The Seventh Cell of a Six-Cell Battery

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***Abstract*—Increasing the capacity of existing battery technologies could play an important role in today's mobile society. To improve the reliability and efficiency of modern portable power sources, it is critical to not only manage the hardware and software relying on the power, but also the discharging of the battery cells. In this work, we propose an alternate method, called autonomous battery clusters (ABC), of building batteries and new ways to manage the discharging of the individual power cell. Our three discharge management policies attempt to maximize the energy utilization of any devices that could be powered by Lithium Ion batteries. Experimental results showed an increment of up to 16.2% of the power delivered by battery cells in a heavily loaded situation, which would amount to a much longer running time of any device requiring mobile electric power source.**

***Index Terms*—Energy Efficiency; Energy Management; Battery Discharging**

I. Introduction

Mankind's natural inclination for mobility has always been a strong driver for social and scientific progress. Over the past decades, we have successfully gone through iterations of different kind of batteries, extending the operational life span and capacity of battery cells. Portable power cells today are easy to maintain, quick to charge and safe to use. The most familiar battery is lithium-ion battery, which has twice energy density of standard nickel-cadmium, and easy to maintain since there is no memory and low self-discharge [2]. Therefore, many applications use lithium-ion battery as their power supply, such as electrical vehicles, energy-efficient cargo ships and locomotives, aerospace [5][13][19]. Normally, the voltage of a lithium-ion battery cell is 2.8-3.7 V [2]. It could not offer enough power for electric devices, like laptop or radio-controlled model in cars, boats, planes, and even in helicopters. In order to get the required working voltage, we usually series/parallel connected the cells. As Figure 1 shows, the battery is composed of 8 cells, the total capacity is 50 ampere-hour, it can get 30 volts [3]. Usually the radio-controlled model is powered by 3-cell battery, and laptops' battery is 6-cell or 9-cell.

The number of the electric devices we use increases, so dose the requirement of battery's capacity and size. However, adding capacity to existing battery technologies comes with a significant trade-off: the more capacity a battery has, the larger the cell-size will be, which inevitably brings higher overall transportation cost. Therefore, every additional bit of capacity that could be safely and cheaply extracted from an existing cell is certainly an important contribution.

As we know the typical chemical battery creates a potential between the electrodes as a result of a chemical reaction within its body. If we look deeper into the reaction, we will notice a surprising phenomenon that the potentially useful capacity is not actually discharged, part of it is locked in the Lithium Ion cell [14]. As Figure 2 describes, the cell produces energy through an oxidation-reduction reaction which results in the transfer of electrons from the anode to the cathode. It causes a current through the circuits connected to the lithium ion cell. Lithium ions move from the cathode to the anode. They are consumed at the electrode surface and replenished by diffusion from the electrolyte. A crucial observation is that when the battery is under a heavy load, the diffusion process is not fast enough to compensate the consumption rate. The mismatch will eventually result in a build-up of a concentration gradient across the electrolyte. The higher the current is, the higher the build-up of the gradient and the lower the concentration of lithium ions at the electrode will be. Obviously, when ion concentration at the electrode surface drops, so does the battery voltage. The electrochemical reaction in lithium ion batteries can not continue if the voltage falls below a given limit, which results in loss of power from the cell. A certain amount of charged ions remain at the cathode, which is a potential energy that remains untapped. Through this discovery, we could

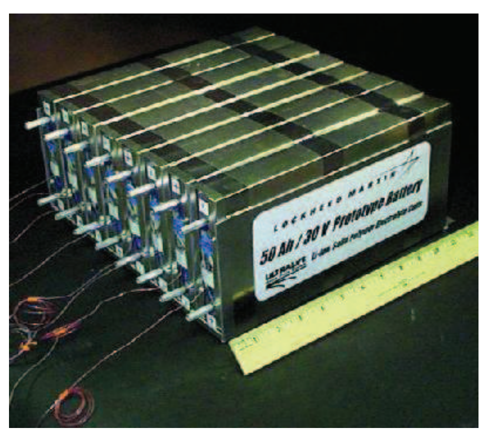


Fig. 1. Prototype lithium-ion 8 cells, 30 volts battery.

search for a method to unlock a hidden potential of the portable power container, "add" capacity to the system without actually increasing the weight and changing the physical construction. The physical gap between the electrode and the remaining ions is the reason for the appearance of total battery exhaust. Our goal is to find a way to resolve this chemical lock-up and provide a path for the ions to the electrode. Fortunately, if we can provide a sufficient rest period, the gradient will disappear, which allows the remaining capacity to be utilized.

Another reason for losing battery capacity is the cell balancing problem. We know that in order to satisfy the voltage requirement, we use series/parallel connected battery cells. Manufacturers try their best to put same cells in a battery pack, these cells have same state of charge, self-discharge rate, capacity and so on [6]. However, no two cells are identical even they are in the same production pool. The slight differences in these parameters will lead to a huge mismatch after using the battery for a certain time. Some of the cells become less capacity, when these cells hit the lowest voltage limitation, the system will shut down the whole battery for safety. Because good cells are not fully discharged, we lose total battery capacity [7]. The charging process is the same. These cells charged so fast that good ones could not reach their fully charged status. Since we treat the cells as an entirety, any cell could influence the battery's performance.

Currently, scientists and software developers have been able to extend the running time of a device per battery charge by either adding capacity to the power storage or decreasing the consumption[21]. In the first case, the weight of the device increased. In the second case, a variation of the software approach to increase battery life per charge is implemented by using software to supervise devices and cut down the unnecessary energy consumption[17]. Either of these cases requires the user of the battery-powered equipment to make a significant sacrifice. In this paper, we propose a new method of extracting more energy from existing battery technologies with minimal changes to the present hardware and the addition of a non-resource intensive software for battery monitoring and control. The proposed method can extend the running time of an electric device relying on Lithium Ion batteries with up to 16.2%.

In this paper we have two contributions:

- We propose Autonomous Battery Cluster (ABC) system, which could control cell groups and increase battery working time without complex modification of present hardware.
- In addition, we implement the system and three discharging policies. Multiple experiments prove that it can increase working time up to 16.2% under heavy workload.

In the following sections of this paper, we introduce the ABC System we designed, which could control the battery cells. And some corresponding policies to test the performance in Section II. The implementation of these policies and devices is addressed in Section III. Following that, we describe our experiments and evaluate them in Section IV. Related work and concluding remarks are described in Section V and Section VI respectively.

II. System Design

In this paper, we propose a method to deal with the problem of batteries holding back charge. Our approach allows a battery to be used to its fullest potential by giving each hard-working cell time to recover. Since a traditional Li-Ion battery consists of multiple 3.6 volt cells, we split them in parallel connected ABC. Each ABC only supplies a fraction of the total capacity, measured in mili-Amper hours (mAh). Since each ABC can power the device for a short time by itself, we choose to use one ABC at a time and give sufficient time for others ABCs to rest and recover from the previous load. Thus we create a system of alternating ABCs, which have the potential to increase the capacity of an existing system with up to 16.2% in our experimental setting.

The ABC system is a modified version of the existing Lithium Ion batteries on the market. Most portable electronic

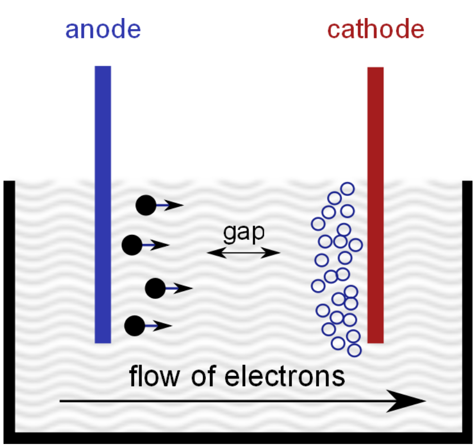


Fig. 2. The chemical reaction inside the battery.

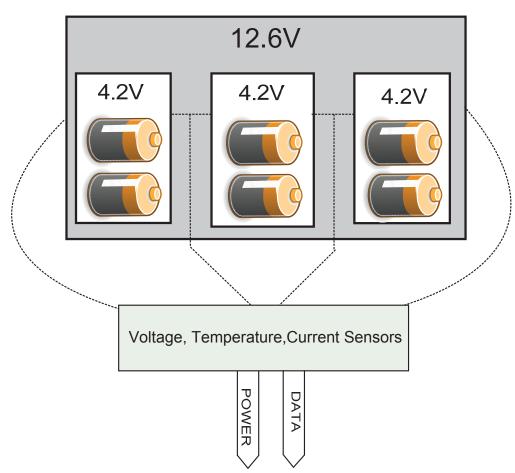


Fig. 3. The design of current laptop battery.

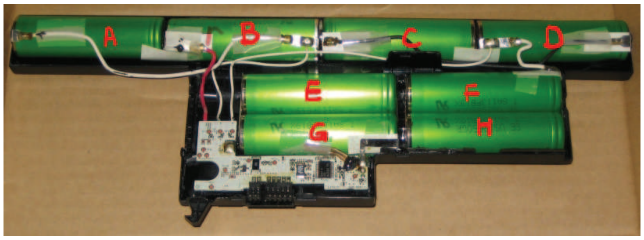


Fig. 4. Inside of the thinkpad 60 series battery.

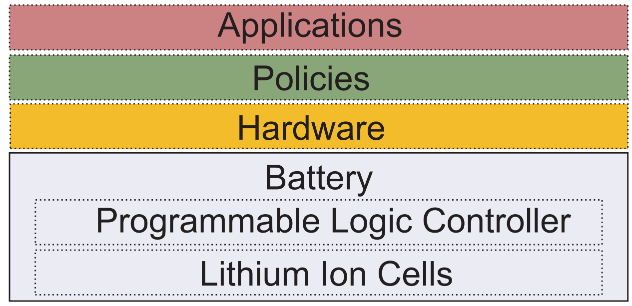


Fig. 5. The architecture of the ABC system.

devices use lithium ion cells connected in mixed parallel/serial manner to provide an amount of power overtime. Batteries' ability of providing a current for a given amount of time is calculated by summing up the capacity of each cell inside the entire unit. Figure 3 shows a traditional laptop battery , a typical 12 volt power source with 6 cells coupled in 3 groups. Each group consists of two 4.2V lithium-ion cells connected parallel, resulting in total voltage equal to the potential of the individual cells. On the other hand, the three couples are connected serially, which offers a total of 12.6 volts for the entire system. Existing batteries are capable of gathering data from the component cells, such as voltage, current and temperature. A microchip inside the enclosure of the battery system is able to control the charging of the system by turning it on or off. Figure 4 describes a 8 smaller cells battery for thinkpad T60 series, the voltage is 14.4 V. We can see that a temperature sensor is pasted on cell G. However, existing battery technologies do not have the ability to control the cells individually. Devices are limited to access statistical information of the battery, not even to mention the control over the power source. The ABC system has a duplex information channel, rather than the battery system simply reports data to the hardware, the information could also flow from the hardware to the battery.

A. Architecture

The ABC system modifies the traditional monolithic battery by including both hardware and software components within the enclosure of what is already available today. The intelligent battery model we propose is closely integrated with the operating system and allows the battery to make certain decisions based on the power dissipation of the hardware. As Figure 5 shows, we extend the mobile power storage system by adding a software layer and a monitor within the operating system. The goal of this addition is to gather statistical data and communicate it to the battery. Another piece of logic is added to the battery itself, which controls the ABCs by toggling relays. It turns on or off the charge/discharge of a certain cluster of lithium ion cells. This piece also collects data from the clusters, for example, the status of all cells, and reports these information to the operating system. The power management policies we introduce are based on the data gathered by the sensors within the battery.

B. The ABC system design

We build the ABC system on a widely accepted model of a basic portable device battery, which consists of cells arranged in series, parallel connected, or a combination of both. The exact configuration and layout depend on the specific voltage needed by the hardware and the available space within the device. The ABC system, as the name suggests, proposes a configuration that the same building units of lithium ion battery are split into clusters and connected in the appropriate way to achieve the desired voltage. The goal is to allow each cluster to independently power the hardware without the help of the other cells, that would allow some groups of cells to be off and rest for a while.

To clarify the approach, we reconfigure an existing 9-cell laptop battery. A typical modern laptop would require 12.6 volts for operation. A 9-cell lithium ion battery splits its cells in 3 groups, 3 cells in each group. Within each group, the cells are connected in parallel, the 3 groups however are in series, thus achieving overall 12.6 volts with 9 4.2V cells. As Figure 6 shows, in our design each cluster connects to the rest of the system via a relay. Fast-switching, low-voltage relays would be used to control whether certain ABC is discharging, charging or resting. It is also important to note that the relays we designed in the system must not only be very responsive, but also provide feedback. They must be able to signal to a programmable logic controller within the battery the information, for example, whether a switch operation was completed successfully. Each cluster, following the relay connection, is then connected to a common point, leading to the terminal of the entire power storage system. Another vital component is a voltage stabilizer, connected between the hardware and the summation of all ABC links. Because each cluster of lithium ion cells supplies lower and lower voltage as they discharge, one must ensure that the hardware is being supplied the correct and constant voltage. Moreover, changing voltage to sensitive digital components is detrimental to the entire system and thus the voltage stabilizer serves an important safety role. Then it comes to sensor part, in our design we connect voltage, current and temperature sensors to each cluster in order to monitor each group individually. That is necessary as these clusters would individually power the system on separate occasions, which would require separate information feeds. Furthermore,

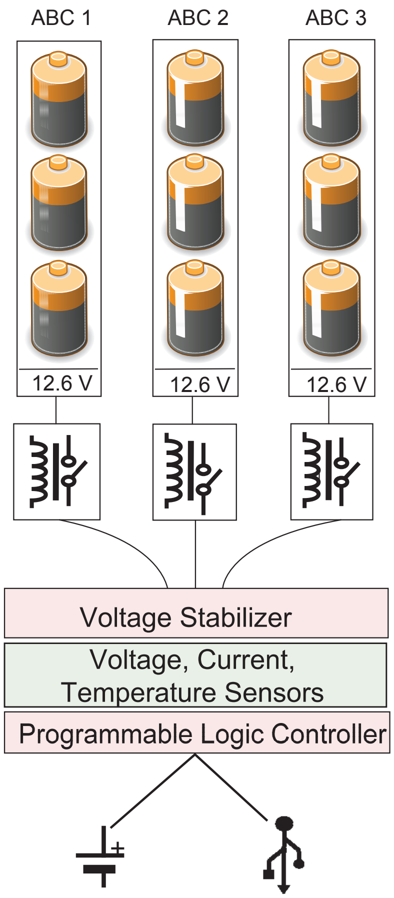


Fig. 6. The design of the ABC system.

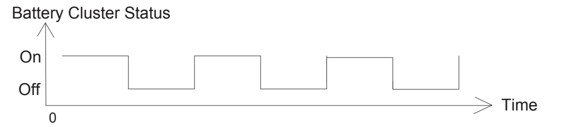
within some of the more complex policies it is possible to monitor the current and voltage of multiple groups at the same time. A programmable logic controller (PLC) is included to allow hardware abstraction of the battery system more easily access information. On the other hand, the controller within the enclosure would also collect information from the operating system.

Compared with the original battery design, we only add voltage stabilizer which output is 16V and PLC for safety and flexibility. They are not complicated devices, and do not cost too much. For sensor part, we add more sensors to each battery cell so that these cells could be monitored at the same time. Besides, the circuit inside the battery also can be used after we add sensors' information in it. Actually, the total cost of the battery does not increase too much, while at the same time we could gain more capacities. Moreover, it is a simple rearrangement for battery cells. Except the laptop battery, the approach could be easily applied to many other electric devices.

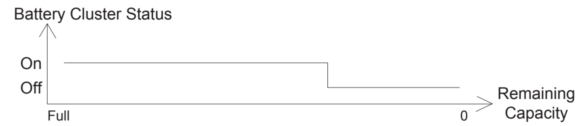
C. Controlling policies

We propose three control policies in the ABC system:

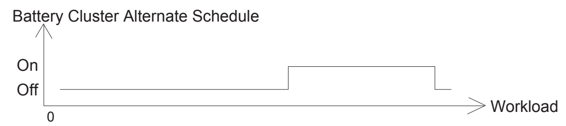
P1. Fixed time: We use $U_{(x,y)}$ to represent an instance of the policy, where *x* is the working time of a given cluster, and *y* signifies the rest time. In this policy, we discharge an ABC for *x* minutes, then we put it in the *rest* mode for *y* minutes, as showed in Figure 7(a). In the *rest* mode the cluster of lithium ion cells is neither discharging nor charging, there is 0 current floating through it. We calculate the total battery system operational time from fully charged to fully discharged.



(a) P1: Fixed time policy



(b) P2: Capacity-driven policy



(c) P3: Workload-driven policy

Fig. 7. The illustration for three policies.

P2. Capacity-driven: In this policy, we get the maximum result by monitoring the voltage of each ABC, which can determine the state of charge. The work time of a cluster is not extended to a constant value but to reach a minimum discharge value V_{min}. When ABC1 discharges to level V_{min}, we toggle to the next cluster ABC2. While ABC2 is powering the system, ABC1 is resting. The Figure 7(b) illustrates a situation that if a cluster could recover enough capacity to power the device, it will be turned on again. In the case of *n* clusters, we continue this round-robin power switching until neither one of them is able to power the device even after recovery. At this point we consider the entire battery system completely discharged.

P3. Workload-driven: Another way of managing the discharging of the batteries is through monitoring the workload of operating system, e.g., CPU utilization. Theoretically, if the computing workload is light or in normal level, we usually do not care about the time battery could last. In that situation, we use battery as usual and do not consider any alternate schedule for battery clusters. It could also cut down the extra cost of toggling the battery. However, when the workload is heavy, we could let battery alternate between discharge and rest to gain more capacity to power the device. In extreme high workload case, since ABC could just provide enough voltage not the current, itself make not work under high current case. So we choose to discharge all ABCs to offer enough current to power the device. In Figure 7(c), the *On*/*Off* represent whether we schedule the clusters, not the single cluster status.

III. Implementation

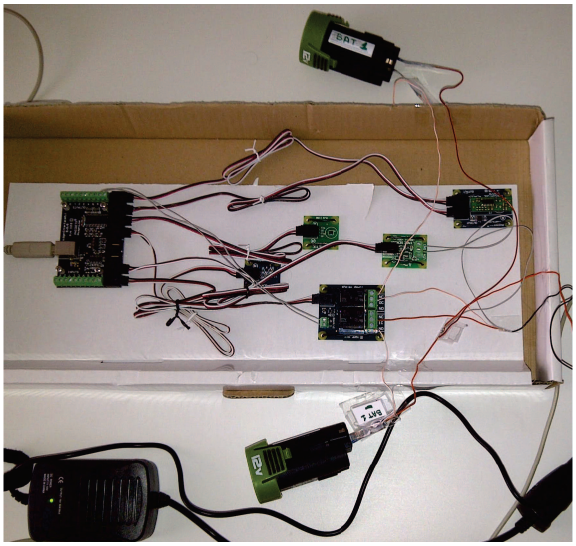


Fig. 8. An ABC prototype

To setup a prototype of the system, we use IBM Thinkpad T42 as the platform. In order to avoid errors in gathering the data, we use neither the internal battery, nor the AC adapter of the laptop. Instead, we use PowerSmith Maglithion MLAB12 12-Volt Lithium-Ion Battery Pack to power the laptop, and it uses the same lithium ion cells as a laptop battery does. Each 12-volt lithium ion battery we use contains 3 cells of 4.6V. As the description of the power-tool battery implies, the potential between the battery terminals is 12 volts, which is exactly what is required for IBM Thinkpad T42. We use 2 such power-tool battery packs, each independent one containing 3 cells. Then the total lithium ion cells are 6, which equal that of the internal battery. At the same time, each autonomous group can power the hardware separately or together. Parallel connected the 2 batteries as the Figure 8 shows, power flows go from the parallel connected ABCs, through the control relays, the voltage and current sensors, the voltage stabilizer and then reach the hardware. Except the battery pack, we also use following devices to implement the system: Generic voltage stabilizer for Thinkpad T42 (input 10V-14V, output 16V); Phidgets 8/8/8 controller to control the ABCs.

```
while (true)
{
    for ( i=1; i <= maxCluster; i++ )
  {
    \\ Ensure next ABC has charge
       if ( GetVoltage(i) > voltageThreshold )
          {
           SetClusterOn(i); \\turn on cluster i
             WaitUntilRelaySuccess(i);
             SetClusterOff(previousCluster);
             previousCluster = i;
       \\allow the cluster to discharge
             Wait(clusterWorkTime);
        }
       if ( AllClustersDischarged() )
             break; \\stop the infinite loop
  }
}
```

Listing 1. Round-robin loop through all clusters.

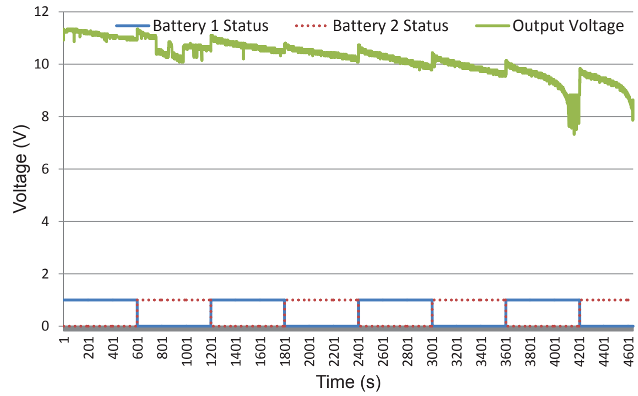


Fig. 9. Discharging ABC according to fixed time policy.

The software component of the ABC system is a simple script accessing the programmable logic controller and requesting the toggling of batteries. Listing 1 we implement a function called *switchToNextCluster( )*, which would turn on the relay of the next well-rested ABC, wait for the relay to switch and then turn off the working battery cluster. In order to keep the device be continuously powered, we'd better change to next battery cluster first, then turn off the current working cluster.

IV. Evaluation Results

We implement an ABC prototype and run multiple tests, through the results of experiments we know that each policy is proved efficient and appropriate for different configurations. For instance, while the fixed time policy may bring satisfactory results in medium load applied to the battery, the workload-driven policy provides best results in extreme situations where the hardware is drawing maximum power.

P1. Fixed time: Using a fixed time to alternate between the available battery clusters is the most basic method of optimizing the battery's performance. As described in Figure 9,

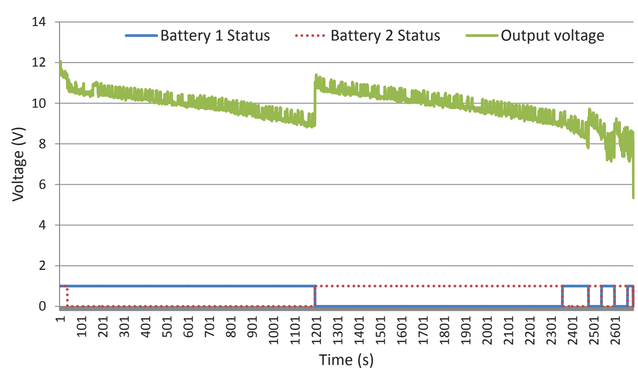


Fig. 10. Discharging ABC according to capacity-driven policy.

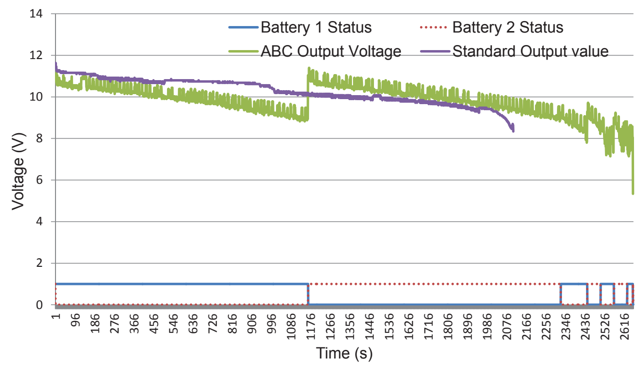


Fig. 11. The comparison of standard battery discharging and workload-driven discharging under maximum workload.

at the bottom of it, *1* represents the battery is working, while *0* represents the battery is resting. After every 10 minutes, the working battery is switched. In this experiment, the CPU usage is around 8% and the fully discharged time is near 75 minutes.

P2. Capacity-driven: We utilize an automatic voltmeter connected to the battery system to obtain current ABC's voltage, convert it to expected remaining capacity and make a decision on whether to switch to the next available cluster and allow the current one to rest. When we perform the experiments, we allow a full discharging of each ABC before shifting to the next available cluster. In order to avoid shutting down the system when all ABCs are discharged, we leverage the internal battery of the laptop as a safety fall-back. We use the API, thinkpad_smapi [4], provided by the manufacturer to monitor the internal battery. Our data gathering for this experiment concludes as soon as the internal battery switches from "idle" to "discharging". We can know from Figure 10 that after resting for a period, ABCs recovery an amount of capacity, even it does not afford to run much longer compared with its first discharging time. The fully discharging time is near 43 minutes, and the average CPU usage is 75%.

P3. Workload-driven: The main idea of the policy is to determine whether we start clusters schedule and how to alternate according to computer workload. First, we should find the relationship between workload and battery working time. So strictly speaking, these experiments are the preliminary work for implementing the workload-driven policy. We plan to explore more details in the future.

For each distinct experiment, we chose one of 3 power loads on the battery - minimum (around 0.5 Amperes), medium (2 Amperes) and maximum (4 Amperes). From computer's point of view, the workload is determined by the CPU utilization. The method we chose to put a maximum load on the system is a simple *tar* archiving of a Debian GNU/Linux DVD. This operation uses most components of the computer system: maximum CPU, hard drive, DVD-ROM drive, memory, etc. For medium load on the battery we use less intensive software functions, such as playing a multimedia file. For minimum load, we just use Internet to search information. The workload of the hardware we test is directly related to the power consumption from the battery system. After both battery clusters are fully charged we connect them to the laptop and start the software.

We consider batteries to be discharged until the voltage reaches a threshold, below which the voltage stabilizer is no longer able to provide constant power to the machine. As Figure 11 shows, the battery total working time increases about 6 minutes by using the ABC system. In standard battery discharging process, all ABCs are treated as a whole battery, so the experiments are done by discharging both of the ABCs. The summarized data in the Table I shows the comparison of using battery in a normal way and under workload-driven policy as we described above. It proves that the ABC system could provide tremendous increases in the efficiency of the existing lithium ion battery technology when under heavy load.

load	method	time (mins)	increase
4A	standard	37 mins	
4A	ABC	43 mins	+16.2%
2A	standard	70 mins	
2A	ABC	75 mins	+7%
0.5A	standard	96 mins	
0.5A	ABC	97 mins	+1%

TABLE I
THE COMPARISON OF TOTAL WORKING TIME UNDER DIFFERENT WORKLOAD.

V. RELATED WORK

The work done within the realm of this paper targets finding solutions to the challenges presented by the desire using electronic devices while away from power sources. We attempt to extend the life of a laptop battery per charge; besides, our research could also be extended to any devices that use batteries, from cell phones and mobile computers to power tools and even automobiles.

Our work based on existing researches related to power saving technologies in mobile hardware, one of them is widely adopted: battery management system, and the other is the scientific work done on extending battery life of network nodes by appropriate scheduling. In general, the usually has three main functions [1]: the safety of the battery; prolong the life of the battery; maintain the battery in a health state. Battery management systems are commonly used in mobile devices, most of which devote themselves to one specific aspect in order to improve the system's efficiency and accuracy. For instance, some systems calculate battery state of charge according to loaded terminal voltage [18], or perform a simple calculation on the current and time of charging of the battery [8]. In this case, it seems that the nonlinear battery effect is not considered, so the results are not always necessarily correct. It is important to underline that when it comes to discharging time, context-aware battery management systems calculate it by discharging speedup factor [16], then simulate the process and compare with actual data. The actual data is recorded as the base curve, we could see that after a specific value, the capacity would decrease sharply, that is also why in our policy we allow two batteries discharged together. In that way, we would make an attempt to warn the user ahead of time and offer as many capacities as we have to complete the work.

There are numerous sophisticated systems use microcontrollers to implement functions [9]. In our experiments, we use two groups of 3 cells battery to replace the internal battery/AC power. The data is gathered for these two groups and we treat them independently, which makes the policy much more flexible. From past work, we know that pulsed current discharge instead of a constant discharge can result in an improvement of battery performance [10], although it is for communication devices, which have interval time between sending and receiving data. We could let a cell rest during the discharge interval so that it could recover part of its capacity, and the total working time is increased. In some situations, the rest time for cells could not be set randomly, because it depends on the time of the end of one job and the arrival time of the next job [11].

We increase the battery working time by reconfiguration battery cells. Compared with other reconfiguration approaches, we think our idea is much easier to implement. In [15], the authors designed their smarter battery named IntellBatt. In order to get high performance, they applied rapid switch which could work under pico seconds. Besides, they considered the discharge cycle length to calculate the battery life. In our approach, we do not need so fast switch, and we calculate fewer parameters to keep the battery safe. Except we do some work in battery cell, [12] extends battery life by dynamically change the connection among cells. They model different cell connections: series, parallel and mixed, according to these data and system condition, they could dynamically adjust the circuit to meet the power requirement. The idea is good and understandable, but it might be difficult to implement and apply. The same idea appears in [20], but they focus on system load. When the load is not heavy, they could decrease the input voltage to make battery working longer. While in our approach, we also have workload policy, we do not need to change battery voltage according to that, it is a parameter for us to test the performance and set clusters working time. In conclusion, our idea is easy to implement and apply to many electric devices, and we can effectively extend the battery working time.

VI. Conclusions and Future Work

We implement the ABC system which could control individual cell group, and three polices to increase the battery working time. With the theory developed and the experiment performed this paper proves that modern batteries are capable of supplying higher capacity in certain situations without adding other cells. The extraction of an additional 16.2% capacity becomes possible at heavy power consumption.

The experiments on the ABC system are performed with a limited set of parameters; however, there are a lot of factors that could affect the battery behavior. Additional policies may be developed to encompass more control of particular factors of the battery system. While the adoption of batteries is far wider in daily life, great possibilities for research are available in the area of battery powered automobiles as these could charge and discharge within one continues usage time period, which is our ongoing work.

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