A First Experimental Investigation of the Practical Efficiency of Battery Scheduling

Damien Miliche, Thales, Innovation Research & Technology, Huizen, The Netherlands
Maurits de Graaf, Thales, Innovation Research & Technology, Huizen, The Netherlands
Gerard Hoekstra, Thales, Innovation Research & Technology, Huizen, The Netherlands
Marijn Jongerden, CTIT, University of Twente, Enschede, The Netherlands
Boudewijn Haverkort, CTIT, University of Twente, Enschede, The Netherlands
Embedded Systems Institute, Eindhoven, The Netherlands

Abstract

Nowadays, mobile devices are used more and more, and their battery lifetime is a key concern. In this paper, we concentrate on a method called *battery scheduling* with the aim to optimize the battery lifetime of mobile devices. This technique has already been largely theoretically studied in other papers. It consists, for systems containing multiple batteries, in switching the load from one battery to the other. Then, while following a given scheduling sequence, advantage can be taken from the recovery and rate capacity effects. However, little studies with experimental data of battery scheduling have been found. In this paper we describe a simple setup for measuring the possible gain of battery scheduling, and give some exploratory results for two types of real batteries: a smart Li-Ion battery used in the Thales personal communication system and a more commonly used NiCd battery. The results, so far, show that system lifetime extension is not systematic, and generally can only reach less then 10%.

1 Introduction

Most mobile devices rely on batteries for their power supply. While the battery capacity is finite, the system lifetime is limited by the battery lifetime. In this study, the battery lifetime is the time it takes to discharge the battery from full to empty. Recharging of the battery is not taken into account. Battery lifetime mostly depends on the battery capacity and on the level of the discharge current. However, another important influence is how the battery is used [1], i.e. the usage pattern. When a battery is continuously discharged at a high discharge current, it will provide less energy than when discharged at a lower current. This effect is termed the *rate capacity* effect. Another important effect is the *recovery effect*: during periods of low or no discharge, the battery can recover to a certain extend, and deliver more energy.

Influencing the usage pattern of a battery is hard in a single battery system. However, some devices allow the connection of multiple batteries. In these systems one can, instead of using the two batteries sequentially, switch between the batteries. In this way, one can easily influence the usage pattern of the batteries.

Battery scheduling can be done in many different ways, for example by choosing the battery that has the highest output voltage or by switching with a fixed frequency between the batteries. Some research has been done on finding the best way to schedule the batteries, for example [2, 3]. Besides comparing the system lifetimes obtained by several scheduling schemes, also research is being done on what the optimal scheduling scheme is, and what the maximum system lifetime is [4].

These studies show that a considerable gain can be made by using battery scheduling instead of discharging the batteries sequentially. However, this work is largely of a theoretical nature. The results are obtained using various types of battery *models* that describe the rate capacity and recovery effects. In this paper, we put the theory to the test. In a two-battery system one of the simple scheduling schemes is applied, and the battery lifetime is measured. The results show that some gain is reached, but that this gain is relatively low compared to the modeling results and not systematic. Moreover, a strong dependency on the parameters of the battery and the currents profile does exist.

The rest of the paper is structured as follow. Section 2 gives an overview of the main approaches taken in the literature to model battery scheduling. In Section 3 the scheduling experiments are described, and the results are given in Section 4. Finally, we conclude in Section 5.

2 Battery Scheduling

The scheduling of batteries has attracted quite some attention in the literature. The studies are mainly theoretical. Over the years various kinds of battery models have been developed [5]. Parts of these models have been used to study the problem of battery scheduling. We consider here the main approaches. The most important scheduling schemes that are studied are:

- Sequential scheduling: another battery is only picked when the previous one is empty.
- Round robin scheduling: at fixed moments in time another battery is used. The batteries are used in a fixed order.
- Pick-best scheduling: at fixed moments in time the status of all batteries is checked and the best battery is used. What is the best battery can be determined in several ways, for example the battery with the highest voltage, or the battery that has been used for the shortest period of time.

In [3], Benini et al. use an electrical-circuit model to describe the batteries. They consider sequential scheduling, round robin scheduling and various types of pick-best scheduling, where either the output voltage or the time that a battery has not been used determines which battery is to be scheduled. The different scheduling schemes are applied to several battery configurations containing up to four batteries. The loads that have been used are simple continuous and intermitted loads and two real-life example load profiles. Which scheduler performs best depends on the applied load. However, Benini et al. do show that for round robin scheduling, the system lifetime increases when the switching frequency is increased

In [2], Chiasserini and Rao use a discrete-time Markov battery model to compare three different scheduling schemes in a multiple battery system. In the model, the recovery of the battery is considered as a random process. Also, the workload is stochastic. Next to the commonly used round robin and pick-best scheduler, also a random scheduler is considered. The schedulers are compared for different job arrival rates. The results show that the best-of-two scheduler outperforms the other two. However, the complexity of the used models limits the analysis to cases with only small batteries.

In all this work the battery scheduling is limited to simple deterministic scheduling schemes. All show that battery scheduling gives longer system lifetime than when the batteries are used sequentially. However, they do not indicate whether longer lifetime could be possible by using even smarter scheduling. In [6], Sarkar and Adamou propose an algorithm for computing an optimal scheduling scheme based on the stochastic battery model of Chiasserini and Rao. To do this, they translate the problem to a stochastic shortest path problem. The optimal solution can only be computed for very small batteries. However, they do show that best-of-two scheduling performs close to optimal.

Another optimization approach is taken in [4]. Here, the batteries are modeled using priced-timed automata. With model checking techniques the schedule that gives the maximum lifetime is computed. The result is compared to the simple sequential, round robin and pick-best schedulers. Although the results show that the round robin and pick-best schedulers are sometimes far from optimal, these schedulers are much better than the sequential scheduler. The model actually shows that sequential scheduling results in the shortest lifetime possible.

All these studies show that by applying battery scheduling, the system lifetime will be extended. However, the improvement varies a lot between the different modeling approaches. Where Benini et al. predict an average improvement of approximately 11% for a two battery system, Chiasserini shows improvements of more than 100%.

Besides the theoretical studies, little practical work has been found. The only paper know to the authors is by Bruni et al.[7]. They apply a high frequency round robin schedule in a two Ni-Mh battery system. The measurements show that the lifetime improvement depends on the discharge current. It increases from 10 % at 600 mA to approximately 100 % at 3 A.

3 Experiments

Goal of the experiment

The theoretical results on battery scheduling are very promising in the literature. One may wonder if the battery lifetime can be extended significantly under practical circumstances.

The goal of the experimental setup is to verify whether we can improve the lifetime of real battery-operated equipment by applying scheduling over two identical batteries. To answer these questions, we have performed several experiments on two types of batteries.

Experimental setup

The batteries

The goal of the study is to find a way to improve the lifetime of the Thales personal communication system, called CIM (for *Communication and Information Module) or MOOVE* (*Mobiele Openbare Orde en Veiligheid Eenheid,* for *Mobile Public Order and Security Unit*). This system aims to centralize the data for a radio, a GPS, a display, and other devices constituting the useful equipment for any kind of urgent or dangerous interventions (police, fire fighters, army).

The system is powered by two independent batteries, which are the first type of batteries used in our experiments. These are based on the Li-Ion technology and characterized by a nominal capacity of 7 Ah under a nominal voltage of 14.4 V. Some electronics is added into the battery pack in order to make it *smart*, that is to say to control the charge and the discharge (so-called cell balancing) and to provide an I²C-like interface (SMBus) for the system.

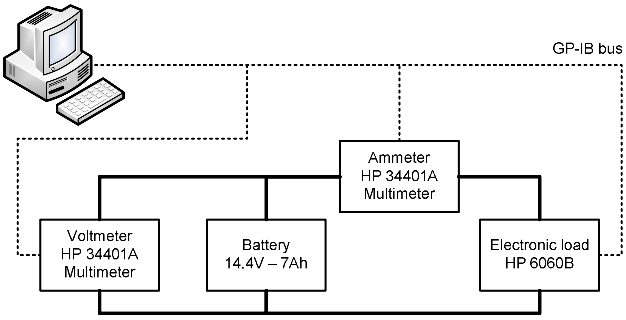

Figure 1 Measurement setup - Devices interconnection.

So far, a simple sequential discharging algorithm is used: the second battery is used only when the first one is completely discharged. The reason for this is mainly operational. It should be avoided that a personal communication system runs out of power with no backup battery available.

The second type of battery used for the experiments is a NiCd battery as is commonly used in remote controlled cars. These batteries are characterized by a nominal capacity of 1.6 Ah under a nominal voltage of 7.2 V.

For both cases, the same experimental setup is used. It is described in the following paragraphs.

The devices

The most important contribution of battery scheduling is supposed to be the extension of the lifetime, which is related to the capacity (in Ah), or the amount of charge, that the battery can deliver before getting empty, i.e. before the cut-off voltage is reached. So, in order to measure the effect of the scheduling it is necessary to measure the provided capacity. To do so, different devices are available, including the Amp-hour meter, the Watt-hour meter, or the Coulomb counter. For practical reasons, however, an indirect way has been chosen: the capacity is computed indirectly from the measurement of the current signal. Actually, the capacity is nothing else than the integration over time of the current intensity.

Figure 1 shows a schematic picture of the used circuit. The actual setup is illustrated in Figure 2. The devices that have been used are:

- an electronic load (model HP6060B) to draw a constant current from the battery ;
- a multimeter (model HP34401A) set as an Ampere meter and put in series in order to measure the current drawn precisely ;
- a second multimeter (model HP34401A) set as a Voltmeter and put in parallel in order to monitor that the battery voltage does not drop too low, which could damage the battery.

The devices are connected to a computer via a GP-IB bus. This allows us to get and log the measured values, but also to automatically configure the devices.

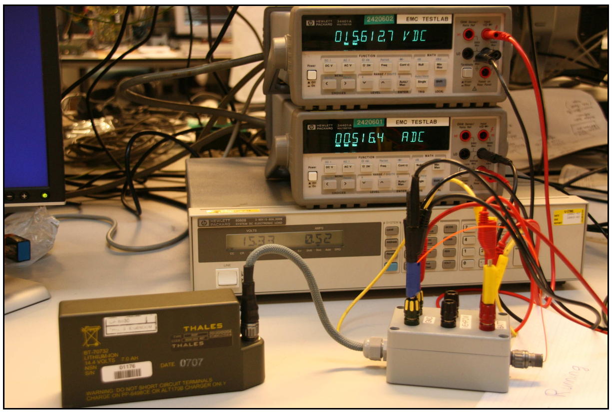

Figure 2 Measurement setup – The devices.

Discharge measurements

A simple C program is used to monitor and log the discharge process, looping until the battery is discharged (the cut-off voltage is reached).

The first series of measurements consists of discharging the battery with a constant current. During the experiment, the voltage and the current intensities are sampled with fixed intervals. In the end, we obtain the discharge time and can compute the provided capacity by numerical integration over the discharge time. This first series aims to give us a reference point (without scheduling) to which we can compare the results of the second series (with scheduling). It also illustrates the rate capacity effect.

In the second series of measurements, we simulate the scheduling using a single battery. The purpose is to observe the impact of scheduling, and not to implement a real scheduling system. The real implementation can indeed be relatively complex, requiring a circuit to manage the switching between the batteries, and an algorithm to determine the switching sequence. Instead, we just look at the behaviour of one battery in a two-battery system, where a battery is used half of the time. The scheduling algorithm we use is the round robin schedule. According to the theoretical results, cf. Section 2, without being the best algorithm, it can already provide significant extension of lifetime compared to sequential scheduling. The advantage of using the round robin scheduler is that it can be implemented quite easily. The alternating battery selection is simulated by turning on and off the electronic load.
Proceeding in the same way than for the first series, the provided capacity and the discharge time are computed.

The two measurement series can then be compared, and it is now possible to determine whether battery scheduling does improve the delivered capacity. We expect that the improvement is such that the discharge time of one battery using a scheduling algorithm is at least twice as long as the discharge time of the first series, or equivalently, that the capacity delivered by one battery increases if such an algorithm is used.

For the first type of battery (Li-Ion), attention has normally to be paid to the charge and the discharge process so that the battery does not get damaged. Fortunately, this is managed by the embedded electronics and an appropriate charger.

For the NiCd batteries, this kind of smart management is not used, neither within the battery pack, nor within the charger, and all the management has to be done manually. Moreover this kind of battery can suffer from a memory effect, if the charge-discharge cycles are not done completely. Indeed, due to crystallization of the electrodes, this effect causes the battery to deliver only the capacity used during the preceding repeated charge/discharge cycles.

The following assumptions over the full and empty states of the batteries have been considered during the tests.
The state-of-charge of the Li-Ion batteries is determined by the integrated electronics. When the battery is detected as empty, i.e. when the cutoff voltage of ~12V is reached, the battery cells are actually disconnected from the battery pack output. For the charging process, a smart charger is used, which communicates with the electronics of the battery pack, and stops the charging when the cells are determined as full.
For the less smart NiCd batteries, the empty state is said to be reached when the voltage drops below the cut-off voltage of 6 V. The full-charged state is considered to be reached when the battery is heating (due to chemical reaction at the end of the charging process), and when the voltage get stabilized around 8.8 V.

As was mentioned previously, two effects have to be taken into account when talking about batteries: the rate *capacity* effect and the *recovery* effect. The scheduling simulation can be performed by varying different parameters impacting on these effects. For our experiments, we worked with two most important ones. The first parameter is the level of the discharge current: as we have already seen, the larger the current, the larger the rate capacity effect. So, a high current drawn continuously can lead to a smaller delivered capacity than a small continuous current. The second parameter is the frequency of the scheduling/switching: the larger the switching period, the smaller the recovery effect. This parameter also responds to the rate capacity effect: if a large current is drawn, the switching may reduce the results of the rate capacity effect.

Given the rate capacity effect and the recovery effect, drawing a constant current has the worst impact on the battery lifetime.

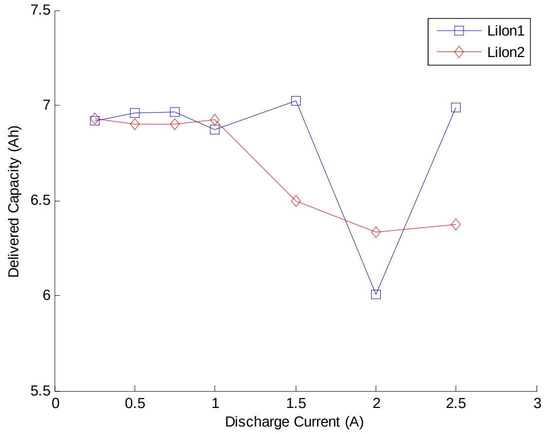

Figure 3 Rate capacity effect for the Li-Ion batteries.

4 Results

Using the experimental setup described above, the following measurements have been done.
For the smart Li-Ion battery type, the experiments have been done with two identical batteries. The batteries have been first discharged without scheduling using the constant current values of 250 mA, 500 mA, 750 mA, 1 A, 1.5 A, 2 A and 2.5 A. With scheduling the batteries are discharged using an intermitted load with fixed on and off periods that are either 0.5 or 5 seconds long. While the experiments are time-consuming, the discharge currents are a subset of the continuous currents: 500 mA, 1 A and 2 A.
Concerning the NiCd battery type, still for timing reasons, a reduced set of points has been considered: 500 mA, 1 A or 2 A, without scheduling and, with scheduling, the same only a switching periods of 0.5 and 5 seconds are used.
Two batteries of each type are used.

So far, the series of measurements is not large enough to be able to draw a definitive conclusion. More measurements points are necessary in order to distinguish the real mean points from the irregular and erratic measurements points. Nevertheless, we can already see a trend in the results.

Figure 3 and Figure 4, from the first series of measurements, aims to show the rate capacity effect. While this effect is not really obvious in Figure 3 for the Li-Ion batteries, it can be observed more clearly in Figure 4 for the NiCd battery, where the delivered capacity decreases with the current intensity.

An explanation of the distinctions in the results between the two types of battery can be found in the fact that the Li-Ion batteries are enriched with some electronics, making them *smart*, while the NiCd batteries are used without.
Another explanation can be the difference in their nominal capacity: the batteries may not react in the same way to the used discharge currents.

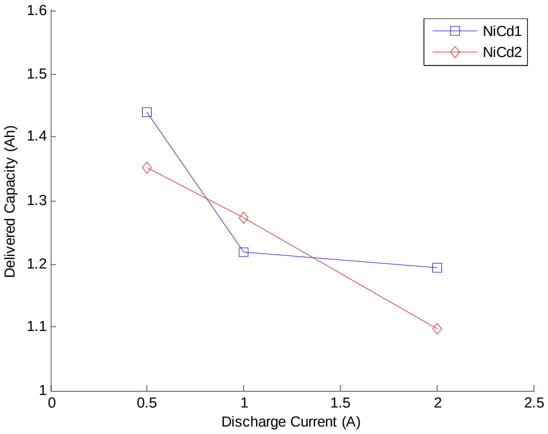

Figure 4 Rate capacity effect for the NiCd battery.

Table 1 shows the relative lifetime extension for both types of battery while using scheduling. Both scheduling periods of 0.5 and 5 seconds have been used for the NiCd battery and for the Li-Ion battery.

One can see, for the NiCd batteries, that the gain varies between -8.2% and +3.5% with the 0.5 seconds scheduling, and between -5.3% and +5.3% with the 5 seconds scheduling. For the Li-Ion batteries, the gain varies between -13.9% and +9% and between -15.9% and +21% respectively.

According to the literature ([3]), the smaller the switching period, the bigger the battery lifetime improvement should be. This is not seen in the experiments.

The results are not fully as expected. In the given set of experiments some anomalies were observed. Scheduling does not always improve the lifetime, and the gain does not have a monotonic relation with the current. The results obtained so far cannot be fully explained. One explanation can be found in the fact that the measurement process is not the most accurate in comparison with a real Amp-Hour meter. Furthermore, it is difficult to do the measurements in exactly the same conditions. The state of the battery before each discharge is hardly ever precisely the same, as the battery ages and thus its parameters vary.

For the *smart* Li-Ion batteries, we can find an other explanation for the unexpected results in the presence of some electronics inside the battery pack, which controls the cell balancing and thus the discharge of the batteries.

Nevertheless, more measurements points should be made in order to get better statistics in the results, canceling the measurement errors and the erratic points.

Battery	Disch. Curr. (A)	No sched.	0,5s sched.		5s sched.	
		Cap. (Ah)	Cap. (Ah)	Δ%	Cap. (Ah)	Δ%
NiCd1	0,5	1,440	1,470	2,1%	1,457	1,2%
	1	1,218	1,261	3,5%	1,283	5,3%
	2	1,193	1,095	-8,2%	1,164	-2,4%
NiCd2	0,5	1,352	1,451	7,3%	1,420	5,0%
	1	1,272	1,222	-3,9%	1,205	-5,3%
	2	1,098	1,114	1,5%	1,086	-1,1%
LiIon1	0,5	6,957	7,08	1,8%	7,184	3,3%
	1	6,874	6,418	-6,6%	6,649	-3,3%
	2	6,005	6,546	9,0%	7,265	21,0%
LiIon2	0,5	6,898	5,942	-13,9%	6,547	-5,1%
	1	6,922	6,003	-13,3%	5,824	-15,9%
	2	6,335	6,868	8,4%	5,927	-6,4%

Table 1 Capacity extension

5 Conclusions

Literature regards round robin scheduling as a promising way to improve the system lifetime for systems composed of multiple batteries. These studies are mainly based on theoretical battery models. We have developed an experimental setup to measure the gains for two real types of batteries: one as currently used in the Thales personal communication system, and one comparable set of batteries which are taken off the shelf. Despite our high expectations and the theoretical support, it appeared that the gain to be expected from round robin scheduling is rather unpredictable. The gain in lifetime, if any, is not as high as predicted by the various models, and not systematic. Concerning the Li-Ion batteries, this effect is probably strengthened due to the electronic circuitry in the batteries that control the discharging. However, so far, we are not able to confirm the results given in [3].

Waiting more promising results, we do not see any reason to change the battery system used in the Thales personal communication system for the moment, even more if it is uncertain whether any positive gain can be obtained at any time..

Based on the outcomes we have obtained so far, preliminary conclusions can already be drawn. However, further experiments are to be conducted to more firmly sustain our claims. Therefore, much more measurements points are needed to be able to distinguish the erratic measurements from the mean points. An other parameter to study further would be also the switching frequency. However to do this, the set-up needs to be changed, since the response time of the currently used devices prevents us from easily use higher frequencies..

6 Acknowledgements

This research was supported by the ITEA2 GEODES project 07013 (grant: PNEI081011).

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