A Novel Design of Adaptive Reconfigurable Multicell Battery for Power-Aware Embedded Networked Sensing Systems

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Abstract—Battery-powered embedded networked sensing systems become more and more pervasive with the fast-paced deployment of various remote sensing applications. How to prolong the battery operating time is one of the most challenging areas in the design and development of these sensing systems due to the fact that the battery operation is much more dynamic and complex than considered, which is derived from its application and its internal structure (multiple hardwired series/parallel cells) to produce a specific voltage and capacity. Current research on prolonging the battery operating time is mainly focusing on the low-power hardware and energy-efficient network protocol designs, and simply treats the battery as a passive two-terminal energy source. In this paper, we will propose a novel adaptive, proactive, and reconfigurable multicell battery design for supporting power-aware hardware and energy-efficient network protocols for embedded networked systems, which provides a whole new perspective to look at the energy problems of battery-powered embedded networked sensing systems. A theoretical modeling of the proposed design is provided, and simulation results show that the proposed design can significantly enhance the energy performance, especially for low voltage and low discharge current scenarios.

I. INTRODUCTION

With the rapid development of computing technologies, more and more embedded networked sensing systems have been developed for various future ubiquitous computing paradigms. When hundreds even thousands of such systems configured to communicate through sophisticated protocols, we have a very powerful platform with a huge potential to change the remote sensing applications. The power of ubiquitous embedded networked sensing systems lies in their ability to monitor the physical environment through ad-hoc deployment of numerous self-configured sensor nodes. Wireless sensor networks are useful in a wide spectrum of applications ranging from environmental and biological monitoring to military and homeland security. However, usually most of the embedded networked sensing systems are disposable, or at least not being able to change battery every often. Thus, the energy efficiency problem becomes most prominent.

Battery operating time is among the most important performance parameters for the networked embedded systems such as wireless sensors, active RFID tags, and other battery powered devices. In some critical mission scenarios such as emergency rescue, law enforcement, fire fighting, and battlefield, longer battery operating time could save more lives. Furthermore, each year tens of millions of dead rechargeable batteries are discarded, causing a daunting high cost to dispose them, and this has been becoming a serious environmental issue. It is known that battery lifespan is closely related to the number of charge/discharge cycles. Therefore, longer battery operating time means longer battery lifespan.

However, enhancing the battery operating time is a big challenge due to 1) the behaviors of energy consumption of each system component is dynamically changing according to the time-varying nature of the computing environment such as applications, network load, and link quality; 2) the battery operating time is much more dynamic and complex than considered derived from its application and its internal design structure (multiple hardwired series or/and parallel cells) to produce a specific voltage and capacity [1]. In other words, maximizing the battery operating time is a very difficult problem due to the nonlinearity of the battery behavior and its dependence on the characteristics of the discharge profile [2]. Moreover, current research to prolong the battery life is mainly aiming at the low-power design and the development of energy-efficient algorithms, resulting in the treatment of the battery as a passive two-terminal energy source rather than a dynamic system. Ignoring the discharge balance of the whole battery pack will lead poor battery performance, since the battery configuration can significantly affect the battery performance.

In this paper, we will propose a novel design for an adaptive, proactive and reconfigurable multicell battery pack which utilizes the power-aware system modules such as the widely-used dynamic voltage scaling (DVS) capability of CPU, memory controller, and network interface cards, leading to a unified design framework of power-aware embedded networked systems. The proposed design will significantly improve both battery operating time and battery lifespan, which will greatly improve the energy saving performance of current embedded...
networked sensing system as well as protect the environment by significantly prolonging the battery operating time via adaptive management of each cell in a battery pack, leading to improved utilizations of many battery characteristics including higher remaining usable capacity. Furthermore, the proposed adaptive reconfigurable battery system also provides a solution for an emergent power supply for mission-critical tasks.

The rest of the paper is organized as follows. The related works on battery design for power-aware embedded networked sensing systems and ad-hoc networks are reviewed in Section II. Section III is the theoretical system model of the proposed battery design. Simulation results are discussed in Section IV. We conclude this paper in Section V.

II. RELATED WORKS

So far, there has a lot of research having done on battery-aware energy-efficient of embedded networked sensing systems. In [3], [4], the charge recovery effect of batteries was exploited to minimize the energy consumption by addressing battery management techniques under bursty or pulsed discharge conditions caused by the bursty nature of many data traffic sources. In [5], [6], the node level power control scheduling and routing on densely deployed sensor networks was studied to achieve maximal network lifetime with dynamic power management on sensor nodes. In [7], a new framework was proposed to analyze the relationship between the energy efficiency of the routing tasks and the extension of the range of the topology knowledge for each node, and a new forwarding scheme was introduced. In [8], a theoretical model for estimating battery remaining capacity was presented for battery-aware computing. In [8], [9], the characteristics of existing rechargeable battery cells have been studied in terms of the discharge current rate-capacity characteristic and the relaxation induced capacity recovery, and temperature effects.

Multiple battery systems are being incorporated to handle the increasing energy demand of equipment and systems [10]. The Compaq Ipaq PDA is equipped with an add-on module that contains PCMCIA expansion and an auxiliary battery pack. Similarly, the HP omniBook 500 notebook when latched to its docking station is powered by a 11.1V, 3100mAH primary battery and two 14.8V, 3400 mAH secondary batteries that enable plugged in and out independently. Due to size and weight constraints this option is still in its infancy. However for some applications, it is a desirable option that increases the reliability and efficiency of the system. When multiple battery systems are considered, smart management policies are being integrated to enhance the operation of each battery and increase its performance and operational life. Also, with multiple batteries in a system, studies have shown increased life cycle using several charge/discharge methods and scheduling approaches as part of battery management techniques [11], [12], [13].

However, the approach to multibattery systems still considers a battery pack with a number of series/parallel connected cells as a single battery. Active research is centered on this single entity to provide means to prolonging its life and performance. Hence, this dynamic and complex battery system is treated as a passive two terminal component. However, using a recently developed reconfigurable configuration [14], the battery system is no longer a single entity but a manageable system that can be manipulated to provide gains and characteristics desired by any operating system as will be discussed in the following sections.

III. ADAPTIVE RECONFIGURABLE BATTERY DESIGN

A. Motivation

In the context of multicell battery pack, the connections among different battery cells lead to different usable capacity for the given voltage and discharge current requirements. In general, the larger the discharge current of a battery, the usable capacity of a battery turns into less [14], [15], [16]. This is because the discharge current of each cell in the battery pack will be changed by the internal connections among them. Figure 1 shows the nonlinear relationship between usable capacity and discharge current, where we can observe that the discharge current of each cell in the battery pack will be changed by the internal connections among them. Figure 1 shows the nonlinear relationship between usable capacity and discharge current, where we can observe that the discharge current of each cell in the battery pack will be changed by the internal connections among them. 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Therefore, the motivation of the proposed adaptive reconfigurable battery design is to dynamically reconfigure the internal connections among the different battery cells to maximize the remaining usable capacity of a given battery pack. Figure 2 illustrates the proposed battery design, which provides the flexibility to connect or remove any single battery cell from the connection matrix and allows the connection of multiple cells in a series, parallel, or a mixture of series-parallel configuration.

B. System Modeling

1) Model of series connected multicell batteries: According to the definition of the series circuit, their output currents of a series connected batteries are the same. However, the output voltages are independent, i.e. if \( n \) battery cells are connected in series together, and current of each battery cell is \( i_1, i_2, \ldots, i_n \), then

\[
i_1 = i_2 = \ldots = i_n = I
\]  

(1)

Based on these parameters, the Remaining Capacity (RC) of this configuration is

\[
RC_{\text{series}}(i_1, i_2, \ldots, i_n, v_1, v_2, \ldots, v_n) = \sum_{j=1}^{n} RC_j(i_j, v_j)
\]  

(2)

Here, \( v_j \) can be obtained from Eq. (3), and each \( RC_j(i_j, v_j) \) can be derived from the model in [8], based on the required voltage and discharge current. If we know the terminal voltages \( v_{1j} \) and \( v_{2j} \), for different currents \( i_{1j} \) and \( i_{2j} \), then the output voltage \( v'_{ij} \) of the each battery cell with the discharge current \( i \) at time \( t \) can be calculated as

\[
v'_{ij} = \frac{v_{2j} - v_{1j}}{i_2 - i_1} i + v_{2j}
\]  

(3)

\[
RC_j(i_j, v_j) = \left\{ \frac{1 - \exp\left(\frac{-r_{n,j} I - (v_{n,j} - v_{\text{cutoff}})}{\Delta}\right)}{b_{ij}} \right\} \frac{v_{2j}}{i_2} - \left\{ \frac{1 - \exp\left(\frac{-r_{n,j} I - (v_{n,j} - v'_{ij})}{\Delta}\right)}{b_{ij}} \right\} \frac{v_{2j}}{i_2}
\]  

(4)

2) Model of parallel connected multicell batteries: For parallel connection, the output voltages across the parallel connected battery cells are the same, however, their output current is independent, i.e. if \( n \) batteries are connected in parallel, and the voltage of each battery cell is \( v_1, v_2, \ldots, v_n \), then

\[
v_1 = v_2 = \ldots = v_n = v_{\text{parallel}}
\]  

(5)

Therefore, the Remaining Capacity (RC) of this configuration is

\[
RC_{\text{parallel}}(i_1, i_2, \ldots, i_n, v_1, v_2, \ldots, v_m) = \sum_{j=1}^{n} RC_j(i_j, v'_j)
\]  

(6)

Where, \( v'_j \) can be obtained by the equation (3). If the required current of user is \( i \), then

\[
I = i_1 + i_2 + \ldots + i_n
\]  

(7)

If we know the terminal voltages \( v_{1p} \) and \( v_{2p} \), for different currents \( i_{1p} \) and \( i_{2p} \), and the output voltage of the parallel connected battery cells is \( v_{\text{parallel}} \), then the terminal voltage at current \( i \) at time can be calculated as

\[
i = \frac{i_{2p} - i_{1p}}{v_{1p} - v_{2p}} v_{\text{parallel}}
\]  

(8)

\[
RC_{\text{parallel}}(i_1, i_2, \ldots, i_n, v_1, v_2, \ldots, v_m) = \sum_{j=1}^{n} RC_j(i_j, v_j)
\]  

(9)

If we choose an \( n \) identical cells battery package, all with the same state of charge (SOC), connected in parallel, then

\[
RC_{\text{parallel}}(i_1, i_2, \ldots, i_n, v_1, v_2, \ldots, v_n) = \sum_{j=1}^{n} RC_j(i_j, v'_j) = n \times RC_1(i_1, v'_1)
\]  

(10)

3) Model of batteries series-parallel connected multicell batteries: In this case, the \( n + m \) batteries can be series-parallel connected together. The \( i_{11} = i_{12} = \ldots = i_{nm} \) can be obtained through Eq. (9). The remaining capacity is

\[
RC_{\text{s-p}}(i_{11}, i_{12}, \ldots, i_{nm}, v_{11}, v_{12}, \ldots, v_{nm}) = \sum_{i=1}^{n} \sum_{j=1}^{m} RC_{ij}(i_{ij}, v_{ij})
\]  

(11)

where \( v'_{ij} \) can be obtained by Eq. (3). Thus, all kinds of connections can be calculated by Eqs. (2), (6), and (11). when \( p \) battery cells are series connected with \( n + m \) series-parallel connected battery cells, and the required discharge current is \( i \), then the remaining capacity \( RC_{s-s-p} \) of the \( p + n + m \) battery pack is

\[
RC_{s-s-p} = RC_{s-p}(i_{11}, i_{12}, \ldots, i_{nm}, v_{11}, v_{12}, \ldots, v_{nm}) + RC_{\text{series}}(i_1, i_2, \ldots, i_n, v_1, v_2, \ldots, v_n) + \sum_{i=1}^{n} \sum_{j=1}^{m} RC_{ij}(i_{ij}, v_{ij}) + \sum_{k=1}^{p} RC_k(i_k, v_{ik})
\]  

(12)

IV. SIMULATIONS

In this paper, extensive simulations have been carried out for evaluating the proposed design. We adopt the model of Bellcore PLION cell [8], [18], [19] which has 4.1 volt open voltage, 3 volt cutoff voltage, and 41.3 mA (1C) battery capacity. We also use the battery simulation software DUALFOIL program [20], which is a low-level simulator for the cutoff time and the useable capacity of Lithium-Ion batteries. In our simulations, the cutoff time of a battery cell is determined by the time at which the battery cell voltage falls below the cutoff voltage from the output file produced by DUALFOIL. All parameters of Bellcore PLION are set up according to [20]. First, we charge the battery at a very low rate, i.e., 0.1C, to 4.1v. Next, the battery is discharged from the current state to exhaustion at different k.C discharge rate (\( k = 0.1, 0.2, \ldots, 1 \)),

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and we can get the cutoff time of the battery cell. The voltage of the battery cell is determined by the analytical model for predicting the remaining battery capacity of Lithium-Ion battery model as reported in [8].

We have compared the proposed design with two mainstream multicell battery designs. Assume the system working voltage is 11.1 volts and the cutoff voltage is 10 volts. Figure 3 shows one of the two popular multicell battery designs where six battery cells are organized as two series cell groups which are further connected in parallel, termed Configuration 1. Figure 4 shows the other popular design where a six-cell battery is organized as two series cell groups which provide power supply to the system alternatively, termed Configuration 2. In order to compare the proposed design with the existing designs under a non-uniform SOH (state of health), we assume that the SOH of cells 3, 4, and 6 is 0.8. For any series connected group of battery cells, a battery pack is considered being fully discharged when its output voltage falls below a given cutoff voltage threshold such as 80% of the nominal voltage [21]. For our simulation paradigms, this means that when the voltage of any cell in that series group drops below 10 volts, that group of battery cells is thought of as exhaustion. Figure 5 shows the relationship between the normalized usable capacity and the battery operating time. In this figure, we can observe that the existing battery design is not functional when the normalized remaining capacity (in blue) drops to 0.2, but our proposed design (in red) can further explore the remaining capacity and prolong the battery operating time by more than 14%.

Figure 6 shows the performance comparison of three battery designs in terms of voltage. In this figure, the blue curve is corresponding to the performance of existing configuration 1, the black curve is of the existing configuration 2, and the red one is the one from the proposed design. Here, the cutoff voltage of the given battery pack is 10 volts. Therefore, we can observe that the normalized useable capacity of our proposed battery design is 1, and the normalized useable capacity of existing battery configuration 1 is 0.8542 and the normalized useable capacity of existing battery configuration 2, which is widely used in current portable devices, is 0.778. To compare with existing battery configuration 2, the normalized useable capacity of our proposed battery design has been improved by 28.5%. Compared with the existing battery configuration 1, the normalized useable capacity of our proposed battery design has been improved by 14.58%. The gain of the proposed design is attributed to be able to dynamically remove the exhausted or failed cells and reconfigure the remaining useable cells until all cells in a battery pack are fully discharged. Our study shows that the small the discharge rate is, we can achieve more gains. This is especially important to the embedded networked sensing systems such as wireless sensors where the smaller voltages and discharge rates are adopted.

Figure 7 shows the relationship of the sustainable voltage performance and the operating time. In this case, under the same voltage and current requirements and the same initial battery conditions in terms of SOH, the battery pack using configuration 2 can last 104 minutes; the battery pack using configuration 1 can last 114 minutes; and the reconfigurable battery pack has 134 minutes operating time. In addition, our study shows that the battery operating time will turn into longer when smaller voltages and currents are used.

V. CONCLUSION

In this paper, we have proposed a novel multicell battery design for embedded networked sensing systems such as wireless sensors. The major contribution of this work is that we have proposed and modeled an adaptive reconfigurable multicell battery structure to dynamically change the connections among
the proposed adaptive reconfigurable battery pack performs better in low voltage and low discharge current scenarios, which provides a very promising power supply for future wireless sensors and sensor networks and any other portable equipment of mobile ad-hoc networks.

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