IntellBatt: Towards Smarter Battery Design

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ABSTRACT

Battery lifetime and safety are primary concerns in the design of battery operated systems. Lifetime management is typically supervised by the system via battery-aware task scheduling, while safety is managed on the battery side via features deployed into smart batteries. This research proposes IntellBatt, an intelligent battery cell array based novel design of a multi-cell battery that offloads battery lifetime management onto the battery. By deploying a battery cell array management unit, IntellBatt exploits various battery related characteristics such as charge recovery effect, to enhance battery lifetime and ensure safe operation. This is achieved by using real-time cell status information to selects cells to deliver the required load current, without the involvement of a complex task scheduler on the host system. The proposed design was evaluated via simulation using accurate cell models and real experimental traces from a portable DVD player. The use of a multi-cell design enhanced battery lifetime by 22% in terms of battery discharge time. Besides a standalone deployment, IntellBatt can also be combined with existing battery-aware task scheduling approaches to further enhance battery lifetime.

Categories and Subject Descriptors

B.8.0 [**Performance and Reliability - General**]: Embedded System performance, Reliability in terms of active life

General Terms

Management, Performance, Design, Reliability

Keywords

Smart battery, battery management, intelligent battery scheduling

1. INTRODUCTION

The predominance of battery-operated, wireless handheld devices motivates the efficient and robust use of the limited energy supply. Managing battery life and safety of the system is a critical design constraint. Traditional approaches utilize battery-aware task scheduling to ensure maximal utilization of battery, while considering discharge/recharge characteristics [1-3]. Smart batteries to manage safety of battery packs have been deployed to manage concerns due to high temperature, over-discharge and overcharge [4].

An alternative to these traditional approaches would involve deploying a smarter battery into the system. This intelligent battery would manage the discharge/recharge of the cells while ensuring battery life. Battery safety is also managed to ensure robustness. This research proposes **IntellBatt**, an *intelligent battery cell array* (BCA) novel design. This design utilizes multiple cells and is managed by a management unit that ensures battery life and safety. Using a BCA organization provides the following benefits: (1) close monitoring of cell status, (2) dynamic selection of cells to match the device requirement, reducing loss in DC/DC converters or similar regulators, (3) exploit charge recovery effect in cells, thereby giving advantages over monolithic batteries, and (4) provides the possibility of preprogramming the discharge pattern if the current profile is stable and known a priori. IntellBatt assumes no knowledge of the device as such. IntellBatt can operate in either a standalone fashion or be combined with battery-aware task scheduling techniques. Experimental results presented in this research demonstrate the observed improvement.

The main contributions of this research are as follows:

- *Design of* IntellBatt*: A novel intelligent battery cell array design that consists of multiple cells and a management unit*
- *Simple cell selection algorithm that can provide functionalities like cell selection, monitoring and scheduling previously not considered.*
- *Demonstration of the proposed design via simulation using available accurate battery models and typical application traces.*
- *Further enhancement of battery life by combining its operation with battery-aware task scheduling approaches.*

The remainder of the paper is organized as follows. Section 2 describes related research. Section 3 presents IntellBatt, its design, technology and behavior. Section 4 describes the evaluation of IntellBatt and demonstrates its effectiveness. Section 5 concludes the paper and presents possible future directions.

2. RELATED WORK

2.1 Battery-aware task scheduling

In battery limited systems, to ensure that battery lifetimes are considered during system operation, tasks are scheduled while considering battery charge/discharge patterns. [1-3] present task scheduling using battery model information. These techniques mainly attempt to tailor the current profile of the device to match

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[1]This was completed while the author was at Texas A&M University.

the optimum discharge rate of the battery. Battery pack scheduling on the system side has been explored in [5]. To contrast these system-side battery management techniques, this research proposes the deployment of smarter batteries to self-manage lifetime.

2.2 Other 'Smart' Batteries

State of the art smart batteries have safety circuits that cut off the battery in case of high temperature, overcharge and over-discharge. They provide safety features while lacking the capability of scheduling cells. Additionally, they monitor voltage levels of the cells as a whole and not at the individual cell level. This lack of precision forces stricter voltage cut off thresholds. This prevents utilization of available energy towards the end of charge cycle and can be critical in mobile applications. Asumadu et al. proposed a similar battery management system [4]. But their design lacked the cell scheduling capability and hence does not optimize the discharge and recovery effect.

2.3 Cell Model

In a simulation environment, the cell model is used to mimic the behavior of a real cell. There are three types of cell models in research literature; electrochemical, stochastic and analytical models. Electrochemical models are the most accurate and complex. Doyle et al. [6] presented an electrochemical model of Lithium cell which is by far the most accurate available model [7, 8]. Though this is the most accurate cell model available, it is limited by its speed. Benini et al. proposed a discrete time battery model for fast computation and quick estimation of battery lifetime [9]. More recently, Chen and Mora proposed a simpler model for Lithium Polymer cells [10]. This model can estimate the cell voltage with an error in accuracy of less than 0.4%.

In the following sections, we describe the IntellBatt structure and operation and evaluate its performance.

3. INTELLBATT

In designing a smarter battery, this research proposes to offload the battery management responsibility from the host system onto the battery. Battery Cell Array management is essential during both the discharging and charging. This research only focuses on the enhancement of discharge management. The key responsibilities during both stages are the management of battery life and safety of the BCA. To achieve the desired functionality, IntellBatt is composed of three components: (i) *cells*, (ii) *cell switching circuit* and (iii) *battery cell array manager*. Details regarding their function and operation are presented later in this section.

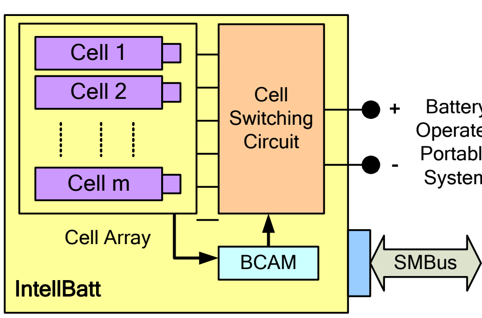

Figure 1: IntellBatt Architecture

3.1 Battery Cell Array Structure

As stated earlier, the Battery Cell Array consists of three components. Figure 1 illustrates the envisioned system. The cells in IntellBatt are organized into banks of cells that are connected to the main terminals of the IntellBatt via a Cell Switching Circuit. The Battery Cell Array Manager (BCAM) manages the cells and determines their interconnection based on the required system load current. The SMBus interface [11] between IntellBatt and the system will provide for information exchange between the two entities. For simplicity the SMBus implementation is ignored for the purpose of this research. The following sub-sections details the structure and operation of the BCA components.

3.1.1 IntellBatt Cells

The cells are organized as a collection of banks which are connected in series. Inside each bank there can be one or more cells connected in parallel to provide the required current from a selected bank. If the device has a rated voltage requirement V and each cell has voltage v, then the number of banks required is V/v. For applications like laptop computers, with standard V=10.8V~11.1V and standard Li cells with v=3.6V~3.7V [12], we require 3 banks. For smaller devices like portable DVD player or wireless media players with V=7.2V~7.4V the number of banks is typically 2. Typical battery packs uses 3 to 12 cells organized in a series/parallel combination as required. These cells provide the required load current for the target battery operated system via the cell switching circuit.

3.1.2 Cell Switching Circuit (CSC)

The CSC connects cells to deliver the required current to the system it is connected to. CSC configuration is set by the BCAM via a codeword.

The CSC has to be designed to ensure the following:

1. Connect cells in banks, specified via a codeword from the BCAM, to the output terminals of IntellBatt,
2. Rapid switch reconfiguration (order of pico seconds).
3. Support the current drawn by the system without incurring significant losses in the switch.

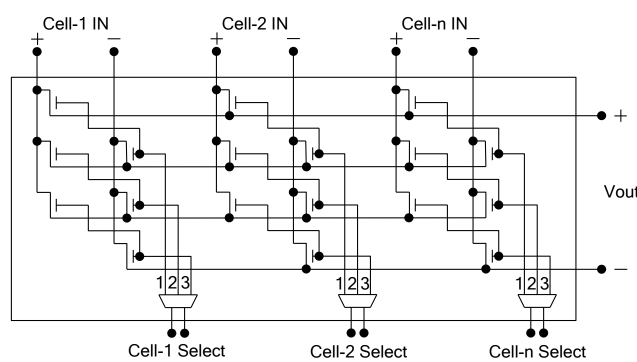

Figure 2: Cell Switching Circuit Design

Figure 2 provides an insight into the CSC design. It has two main components, the *switch matrix* and the *decoder array*. For a design with **k** banks of cells, the switch matrix connects a cell to one of **k** banks based on the configuration bits for each cell. The decoder array activates the switches in the switch matrix based on the codeword issued by the BCAM.

Table 1 gives the detailed specification of the CSC designed for a **n** cell and **k** bank design. The design complexity of CSC switch matrix is linear in terms of the number of cells and banks, with performance limited by the decoder array.

Table 1: Cell Switching Circuit Parameters

Parameter	General Value	Experimental Setup
Cells	n	12
Banks	k	3
Control Word Length	$n * \lceil \log_2 k \rceil$	24 bits
Ports	$2n + n * \lceil \log_2 k \rceil + 2$	50
Current Capacity	Technology dependent	319mA
Power Consumption	Scales with active switches	8 mW
Switching Delay	Depends on k	92 ps

CSC being the component that carries the system load will consume power. However, from the chosen experimental design, the power consumption is only about 0.15% of the typical device power consumption.

3.1.3 Battery Cell Array Manager (BCAM)

Battery Cell Array Manager (BCAM) is the core of the IntellBatt system. It provides the following functionalities: (1) monitor cell status, (2) schedule cells for load current delivery and (3) ensure safety of the BCA.

3.1.3.1 Monitoring

The monitoring logic in BCAM keeps track of the following parameter for each cell: Voltage, Current and Temperature. These values are used to ensure safety and to make scheduling decision. There are available high speed and ultra low power sensing circuits [13, 14] so it does not increase the load on IntellBatt.

3.1.3.2 Cell Scheduling

The main responsibility of BCAM is to schedule the cells for discharge to optimize performance while ensuring safe operation. Additionally, two aspects of rechargeable cells need to be considered during scheduling: *Discharge Cycle Length* and *Battery Life*. *Discharge Cycle Length* refers to the duration for which the fully charged cell can deliver the required current. This is important for handheld and portable devices, because the ability to run longer in a single charge cycle is desirable. *Battery Life* refers to the number of discharge cycles achievable before the battery becomes unusable. This is also a desired feature and more important when the battery is mainly used as a backup power source. In such situations, it may not be necessary to have a long discharge cycle but rather have an increased number of cycles as it directly affects cost of ownership for the device.

The main properties of Lithium Ion cells that affects the lifetime and performance of the cell are: *Rate of discharge* or *discharge current*, *discharge condition* such as temperature, *variation in the rate of discharge* and *charge recovery effect*. Discharge rate of discharge current has a high impact on the cell discharge cycle length [12]. In general the higher the discharge rate the lower the charge delivery capability of the cell. The optimum discharge current is a property of the cell composition. Since the cell discharge is an electrochemical process it is affected by environmental conditions like temperature. Higher temperature (> 45 degrees C) or lower temperature (<10 degree C) have been found to reduce the capacity of the cell [12]. Battery discharge is a complex electrochemical process. If the discharge reaction is slower than the optimum rate (dependent on cell geometry), it results in substance buildup which can clear if the cell is idle for a while. This becomes beneficial when the cells are alternately scheduled. Each cell gets time to recover charge.

The aforementioned BCAM objectives and cell limiting properties aid in formulating the *Cell Selection Problem* as:

Given I_t, the load current, and v_i for each cell, determine the best configuration of cells that meets the following criteria,

i. For each cell k, $I_k < I_k^{\max}$
ii. For each cell k, $v_k > v_k^{cutoff}$
iii. There is at least one cell in each bank (refer to cell organization)

I^{max} is the safe limiting current that can be drawn from the cell safely, i.e. not causing a short circuit. V^{cutoff} is the discharge limit beyond which the cell should not be discharged, failing to do so may lead to adverse reaction in cell that can lead to safety hazard. At least one cell in the block is necessary to maintain the output voltage level. If there are **n** available cells and **k** banks, the problem can be formulated as the determination of a subset of all possible k clusters. The total possible solutions without the constraints is O($C_k^n * n^k$). To limit search time in the large solution space, we use a heuristic-based algorithm to solve problem.

```
Algorithm Cell Select:
Input: Load Current, Individual Cell States
Output: for each cell i a block assignment bi or 0 for idle
Initialize: for all i, bi = 0 ;
Begin
1.  sort cells by voltage ;
2.  for each block assign one cell in descending order
3.  for all blocks with cell voltage < low threshold
    3a. while safe cells left, add cells to match capacity in
        ascending order
4.  check all blocks for assignment
    4a. if incomplete, return failure
    4b. else finish
End
```

The frequency of the cell selection process will be governed by the chosen *scheduling scheme*. Two different scheduling schemes are possible: 1. Periodic and 2 Adaptive. In *Periodic Scheduling,* the cell selection operation is performed periodically independent of the change in state since last selection operation. While in the *Adaptive Scheduling*, the cell selection operation is performed after an interval **T,** which is a function of change in the configuration during the current cell select operation. Besides providing the system with the required load current, the BCAM also ensures the safe operation of the BCA.

3.1.3.3 Safety

The safety logic in BCAM prevents the battery cell array from entering hazardous condition like over-discharge, overcharge and high temperature. *Over-discharge* is a well known problem of Li Ion cells [15]. It refers to the phenomena of cell reversal below a certain cell voltage. Such situations can give rise to gas formation in the electrodes and pressure build up in the cell. This may lead to explosion in the cell including ignition of the cell composites. *Overcharge* of the cell beyond a certain voltage, leads to irreversible reactions in the electrodes which decrease the cells capacity and also generates heat due to increased resistance. Lithium is highly active material and can burn spontaneously. *Increased temperature* in the cell can therefore lead to burnout and/or explosion. And such an occurrence in one cells start a chain reaction and can be hazardous to health and property. Also, high current while discharge/charge, short circuit, freezing condition can cause safety concerns.

To handle these issues, BCAM continuously monitors the cell parameters like voltage level, temperature and current. BCAM schedules the cells to keep current within allowable limits. If the battery temperature rises above a threshold the battery operation is suspended and all cells are disconnected from the supply. Ideally this information is needed to be sent via the SMBus interface to make the device aware of the situation so that it can prepare for the imminent power down. BCAM having information about individual cells and the ability to disconnect every cell independently can keep providing power to the device even when one cell is about to be over-discharged. This is not possible with the traditional smart battery system.

Short circuit safety concerns present in traditional battery packs, also need to be considered in IntellBatt. These may be of three types: *Transient*, *permanent* and *external*. Transient short circuits can arise during the cell selection process of the BCAM. If a cell is assigned to one bank during a scheduling interval and is reallocated into an adjacent bank over the next scheduling interval, the terminals of the cell may be shorted. However, this can be avoided by detecting such allocations and preventing such cell configurations via the codeword set by the BCAM. Permanent short circuits occur due to physical failures in the CSC. To prevent hazardous situations due to this, safety fuses can be added to each cell. External shorts due to improper IntellBatt usage can be detected by the current sensor and can be handled with a cutoff issued by the BCAM.

4. INTELLBATT EVALUATION

4.1 Experimental Setup

To evaluate IntellBatt, a simulation based experimental setup was developed. A portable DVD player was selected to provide a typical application load current profile which would be supported by the proposed IntellBatt design. The following sub-sections discuss various aspects of the simulation environment.

4.1.1 Current Profiling

IntellBatt assumes no knowledge of the device as such. It optimizes cell utilization based entirely on knowledge of cell states and the load current. So it is necessary to obtain a realistic current drain profile using a real device for proper evaluation of the effectiveness of IntellBatt. The current profile used in the IntellBatt evaluation was obtained using the experimental setup illustrated in Figure 3. Here the device is the battery operated device – a portable DVD player - and the battery is the battery powering the device. The device current is redirected through a low resistance shunt and the voltage across the shunt is measured using a National Instruments data acquisition device [16]. The software control in the host computer tracing the current profile, samples the current at 1 second interval until the battery is exhausted. The resultant current profile will be a step approximation for the chosen application. A 1 second step interval is sufficiently fine grained considering the slow response of the batteries [17]. Figure 4 illustrates the obtained the current profile, while Table 2 summarizes the experimental details for the current profiling.

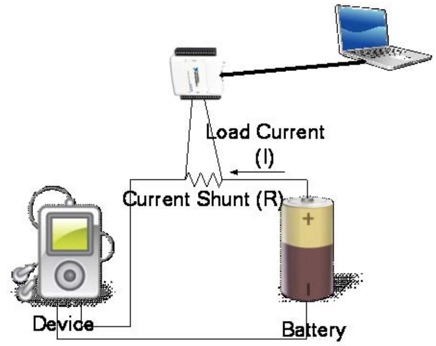

Figure 3: Current Profiling Setup

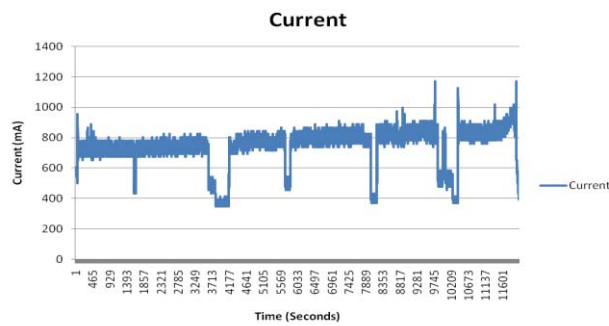

Figure 4: Current Profile of a Portable DVD Player

Table 2: Details of Current Profiling Experiment

Parameter	**Value**
Shunt	0.47 ohm
Supply	7.4 Volts
Device	Portable DVD Player
Battery Capacity	2500 mAh

4.1.2 IntellBatt Simulation

The IntellBatt architecture is modeled using SystemC [18] with the current and voltage sensors replaced by equivalent modules and cells are replaced by the Chen and Mora analytical cell model [10]. For the purpose of this research we did not model the heat

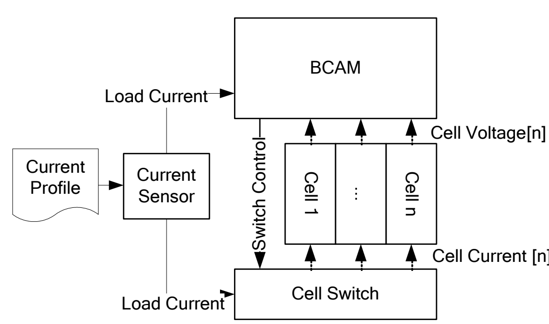

Figure 5: IntellBatt Simulator Architecture

generation by the cell discharge, though the design will include safety mechanism to prevent damage due to heat.

The components of the IntellBatt Simulator are similar to the architecture shown in Figure 1. The different modules are: (i) **BCAM:** BCAM is the main module that simulates the cell scheduling and safety algorithms. (ii) **Current Sensor**: This module feeds the recorded current profile to the BCAM and behaves like an ADC (analog to digital converter) measuring the current. (iii) **Cell Switch**: This module unlike actual cell switching circuit, does not really simulate a switch. It instead computes the current through each cell based on the codeword configuration input by the BCAM. These currents are used to update current usage in the appropriate cell modules in the design. (iv) **Cell**: Each Cell module within itself simulates a lithium Ion cell using model proposed by Chen and Mora [10] combined with charge recovery model proposed in [19]. This computes the current cell voltage and writes it to the BCAM hence mimicking the behavior of a real cell with voltage sensors.

4.2 Evaluation Results

Using the load current trace from a portable DVD player in the IntellBatt simulation environment experiments were performed for evaluation:

1. Justification for the use of multi-cell batteries,
2. Battery pack performance comparison against traditional battery-aware task scheduling approaches,
3. Effect of cell scheduling scheme on IntellBatt operation,
4. Determination of suitable cell scheduling interval for IntellBatt.

4.2.1 Multi-cell battery justification

In this experiment the number of cells in the battery pack was increased without changing the total capacity. This was performed to establish the benefit of having a number of cells scheduled effectively rather than using a monolithic high capacity cell. The use of smaller capacity cell impacts safety [17] and is easier to manufacture. A pack of multiple batteries benefits from the recovery effect and can be observed in Figure 6.

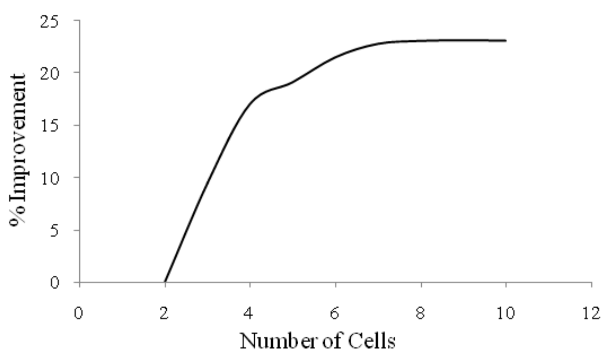

Figure 6: Improvement in Cycle Time

In a scenario of constant load current, the benefit of adding additional cells into a multi-cell battery - to exploit charge recovery effect – saturates at 22%. The additional idle periods provided by the addition of cells begin to plateau after 7 cells.

4.2.2 Battery-aware Task Scheduling comparison

An objective in the design of IntellBatt was the offloading of battery management responsibilities from the system to the smarter battery. Battery-aware task scheduling (BATS) approaches tailor the application current profile to battery characteristics to enhance battery life. On the other hand, IntellBatt manages the cell scheduling within the battery cell array to maximize battery life. These two techniques can either be used independently or can be combined together for further performance improvement.

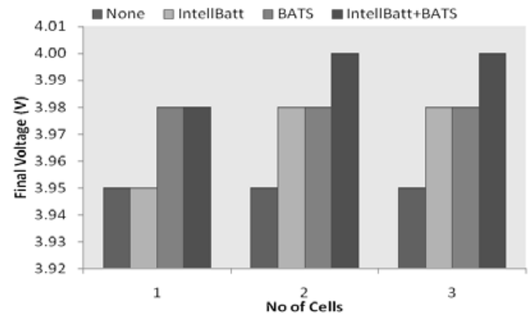

Figure 7: Comparison with BATS

For this comparison, a BATS algorithm proposed in [2] was used. The experiment determined the final voltage available in the battery. Figure 7 compares the performance in the cases of no battery management, standalone BATS, standalone IntellBatt and BATS+IntellBatt, In the case of a single cell battery, BATS outperforms IntellBatt since there is no scope of cell scheduling, while in other cases, it performs just as well. When combined, IntellBatt compensates for scenarios when BATS is unable to tailor application current traces for battery life maximization.

4.2.3 Effect of Cell Scheduling Scheme

To highlight the benefits of cell scheduling, an experiment with different schemes was performed on a particular battery configuration of 2-10 cells. This experiment compared a *serial scheduling* algorithm, that drains each cell at a time, and dynamic *scheduling* algorithm that is strictly periodic with a period of 100 seconds. The dynamic approach is better than serial scheduling since it allows for charge recovery effect, as indicated in Figure 8.

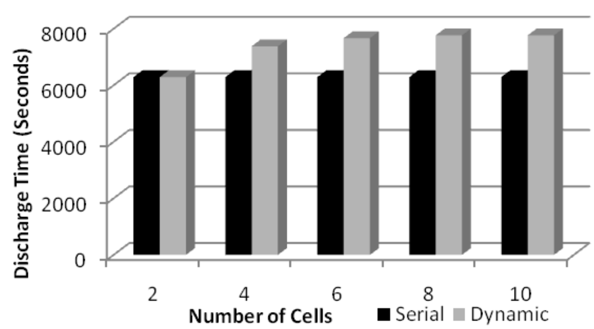

Figure 8: Comparison of Static and Dynamic Scheduling

4.2.4 Determination of Scheduling Frequency

This experiment was performed using dynamic scheduling with varied default period setting. The objective was to determine the effect of idle period length on charge recovery and hence the discharge cycle time. If cell scheduling is too frequent or infrequent, it does not allow charge recovery effect to improve battery performance. Figure 9 demonstrates the effect of cell scheduling frequency on IntellBatt discharge time. For the chosen application, the ideal scheduling frequency was found to be 100 seconds.

4.2.5 *Safety Demonstration*

Demonstrating safety in a simulation environment does not provide any value in this particular case. Without an actual IntellBatt implementation, it is difficult to prove safety. However, since safety is a concern, this research identifies the safety issues that may affect operation of IntellBatt. The issues have been identified and mitigation techniques have been discussed in Section 3.1.3.3.

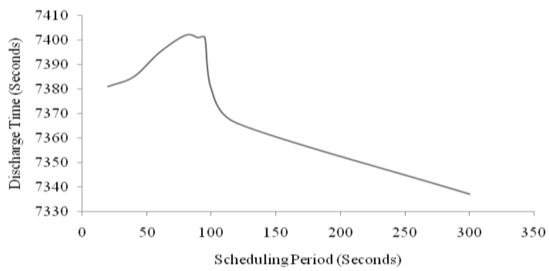

Figure 9: Effect of Scheduling Period

4.2.6 *IntellBatt Overhead*

The overhead of a battery cell array based design is determined in terms of area, power and delay. Area is not a concern since the BCAM and CSC are implemented on the board level. Power and delay overheads due to the CSC were presented in Table 1. The power consumed in the BCAM is orders of magnitude less than that of the CSC which is of the order of micro Watts.

5. CONCLUSIONS & FUTURE WORK

In this research, IntellBatt, an *intelligent battery cell array* novel design has been proposed to offload battery management responsibilities from the system onto the battery. By using multiple cells and battery cell array manager (BCAM), IntellBatt exploits the charge recovery effect of cells combined with a cell scheduling scheme to deliver the required load to the system while enhancing battery lifetime. Besides this support, IntellBatt also addresses safety concerns due to the use of multi-cell battery packs. IntellBatt can either be used standalone or can be combined with traditional battery-aware task scheduling approaches to further enhance battery life for a portable battery operated system. Our evaluation with actual current traces, obtained from a portable DVD player, demonstrated the benefit of using multi-cells and cell scheduling schemes.

Future research activities will focus on a hardware prototype of IntellBatt to further validate functionally, and evaluation of the safety concerns identified in this research. The SMBus interface to the system will also be implemented to provide rich power management capabilities to the battery operated system.

6. ACKNOWLEDGEMENT

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