasing at that rate we shall have a look at the curve I mean plot of that later on.

Than commercial success of these products depend on weigh cost and battery life since, battery life rather the battery dictates, the commercial success of the product why? You see the size of the battery will decide what will be the weight? And how long the battery will last? That will also, decide the commercial viability of the product; that means, whenever you go for buying a laptop, you will demand that the between two charging, it should sustain between may be 12 hours. Similarly, whenever you are trying to buy a cell-phone, you will see that the weight is small, but it can consume much less battery and these are the; that means, weight, cost and battery of course, cost is another important parameter.

So, what we can say that battery is significantly influencing the commercial success of these products. What is the alternative? The alternative we should develop low power design methodology so that, these products have become commercially viable. And as a consequence a new approach has emerged, which is known as battery driven synthesis approach; that means, now you have to consider battery as part of your system design. Earlier battery characteristics were not known, it was assume that battery will supply power, it will supply desired amount of current may be for certain duration.

But if we use a battery driven system design we shall see the life of the battery can be longer; that means, after you charge it will give you power over a longer duration. In other words in some situation the life of the system will decide the battery life for example, in censor network sometime the censor networks are deployed in jungles. So, there is no way that you can replace the battery or recharge the battery; that means, the battery with which it has been deployed, will decide how long that system will work.

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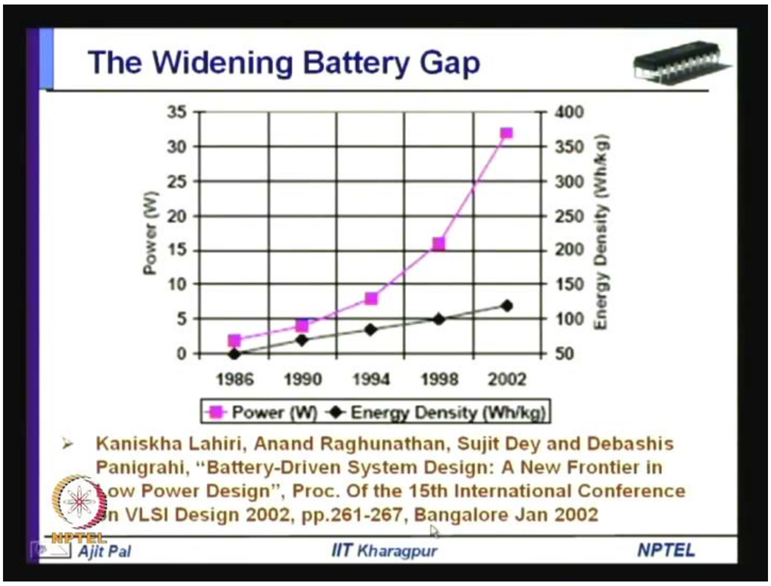

So, battery driven system synthesis is very important and we shall see how it can be done? I was talking about the widening battery gap. Here we find that the power consumption is increasing rapidly in modern systems, this is a little older you know older data. But even in the same data, the rate is increasing; that means, the complexity of these systems are increasing as a result, this pink line as you can see which is representing the power consumption of a battery operative systems is increasing at a very high rate. In the other hand you can see the energy density of batteries; that means.

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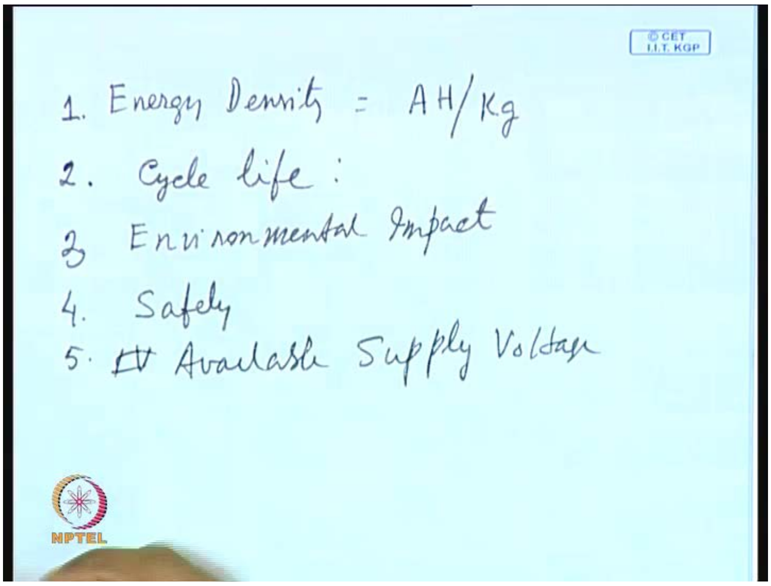

The energy density is represented by energy density is essentially represented by ampere hour is the, you know the energy that can be stored in a battery per k g; that means, larger the weight; obviously, the capacity will be more. So, per kilo gram of battery what is the energy that can be stored in the battery? That is how the energy density of a battery is represented you can see the energy density is definitely improving with the improvement of technology, but their improvement is not really much.

So, it has improved, but compared to the require power requirement it is much less. That means the gap between the need and what actually can be supplied by the battery is widening with time. So, how these gaps can be bridged? That is what we shall discuss. So, this particle diagram has been taken from a paper on battery driven system design, a new frontier in low power design by Kaniskha Lahiri, Anand Raghunathan, Sujit Dey and Debashis Panigrahi it was published in an international conference of on VLSI design.

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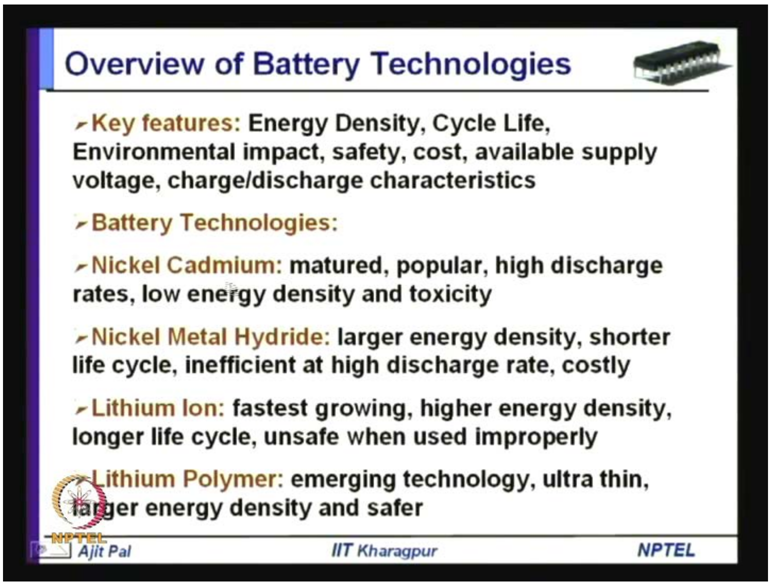

So, now, let us have a look at the different, each features of a of battery that we use to characterize a battery number one is energy density which I have already mentioned. Number one is that means, the ampere over per k g this is a very important parameter and this we would like to have this particular parameter to be improved. That means, we want larger energy to be stored in a battery of smaller weight, second important parameter is life cycle, cycle life what is cycle life? Cycle life is as you know these batteries operated are rechargeable these batteries, which are commonly used in these inbuilt systems are rechargeable.

But question is how many times charging and discharging can take place? For example, if you are using nickel cadmium battery, nickel cadmium battery can be charged and discharged may be 4000 times. So, that means, 4000 times the battery can be charge and; obviously, it can be used when the discharge will take place. So, that decides the life cycle and longer it is better than environmental impact. What is environmental impact? Environmental impact is, you know to realize these batteries, you are using some chemicals which may be toxic for example, in nickel cadmium batteries you are using cadmium is a very toxic material.

And obviously, those nickel cadmium batteries are to be handle with care and after nickel cadmium battery becomes you know unusable you should not discard it anywhere, you should carefully dispose it off. So, that it does not go to the environment otherwise, it may be harmful to the life; that means it has impact to the environment because it can it releases toxic material. Then safety, safety is another feature, which is very important because how safe is the battery when you use it? We have read in the newspaper that a particular device, cell-phone or some inbuilt system has exploded how it has exploded?

Actually, when the battery terminals; that means, the positive and negative terminals are sorted some batteries will explode; that means, if you draw very large current it may lead to some kind of explosion. So, how safe is the battery that is that is also very important feature of the battery then comes the available supply voltage. So, available supply voltage is another feature, available supply voltage you know that different batteries can supply different voltages. For example, the popular batteries that we use those lead acid batteries, that can provide I mean partial 1.5 volt similarly, nickel cadmium battery will provide 1.6 volt.

But our requirement in the system may be different for example, when we are using a 5 volt supply, then you have to use several batteries to get that 5 volt or 12 volt or whatever it may be. That means the voltage that is generated by the battery has to be taken into consideration that is your available supply voltage. And last but not the least is a charge/discharge characteristic. Later on we shall see whenever you will be charging a battery you cannot really charge at a very high rate, that the charging rate is usually much smaller than the discharge rate. So, and also how the discharge rate influences the characteristics of the battery? These things are to be are very important whenever you go for battery driven system design.

Now, let us have a look at some battery technologies which are commonly used. The most commonly used technology is nickel cadmium which is matured and widely used in portable systems in cameras cell-phones many mp three players and. So on it is popular and it gives you high discharge rate; that means, it can supply large load current. And however, the limitation is that it has got low energy density energy density is small compared to other technologies and as I mentioned cadmium is a toxic materials. So, it has got toxicity; that means, it is not very I mean safe to use you have to use then very carefully.

So, this is the characteristics of nickel cadmium battery which is one of the most commonly used batteries. Then comes the nickel metal hydride, nickel metal hydride is also used now a days and it has becoming popular because of large energy density. So, energy density is very large, but unfortunately the life cycle is very shorter compared to nickel cadmium batteries; that means, you cannot really use it for a long durations number of charging and discharging it can do is smaller small compared to nickel cadmium. Then inefficient high discharge rate; that means, the discharge rate the rate at which it can supply current to the load is not very good.

So, it is inefficient moreover it is costlier than those nickel cadmium batteries. Nowadays we are using lithium ion, in most of our you know, cell-phones, mp 3 players and other systems primarily because of much higher energy density, longer life cycle. However, it is unsafe when used improperly as I was mentioning that lithium ion batteries particularly, when the battery terminals are sorted it may lead to explosion; that means, you have to use them very carefully. And then the then the last one is a emerging technology lithium polymer, it is very attractive because of smaller size, ultra thin and larger energy density and also it is safer, but unfortunately it is not yet commercially very successful.

So, it is an emerging technology. So, the most popular present day technology is lithium ion the other technology is like nickel cadmium and nickel metal hydride are also used.

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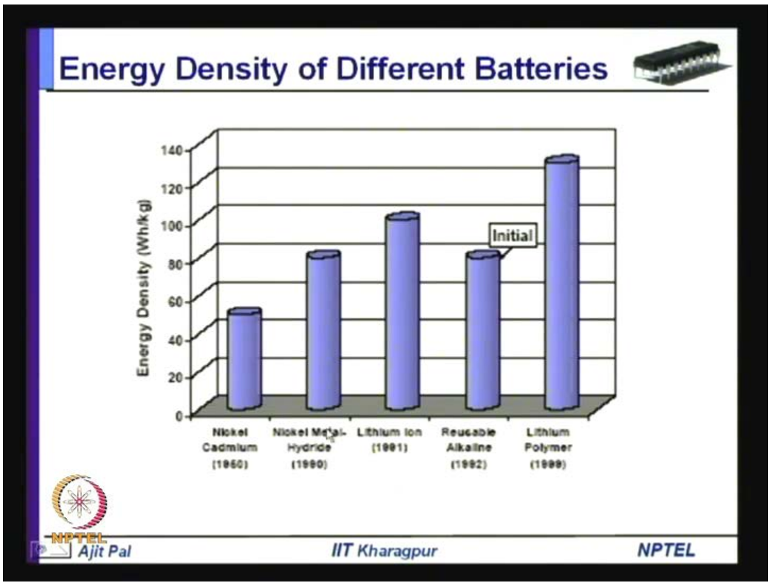

Now coming to the energy density of different batteries as you can see nickel cadmium batteries has lower energy density; that means, your watt hour per k g for nickel cadmium is little more than 40, on the other hand for nickel metal hydride it is more. It is close to 70, little more than 75 and for lithium ion it is maximum it is little less than 100 watt hour per k g. And reusable alkaline batteries which are not commonly used in portable system, which were earlier used initially it gives you good energy density, but not as high as lithium ion.

And that lithium polymer which is a emerging technology as you can see it can give you 120 watt hour per k g, but this technology is not yet matured and not commercially available. So, we have to really use one of this three nickel cadmium, nickel metal hydride or lithium ion in our portable battery operated systems.

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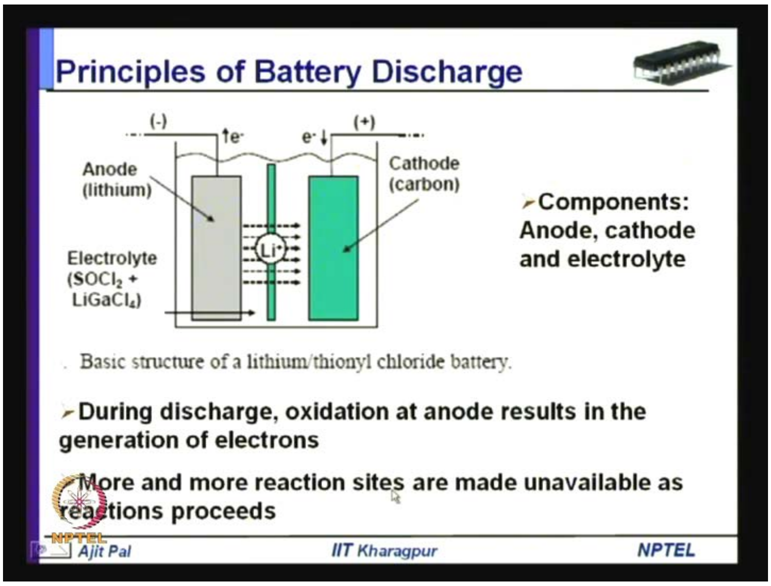

Let us now have a look at the basic principle of battery discharge we know any battery we have to know two terminals, one is anode and another is cathode. These correspond to lithium thionly chloride battery here, as we can see we have the lithium anode and carbon cathode and you can see you have a electrolyte in between electrolyte. And then lithium ions go from anode to cathode whenever you discharge it. And so, the basic components are anode, cathode and the electrolyte suitable type of electrolyte that you have to use.

So, whenever you are doing the discharge oxidation of anode results in generation of electrons and that leads to flow of current between cathode and anode. This is how really the battery discharge takes place and in simple terms. And whenever you draw more and more current, then more reaction sites are made unavailable as reaction proceeds. What happens? As the currents are drawn electrons flow take place what happens? These reactions sites gets covered by some material and those surfaces become unavailable and that is the reason why gradually the lesser and lesser surface area is available and lesser and lesser current I mean can be supplied by the battery after the initial charging?

So, and again whenever you do the charging than those reaction sites get are made available to the user.

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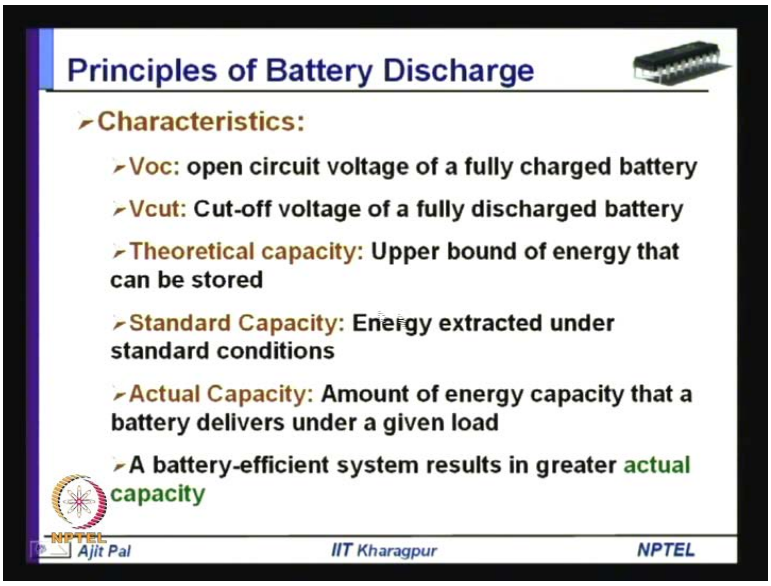

So, this is how charging and discharging occurs in a battery now, let us now have a look at some of the electrical characteristic of the battery because ultimately you will be using a battery. And you have to look at the electrical characteristics and these are some of the important electrical characteristics, one is your open circuit voltage of a fully charged battery; that means, after you charge a battery and if you do not apply any load it will give some voltage, this is known as voc or; that means, the open circuit voltage.

This open circuit voltage is usually higher than the nominal voltage. For example, those lead acid batteries that, is the typical voltage is 12 volt can give you open circuit voltage of 13.5 or even 14 volt whenever it is fully charged and no load is connected to it. Then comes the V cut that is your cut-off voltage of a fully discharge battery; that means, after a battery is fully charged and then if you drawing energy from the battery that voltage level goes down and for example, a 12 volt battery the voltage can go down below 11.5 or 11 volt when the charge is I mean it has no energy stored in it most of the energy has been discharged.

So, this by measuring these voltages you can give an approximate idea about the condition of the battery. We find that in your laptop if you click on the battery symbol, it will say that 75 percent energy is being is stored how that is given? Actually it measures that voltage; that means, your that V that voltage across the terminal and by measuring that terminal it can tell that how much energy is present the available from the battery?

So, far as the capacity is concerned there are several types of capacity, number one is theoretical capacity.

So, theoretical capacity is the upper bound of energy that can be stored; that means, whenever a battery is being designed depending on the weight, depending on the size, depending on materials that is being used theoretically one can calculate how much really energy it can be supplied. So, this is the theoretical capacity. So, usually theoretical capacity may not be same as the standard capacity. So, standard capacity is energy extracted under standard conditions. So; that means, whenever you are using the battery in standard condition, what you really mean by standard condition? Standard condition is that, you have to maintain a particular temperature you have to draw current at a particular rate and based on that how much energy can be supplied?

So, these standard capacity can be less than the actual capacity, actual capacity is the amount of energy capacity that a battery delivers under a given load; that means, these actual capacity is the capacity of the battery that you get whenever you are actual using it. So, in that condition you have to take into consideration the thermal effect for example, the (()) temperature can be small low, can be high. For example, it has been found that, the current delivery the capacity of a battery is heavily dependent on temperature, those who are using cars? They know that most of the situation the car battery fails in winter. The reason for that is temperature is lower that time and as a consequence the battery is not capable of giving high current.

So, temperature effect has to be taken to consideration and not only that, the current discharge profile. You are not really drawing a constant current from the battery which is the done in whenever you define standard capacity normally you draw sometimes heavy current. For example, whenever you are starting a (()) you are drawing very large current to start the motor. On the other hand when it is running battery is essentially not supplying much current. So, similarly, in laptop when you turn on the laptop then it draws heavy current from the battery and subsequently, the current that is being drawn depends on the application you are running.

So, you have a varying load and under the varying load condition varying current is drawn from the battery and under these condition the actual life or actual capacity that will get will be different from the standard capacity and theoretical capacity. So, from this we can really define the objective of battery driven system design. So, what is our objective? Our objective is to maximize actual capacity. Actual capacity of the battery that will be drawn whenever, you are using it in practice so, maximize actual capacity by taking into consideration the characteristics of the battery.

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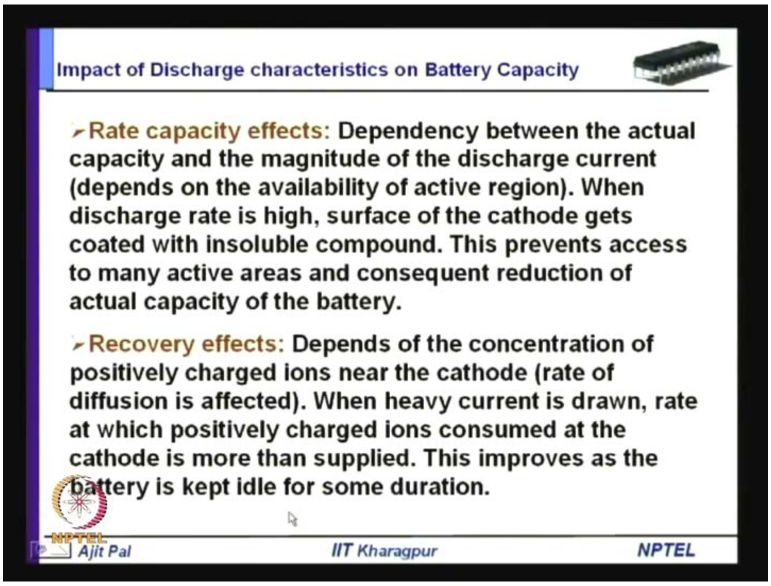

So, that is the goal of the battery driven system design maximizing actual capacity. Now, as I was mentioning that charge discharge characteristics is also very important and actually this happens because of these two effects. One is known as rate capacity effect what is rate capacity effect? So, rate capacity is, effect is dependency between the actual capacity and magnitude of the discharge current is dependent on the rate at which the current is drawn the reason for that is you know as I mention whenever you are discharging a battery that, the active area that is present in the battery will decide how much current it can supply?

So, if you draw at a larger rate; obviously, more area will become unavailable, if you draw at a slower rate, more area will be available for I mean more active are will be available. So, when discharge rate is high, surface of the cathode gets coated with insoluble compound. And this prevents access of many active areas and consequent reduction in the actual capacity of the battery and that is the reason why? Rate capacity plays a very important role in deciding the actual capacity; that means, if you draw at a slower rate you will get longer actual I mean larger actual capacity.

Than another important feature is another characteristics is recovery effects. So, depends on the concentration of the positively charged ions near the cathode; that means, the rate of diffusion is affected by this particular phenomenon; that means concentration of positively charged ions near the cathode that decides the I mean the charge; that means the current driving capacity. So, when heavy current is drawn rate at which positively charged ions are consumed at cathode is more than supplied. So; that means, whenever you are using a battery and that time the positively charged ions available to you reduces.

Now, if you keep the battery in ideal condition for certain duration than again that positively charged ions will be available. It is a common practice those who are driving cars? They know, that suppose you try to start (()) it may. So, happen the engine will not crank, it will not start what did driver do? Normally they will find that, they will switch off the battery and then wait for certain duration. What actually they are doing? They are unknowingly using this recovery effect; that means, the battery will recover more and more positive ions will be available near the cathode and as a consequence the necessary current that can, that is necessary to start the engine will be available now. So, this is the recovery effect.

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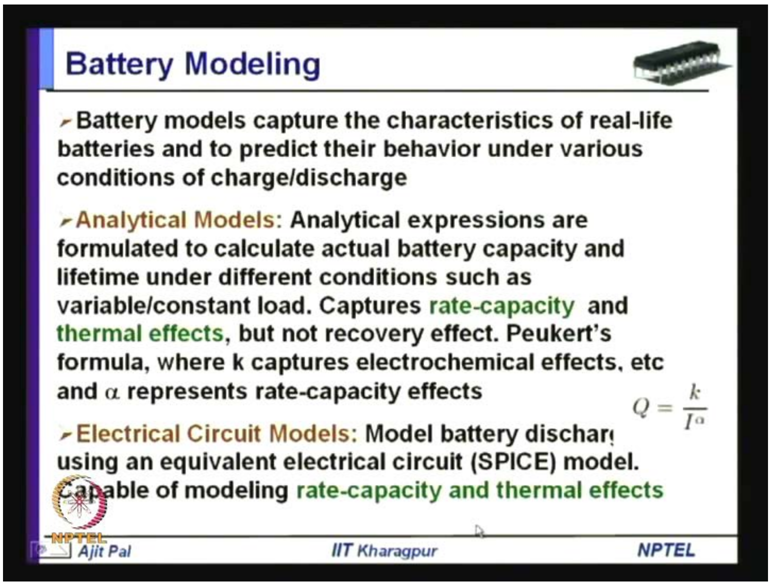

So, these effects are to be taken into consideration in the system design to get larger actual capacity. Now, whenever you do this you have to use a model of the battery. So, battery models capture the characteristics of real-life batteries and to predict their behavior under various conditions of charge and discharge. So, that is the requirement of the model and there are different types of model, number one is analytical model. So, analytical expressions are formulated to calculate actual battery capacity and lifetime under different conditions such as variable and constant load; that means, it takes care of the charge/discharge characteristics.

And based on that it can find out that if you draw this much of current this was this is the initial charge and after drawing this much current at this rate this will be the charge left. So, this type of equation is provided in the analytical model. So, it captures the rate capacity and the thermal effect. So, it also takes into consideration the impact of temperature; that means, thermal effect and, but no not recovery effects. So, analytical model cannot take care of the recovery effect. So, Peukerts formula which is represented by Q is equal to k by I to the power alpha.

So, this is simple formula was proposed by Peukert to model the battery, where k captures the electro electrochemical effect; that means, battery is essentially a electrochemical device. And those electrochemical effects have to be taken into consideration and those are taken care of by this parameter k. And for different batteries the value of k will be different and alpha represents the rate capacity effects; that means, as you draw I to the power alpha where alpha is the takes care of the rate-capacity effect.

That means, as you discharge the battery at a particular rate than the charge that is that will remain present that can be obtained from this. So, analytical models are simple way of modeling battery and there is another type of model based on electrical circuit model. So, in this case model battery discharge using an equivalent electrical circuit that is spice model. So, in this particular case you can really, consider it as if it is a electrical circuit and you can by using spice model the you can represent the characteristics of the battery and this particular model is capable of modeling rate-capacity and thermal effects. Then coming to the third model, that is known as stochastic model.

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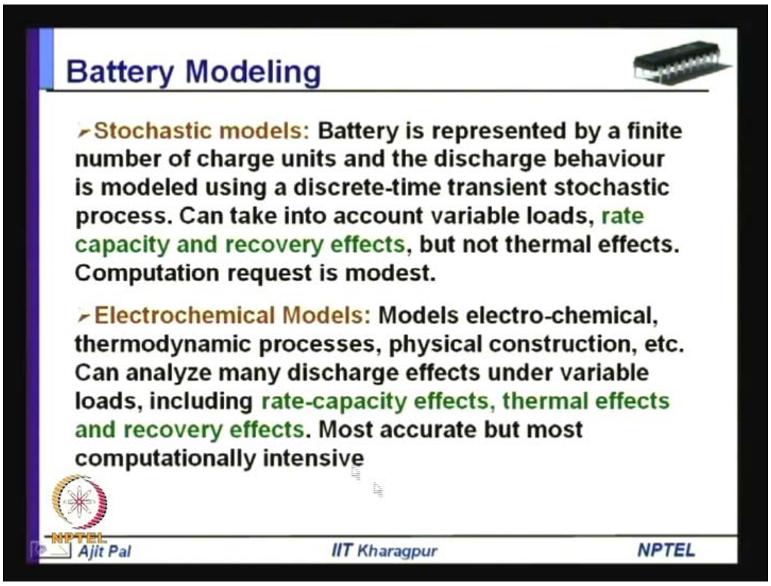

So, in this case battery represented by finite number of charge units and the discharge behavior is model using a discrete-time transient stochastic process. So, this is little complicated technique, but this can take into account variable loads rate-capacity and recovery effects, but not thermal effect. And particularly in this case computation requirement is modest. Coming to the last model, that is your electrochemical model. So, this models electrochemical thermodynamic processors.

So, it takes into consideration the physical construction what is the length? What is the width? What is the thickness? And various materials used and so on. So, actual physical dimensions are taken into consideration and this can analyze many discharge effects under variable loads including rate-capacity effect, thermal effect and recovery effect. And obviously, this electrochemical models are most accurate, but computationally intensive. That means it will take long time to perform computation. So, later on we shall see out these four models analytical models are more commonly used in our analysis and later on we shall see how it is being done in some applications?

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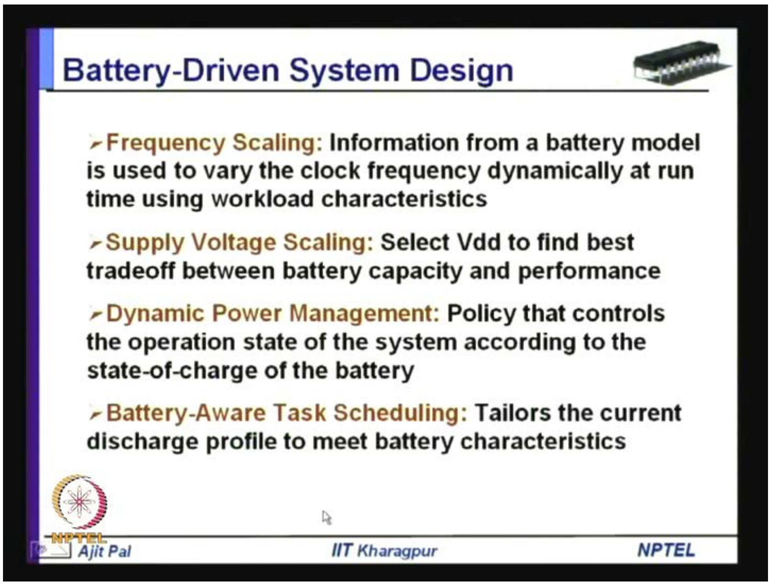

Now, I have discussed about some of the important characteristics of these models. So, based on these, how do you really design battery driven system? I mean how do you perform battery driven system design? There are several approaches number one is frequency scaling. So, information from a battery model is used to vary the clock frequency dynamically at run time using workload characteristics.

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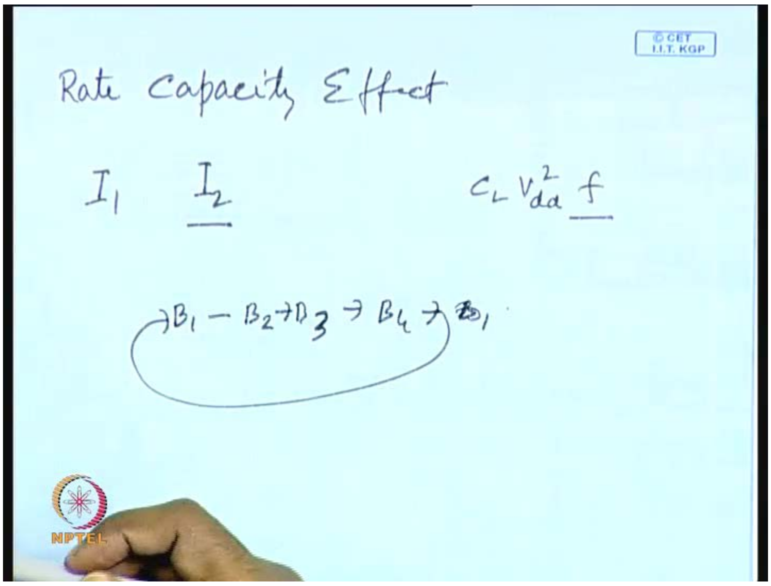

We have seen that a you know that rate capacity effect we have that rate capacity effect tells you that, if you draw with a smaller current I 2 compared to I 1 than you get more actual capacity; that means, if draw at a smaller rate you get longer. I mean longer life or larger actual capacity. So, how do you really draw smaller current as you know based on the workload condition, you can find out what is the frequency at which a particular system can run? So, you can reduce the frequency and as you reduce the frequency, the power requirement for the system will reduce, it will draw smaller current.

We know that because you know that power dissipation is proportional to C L Vdd square f. So, if you reduce f the current will decrease and as a consequence, it will give longer actual capacity. So, you can do frequency scaling. So, to take care of the workload and based on that you can get longer life of the battery. Than you can do supply voltage scaling as I have already discussed select Vdd to find the best tradeoff between battery capacity and performance. So, what you can do? Depending on the workload condition you can do voltage scaling.

So, if you reduce the voltage as we can see here, if you reduce the voltage the current that will be drawn will be reduced and as a consequence you can match the current drawn with the workload condition and in turn will lead to lesser current and longer actual capacity and larger battery life. Then we can do dynamic power management. So, in this particular case the policy that controls operation state of the system according to the state-of-charge of the battery; that means, what can be done see if you find that the charge has charge is getting depleted you can to take into account.

The recovery effect we can switch off some of the system for certain duration and battery will recover again you can turn it on; that means, you can do what is known as a power management? So, you can you can shut down, turn on and you can give required recovery time for the battery to get more actual capacity. Than you can do battery aware task scheduling this tailor the current discharge profile to meet the battery characteristics I shall discuss some technique for that.

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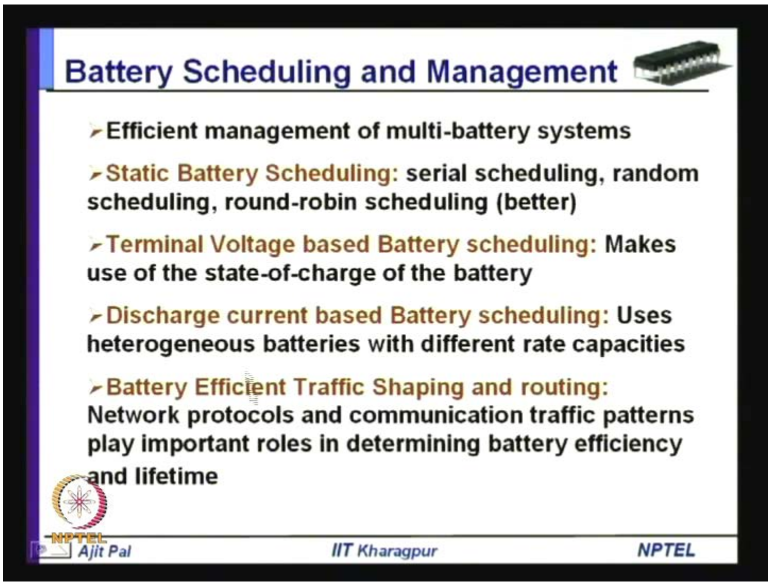

So, battery scheduling and management as I was mentioning efficient management of multi-battery systems nowadays, you know sometimes we do not use a single battery, you can have multiple batteries in a system. And whenever you are using multiple batteries in a system for example I will find that when high reliability is necessary instead of using single battery you will use in multiple battery. And those batteries need not be uniform of same type these batteries can be of different types. In such a case what you can do? You can do static battery scheduling.

So, there are different ways of doing it serial scheduling, random scheduling and round-robin scheduling. That means, say suppose you have four batteries so, use battery one for certain duration, than you can, you switch over to battery two and in a mean time battery one will recover. Then after using battery two for certain duration you can use battery three and after again after using battery three we can go for battery four and so on. In this way you can do it serially, one after the other serially means, after battery one is completely exhausted, you will go to battery two, then battery two will be exhausted then you will go to battery three. So, this is the serial method on the other hand round robin is you know, you are using it for certain duration.

If the battery is not yet fully exhausted than we will switch to battery two, again use it for certain duration it will not be fully exhausted, then you go to battery three in this way you will doing say battery one, then battery two, then battery three, then battery four, then battery one. So, in this way it will be you can say you will come back to this. So, in this way we will be doing using the battery in a round robin fashion. So, whenever you are using these batteries in round robin fashion; obviously, each battery you will get enough recovery time and as a result actual capacity will increase.

Then terminal voltage based battery scheduling so, here makes use of this state of this charge of the battery suppose, you have got four batteries. So, it is may not be necessary that it may not be true that all the batteries will have equal capacity. So, it may depend on how old is the battery? Weather how much? What is the actual capacity of the battery? I mean how much charge discharge has taken place of a particular battery? It by that I mean different batteries will have different energy stored in it. So, you can take into account that by measuring the terminal voltage; that means, accordingly you can schedule the batteries instead of making it round robin the battery which has large capacity, you can use it more than a battery which has less capacity.

So, in this way you can do more intelligent scheduling, based on the state of the charge of battery and discharge current based battery scheduling use heterogeneous batteries with different rate capacities; that means, you know you can have different batteries which can provide different current efficiency. So, depending on the workload you can select a particular battery which matches the discharge profile of that application. So, in this way you have discharge current based battery scheduling or battery efficient traffic shaping and routing. So, network protocol for example, nowadays battery driven system systems are I mean battery operated systems are used in communications censor network and many other applications.

So, their network protocols and communication traffic patterns play an important role, in determining the battery efficiency and lifetime. So, in that case depending on the network protocol that is being used and the communication traffic pattern; that means, that is being that is inherent in the system that can be used in determining the battery efficiency and lifetime. So, in other word I mean in to summarize this, what I can tell? You can do suitable scheduling and management to get maximizes actual battery capacity and longer life of the entire battery system.

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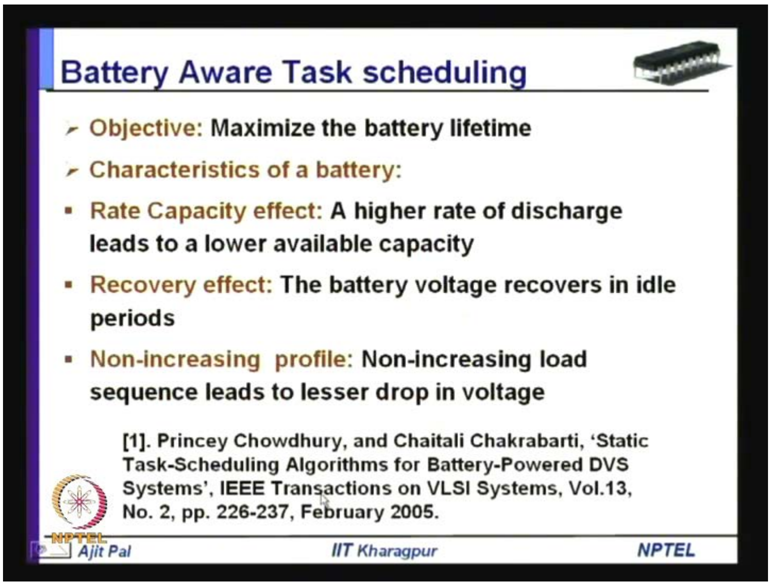

Coming to the last topic, that is battery aware task scheduling. So, here as I mention the objective is to maximize the battery lifetime. And the various characteristics which you like to use? Is rate capacity effect and a higher rate of discharge leads to a lower available capacity that is known, that has to be used, than recovery effect the battery voltage recovers in idle periods that we know. So, that has to be used another feature which has been observed, that is known as non-increasing profile.

So, non-increasing load sequence leads to lesser drop in voltage I shall discuss it in more detail, this has been taken from a paper entitled static Task-Sheduling Algorithms for Battery-Powered dynamic voltage scheduling system. So, this way published in IEEE transactions on VLSI system and the paper was by Princey Chowdhury and Chaitali Chakrabarti.

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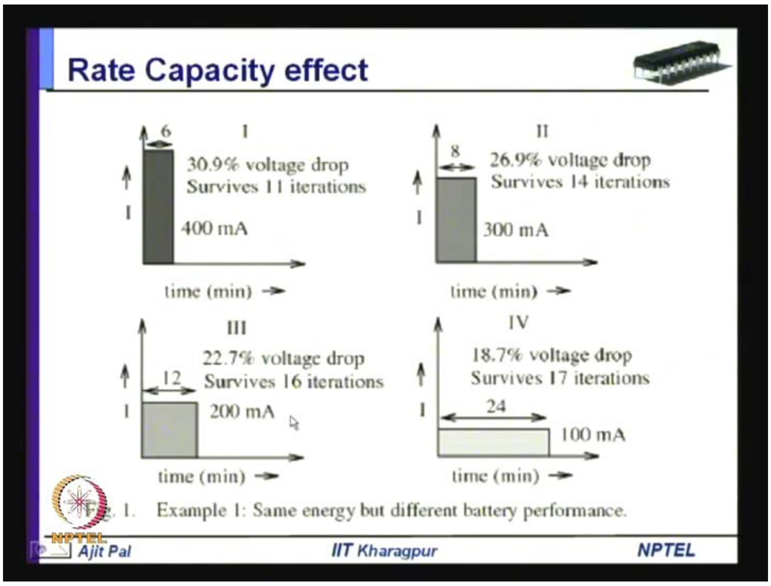

So, in this paper they have utilize these characteristics of the battery and then they use dynamic voltage scheduling. And this is that rate capacity effect that I was mentioning for example, here the battery is supplying 400 mille-amperes and the task will run for 6 minute. So, this is a minute 6 minute, 400 mille-amperes. So, a particular requires that and whenever this is done than 30.9 percent voltage drop take place and after 11 alterations of this. So, this is the this is when you are discharging at a very high rate than you can do voltage scheduling and if you do the voltage scheduling then you can reduce the current; obviously, actually till not the voltage scheduling, voltage and frequency scheduling as you do that than the current can be reduced.

But the execution time will increase as I have mention. So, energy drawn from the battery is same. So, 8 into 300 is same as 6 into 400; however, in this condition you know 26.9 percent voltage drop occurs and after running this and it survives for survives 14 iteration instead of 11 iteration; that means, it can this task can run fourteen time compared to 11 eleven times in this particular case. Similarly, whenever further voltage and frequency scheduling is done scaling is done the current can be reduced to 200 mille-ampere and; obviously, the execution will be 12 minute.

So, in such a case 22.7 percent voltage drop occurs and this will survive 16 iterations. And finally, you can reduce voltage and frequency in such a way the current drawn is 100 mille-amperes. Obviously, it will take longer time to execute the task, that is 24 minutes and the voltage drop is 18.7 percent and it will survive 17 iterations. So, you can see you are getting much larger actual capacity instead of running the task seven you are able to run it seventeen times and because of you are getting larger actual capacity. So, you are drawing same energy, but you know the actual capacity that you are getting is more.

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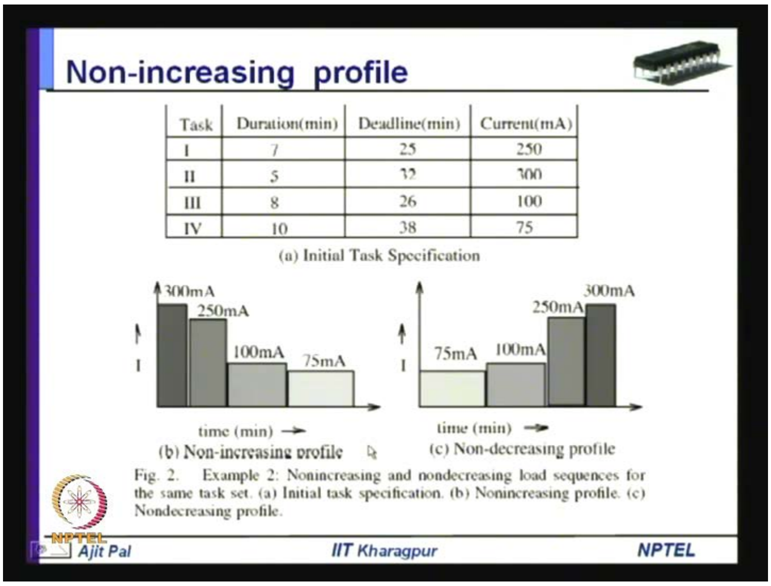

So, that is the rate capacity effect and another feature that I mention that is a non-increasing profile say suppose, you have got four tasks to be executed and duration of each of them is mentioned 7 minute, 5 minute, 8 minute and ten minute and these are the deadline times. So, after meeting the deadline time, you can schedule them and which have different currents as you can see here the scheduling has been done. Where the task? Which draws? Larger current has been scheduled first. Than the task which draws? Next higher current is scheduled second, then the third one is the next I mean the which draws lesser current? then the first two and finally, the task which draws minimum current? Is scheduled. So, this is your non increasing profile.

So, you can schedule it in this or can schedule the other way where the task? Which draws minimum current? Is scheduled first and then in a increasing order you schedule the various task and; obviously, whenever you schedule the task in this manner your I mean the deadlines are not violated. So, both will serve the purpose, but the you can see the voltage that is present that is analytical Q in case of that is that is being.

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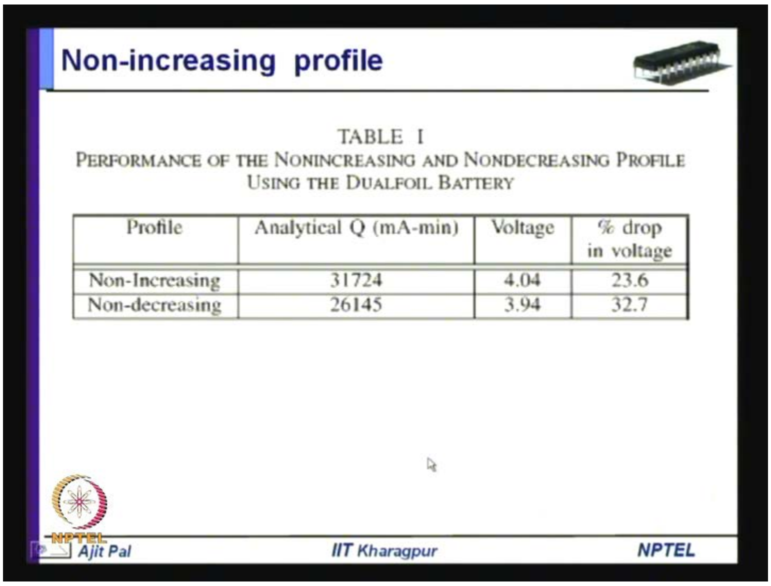

Profile	Analytical Q (mA-min)	Voltage	% drop in voltage
Non-Increasing	31724	4.04	23.6
Non-decreasing	26145	3.94	32.7

That is present in the system in a non increasing profile is 31724 and compared non decreasing 26145. And terminal voltage is 4.04; that means, the battery is in better condition or the battery has got more charge which is represented by this compared to the next situation. So, 3.94 is lesser voltage. So, the voltage drop in the first case is 23.6 the second case is 22.4. So, this shows that non increasing profile this non increasing profile means, you are decreasing the current discharge is better in battery operated systems; that means, initially the batteries in good condition.

So, it can it has larger current drive capability and as you keep on using it lesser and lesser active area is available. So, it is better to schedule in a non increasing profile. So, you can use these three phenomenon rate capacity effect then recovery effect and non-increasing profile effect, using them they developed this paper they have presented a scheduling task scheduling algorithm and they have shown how much? How the actual capacity is increasing?

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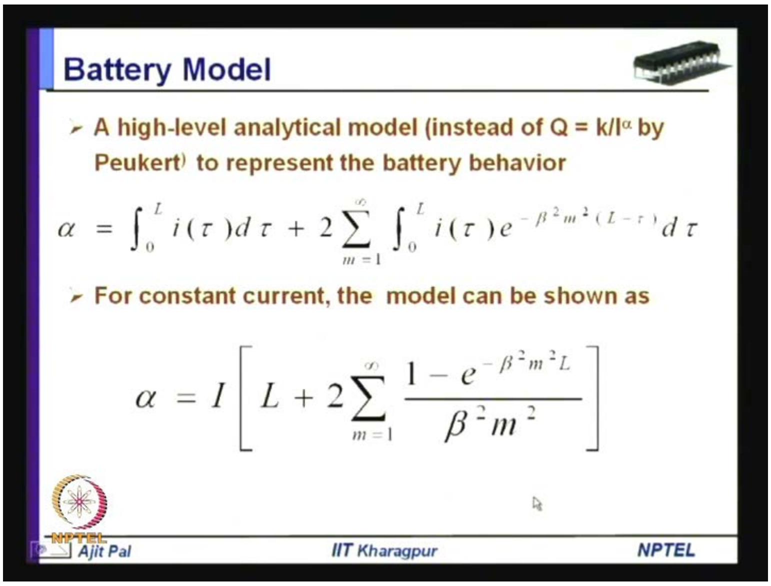

And the battery model that was used is a analytical model instead of using this simple model Q is equal to k by I to the power alpha by Peukert. They use the little complicated battery model and this actually, takes care of variable current and on the other hand for constant current, this reduces to particular expression. Here alpha is equal to this alpha where is, alpha, beta this is the alpha. So, alpha reduces this in case of in case of your constant current. So, this particular algorithm model was used in that paper.

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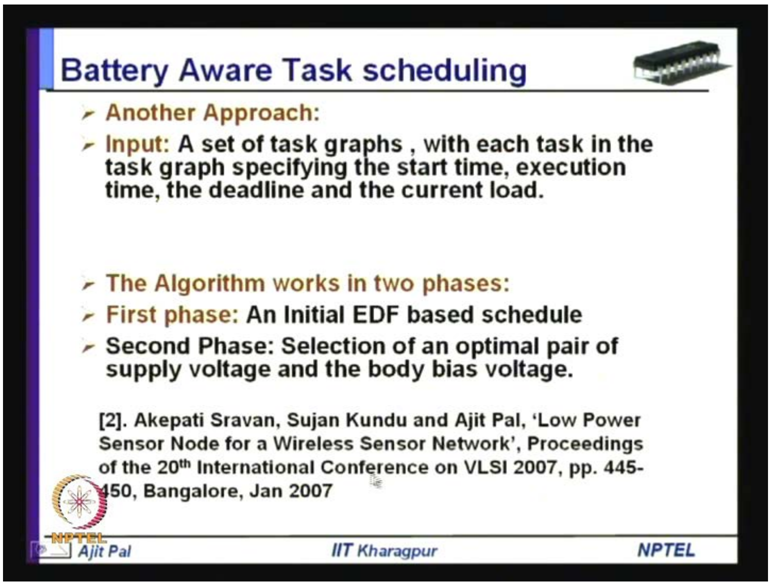

So, subsequently one some students work in this area, they developed another approach and here, a set of task graphs each with task. In the task graph specifying the start time, execution time, the deadline time and current load was provided and the algorithm work in two phases. And initial earliest deadline first based schedule is done and then in a second phase selection of an optimal pair of supply voltage and the body bias. So, in the previous paper what they did they use only dynamic voltage scaling. So, that it reduces only the dynamic it takes care of dynamic power. So, in this particular work not only dynamic power reduction, but leakage power has been taken into consideration so, reduction of, leakage power take place by using body bias.

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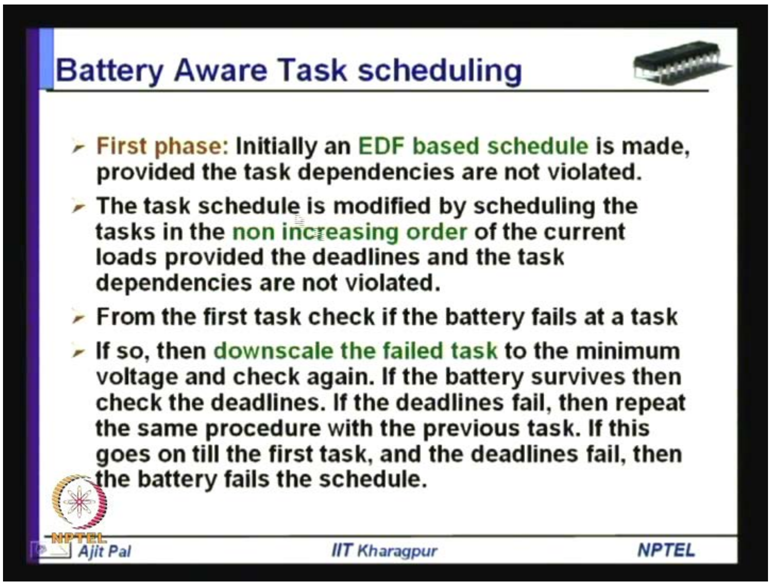

And the as I said there are in works in two phases, in the first phase initially earliest deadline first phase schedule is made, provided the task dependencies are not violated. Then a task schedule modified by scheduling the task in non increasing order as we have seen non increasing order gives you better result of the current loads provided the deadlines and the task dependencies are not violated. From the first task check, if the battery fails at a task.

Than some modification is done then they downscale the failed task to minimize voltage and check again, if the battery survives then check the deadlines, if the deadline fails then the repeat this same procedure with previous task, this goes on till the last task the deadline and the goes on till the last task and deadline fails then battery fails to schedule.

So, there are situations where battery will fail? But in situations where it does not fail? Will get a schedule and that schedule is used.

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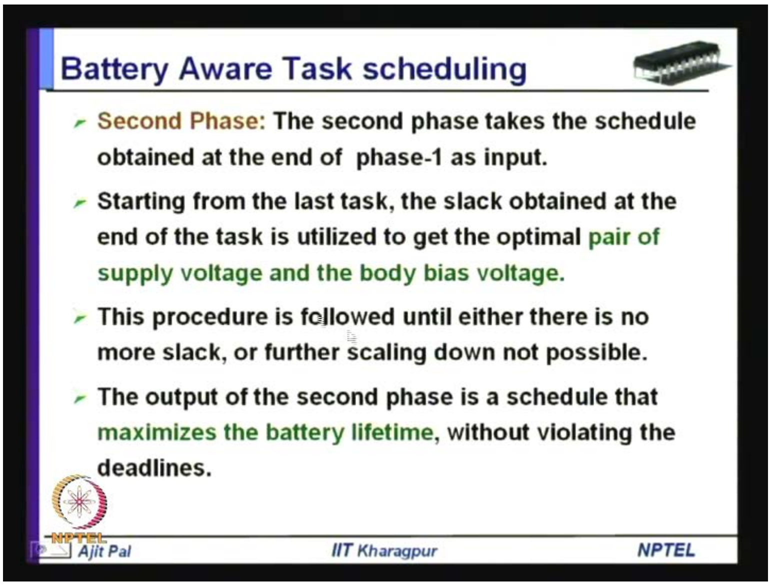

In the second phase, the second phase it takes the schedule obtained in the end of phase one as input. Starting from the last task so, here you are starting the last task. So, you have schedule task, one task, two task, three in the. So, you start with the last task and the slack obtained at the end of the task is utilized to get optimal pair of supply voltage and body bias; that means, slack is being used to do the scheduling to use I mean that supply.

Voltage scaling and body biasing they are combining done such that the reduction in power dissipation there is maximum reduction in power dissipation. So, minimum current is drawn from the battery. Then this procedure is followed until either there is no more slack, or for the scaling down is not possible. So, the output of the second phase is a schedule that maximizes the battery lifetime without violating the deadlines.

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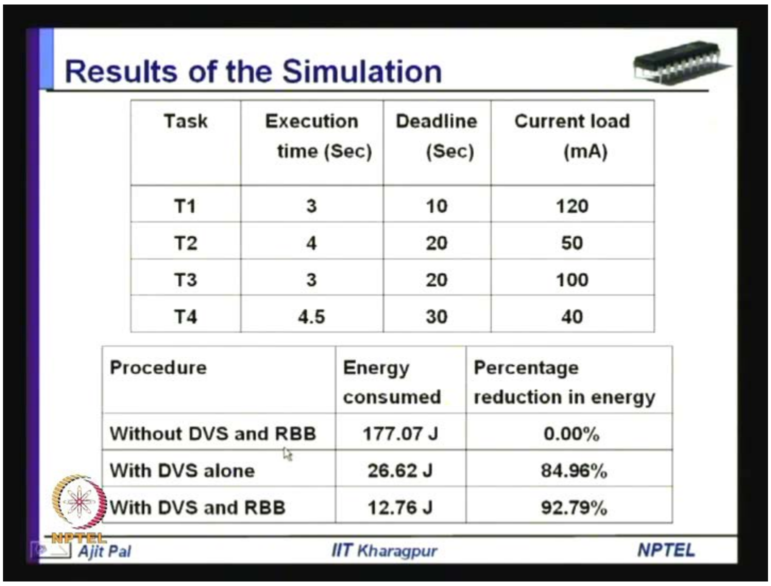

Results of the Simulation

Task	Execution time (Sec)	Deadline (Sec)	Current load (mA)
T1	3	10	120
T2	4	20	50
T3	3	20	100
T4	4.5	30	40

Procedure	Energy consumed	Percentage reduction in energy
Without DVS and RBB	177.07 J	0.00%
With DVS alone	26.62 J	84.96%
With DVS and RBB	12.76 J	92.79%

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So, here is some experimental result. So, these are the task these are the execution times various deadlines and these are the currents which is been drawn? So, schedules were done without dynamic voltage scaling and reverse body biasing. So, the energy consume is 177.07 joule and when only dynamic voltage scaling was used as in the first paper that has shown there is significant reduction you can see energy consumed is only 26.62. So, percentage reduction in energy 84.96, but whenever we use dynamic voltage scaling and reverse body biasing as it is done in the second paper. Then you can see the energy consumed is much less 12.76 and reduction in energy is 92.79 percent.

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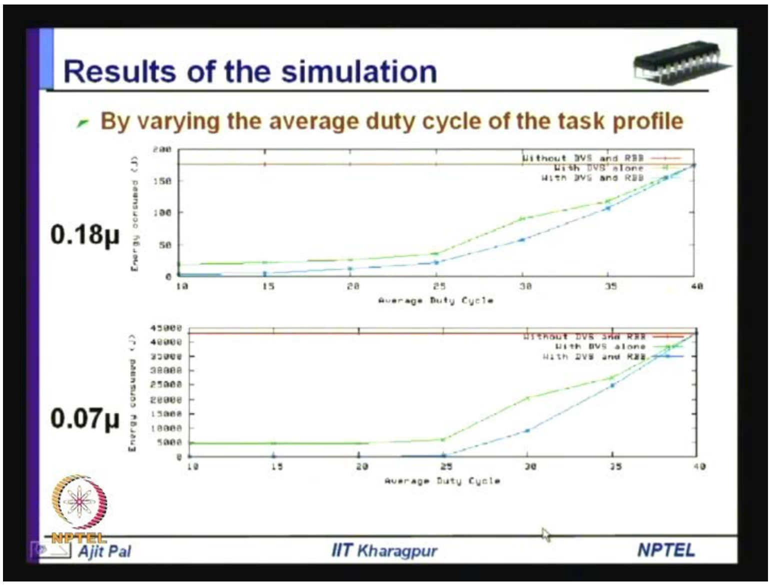

And moreover, there is some technology dependence as we know the leakage current increases or static power dissipation is more in smaller dimension technology. So, some experimentation was done by varying the average duty cycle of the task profile for two different technology generations. So, with using 0.18 micron technology the modeling was done. So, the first line the that red line on the top is without dynamic voltage scaling and without reverse body biasing. Then if you use reverse only dynamic voltage scaling you can see there is significant reduction in the energy consumed whenever the duty cycle is small.

So, duty cycle is 10 percent, 15 percent as the duty cycle increase; that means, the less and less ideal time is available. Then you can see the energy consumption reduces and when 40 percent duty cycle is there then it becomes I mean; that means, there is no ideal time when you can do dynamic voltage scaling? So, then energy consumption becomes same as without dynamic voltage scaling and reverse body biasing. And you can see with reverse body biasing there is a more reduction in energy.

And in case of 17 micron technology you can see the energy consumed is much more because leakage current is much higher. And there is substantial reduction by using reverse body biasing. With this dynamic voltage scaling that, green curve and the lower curve is using reverse body biasing. So, you can see with reverse body biasing the current consumption is very very small, energy requirement is very very small, upto 25 percent duty cycle. And as the duty cycle increases; that means, ideal time reduces then there is lesser scope for dynamic voltage scaling and reverse body biasing and energy consumption increases.

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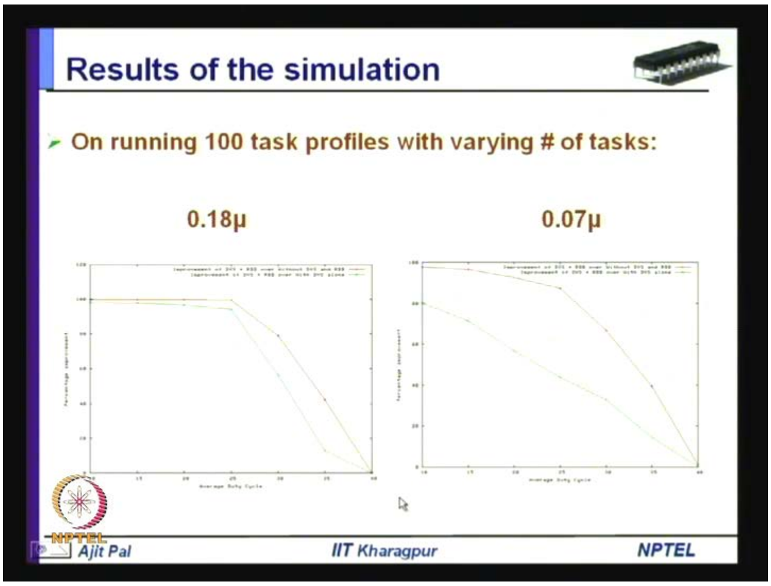

So, and actually on running hundred task profiles with varying (()) of task this is the result that we get. And the two curves for one is with this is percentage reduction with dynamic voltage scaling only and this is using dynamic voltage scaling and frequency scaling and with reverse body biasing. So, we find with 17 nanometer technology there is a big gap between when you use? Dynamic voltage scaling compared to when we when we use both reverse body biasing and dynamic voltage scaling.

So, from this we can conclude that, as the duty cycle increases the utilization increases the reduction in the energy consumption also decreases because of lesser available slack. And as the technology process, technology further gets lower the energy due to static power becomes significant and the algorithm using reverse body biasing becomes more efficient. So, with this we have come to the end of todays lecture. So, we have seen how we can take into consideration? The characteristics of the battery, to prolong the battery life or by increasing the actual capacity of the battery thank you.