A Traffic Control Scheme to Optimize the Battery Pulsed Discharge

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Abstract—**In this work, a model for battery behavior taking into account the recovery effect is presented. The recovery capability of the battery is represented as an exponential function of both the state of charge and the discharged capacity of the battery. Using the proposed model, the benefits of the pulsed battery discharge relative to the constant discharge are shown.**

Then, we introduce a new battery management technique, that, exploiting the traffic shaping algorithm *leaky bucket*, allows us to optimize the gain obtained from the pulsed discharge and maximize the capacity obtained from the battery. Results presenting the effect of the proposed solution on the system performance are presented for different packet arrival processes.

I. Introduction

As portable equipments enjoy a great deal of popularity, a major challenge is to provide battery-powered users with light and reliable systems. However, this is a tough task since advances in battery technology are quite slow compared to the growing rate of the wireless market.

Our work aims at extending the lifetime of the existing systems by introducing low-cost battery management techniques rather than developing a new battery design. We consider a portable communication system where, exploiting the bursty nature of traffic sources, a pulsed discharge of the battery is performed.

Several works [1], [2], [3], [4], [5], [6], [7] show that a battery pulsed discharge may significantly outperform a constant current discharge. When current is drained from a cell[1], active materials are consumed at the electrode/electrolyte interface by the electrochemical reactions and replaced by the active species that move from the electrolyte solution to the electrode due to the *diffusion* mechanism [8]. As the intensity of the current drawn off the cell increases, the depletion of active materials at the electrode/electrolyte interface becomes significant and the state of charge of the electrode decreases. Due to these phenomena the cell is completely discharged before its theoretical capacity is exhausted. However, if impulses of current are followed by a rest time period, the cell is able to recover its charge during the idle time thanks to the diffusion mechanism, and the total capacity delivered by the cell greatly increases [1]. Moreover, in cells characterized by a low conductivity, e.g., lithium-polymer and zinc-air cells, a pulsed discharge allows a much higher power to be drawn off the cell [1]. For these reasons recovery comes up as a key issue in battery discharge.

In [9] the authors summarized the behavior of an electrochemical cell and presented a model for the battery behavior assuming that the recovery probability remains constant during the discharge process.

In this paper, we develop a more accurate model of the cell behavior. The recovery effect is represented as an exponential function that decreases as the discharged capacity increases and the state of charge decreases. The improvements resulting from a pulsed current discharge, relative to a constant current discharge, are measured by computing the average number of packets transmitted under both the operational conditions and under various traffic arrival processes.

Then, to maximize the delivered battery capacity for any kind of cell and arrival process, we apply to the cell discharge the well known traffic shaping algorithm, called *leaky bucket* [10]. Using smart battery packages [11], the state of charge of the battery can be monitored. Whenever the cell state of charge drops below a certain threshold, we let the battery rest by interrupting the packets transmission at the terminal user. The proposed solution forces a low rate pulsed discharge and guarantees that the battery has chance to recover; in this way, the whole theoretical capacity of the cell can be exploited.

The impact of the proposed discharge technique on the packet delay and throughput is studied in the presence of different packet arrival processes.

II. Performance of Cells under Pulsed Discharge

In this section, we analyze the stochastic evolution of a cell from the fully charged to the completely discharged state. Discharges occur at stochastic instants determined by the traffic arrival process and recovery may occur whenever there is no dis-

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[1] A *cell* is the basic electrochemical energy storage device. In this paper, the words *cell* and *battery* are used in an interchangeable way.

charge.

To carry out our analysis, the following assumptions are made:

i) A single cell of the battery system is considered; however, the results can be easily extended to the case of several cells connected in series or in parallel;

ii) A discrete time system with time unit equal to one slot duration is considered;

iii) For the sake of simplicity the background current, i.e., the value of current that must be constantly supplied to the portable equipment [1], is neglected; only the amount of capacity necessary to transmit a packet is considered and defined as a *charge unit*;

iv) Each fully charged cell has a theoretical capacity equal to T, and an initial state of charge equal to N *charge units*. Both N and T are taken as variable parameters;

v) The recovery effect is represented as a decreasing exponential function of the cell state of charge and discharged capacity. Such a model was used in [12], where the behavior of the state of charge of lead-acid cells was studied. We define three recovery values, γ_1, γ_2, γ_3, such that while the cell is discharged, the slope of the exponential function ranges over these values. This approach allows a more accurate model of the real cell behavior [13];

vi) A *multiple pulsed discharge* is considered: at each time slot i charge units are lost if i packets arrive and have to be transmitted, otherwise the battery may recover one charge unit or remain in the same state. However, the recovery process ends once the theoretical capacity is exhausted.

A. Multiple pulsed discharge

The cell behavior is modeled as a transient process that starts from the state of full charge ($V = V_{OC}$), denoted by N, and terminates when the state 0 (corresponding to a complete discharge of the cell) is reached, or the theoretical capacity is exhausted. We assume that, due to the limited theoretical capacity of the cell, at most T packets can be transmitted.

We consider arrivals of bursts of packets and define a_i as the probability that a burst of i packets arrives in one time slot, and $a_0 = 1 - \sum_{i=1}^{\infty} a_i$. Thus, in each time slot the cell has probability a_i to move from state z to $z - i$, with $0 < z \leq N$, where the positions corresponding to $z - i < 0$ add to the probability to move to 0.

As already mentioned, the recovery probability is modeled as an exponential function of the state of charge and of the discharged capacity of the cell. The recovery probability at state j after k packets have been transmitted is as follows

$$p_j(k) = \begin{cases} a_0 e^{-\alpha_N (N-j) - \alpha_C(k)} & j=1,\ldots,N-1;\ k=0,\ldots,\gamma_1 \\ a_0 e^{-\alpha_N (N-j) - \alpha_C(k)\gamma_c} & j=1,\ldots,N-1;\ \gamma_c < k \leq \gamma_{c+1};\ c=1,2,3 \end{cases} \quad (1)$$

where γ_4=T, and α_N and α_C are parameters that depend on the recovery capability of the battery. In particular, we assume that

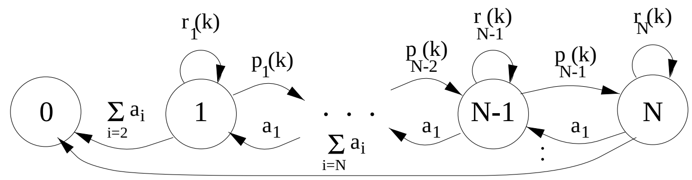

Fig. 1. Markov chain representing the cell behavior.

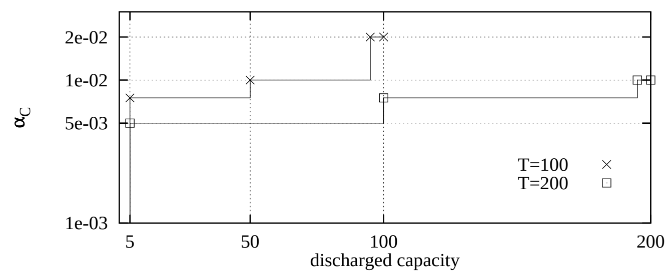

Fig. 2. Behavior of α_C for T=100 and 200.

α_N is a constant, whereas α_C is a piecewise constant function of the number of packets already transmitted, that changes value in correspondence with γ_c (c=1, 2, 3). The probability to remain in the same state of charge is

$$\begin{aligned} r_j(k) &= a_0 - p_j(k) \qquad j=1,\ldots,N-1 \\ r_N(k) &= a_0 \ . \end{aligned} \quad (2)$$

Fig. 1 shows a graphical representation of the process. Notice that in [9] $p_j(k)$ and $r_j(k)$ were assumed to be constant $\forall j, k$ since it was non considered the dependence on the cell state of charge and discharged capacity.

Let us denote by $\overline{m}_p$ the average number of packet transmissions made during the discharge process starting from state N. The ratio of the mean number of transmitted packets to the theoretical capacity is taken as a measure of the cell performance. In case of pulsed discharge, we have

$$G_p = \frac{\overline{m}_p}{T} \quad (3)$$

where $\overline{m}_p$ can be computed from the Markov model presented in Fig. 1.

Moreover, we assume that the charge units drained from a cell under a constant discharge can be fully utilized by accumulating charge in a capacitor whenever it needs. Thus, the gain obtained under constant current discharge, results as

$$G_c = \frac{N}{T} \ . \quad (4)$$

Notice that: $G_c \leq G_p \leq 1$. Pulsed discharge outperforms the constant current discharge to the extent that G_p approaches 1.

B. Results

Results showing the benefit of the battery pulsed discharge were already presented in [9] under the assumptions of constant recovery probability and cell discharge driven by Bernoulli arrivals. Here, the cell performances are derived by simulating the

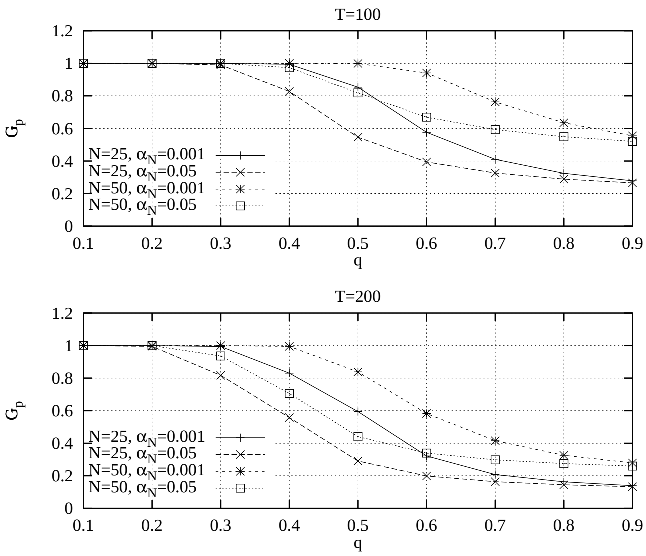

Fig. 3. G_p vs. q in case of Bernoulli arrivals. T=100, 200, N and α_N varying.

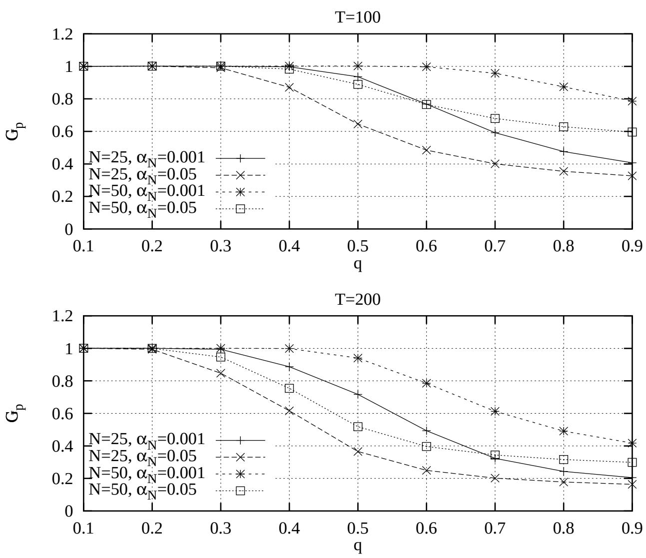

Fig. 4. G_p vs. q in case of Poisson arrivals. T=100, 200, N and α_N varying.

Markov chain shown in Fig. 1 driven by different arrival processes.

We consider that the value of the thresholds γ_c (c=1, 2, 3) and the values taken by α_C depend on T (see Fig. 2). These parameters are chosen such that the behavior of the cell state of charge during the discharge process presents a realistic profile.

First, lets us assume a Bernoulli arrival process with probability a_1=q that one packet arrives in a time slot and $a_0 = 1 - a_1$. Fig. 3 shows G_p versus q for T equal to 100 and 200, as α_N and N vary. As expected, given N (namely N=25, 50) the performance improves as the recovery capability of the cell increases, i.e., α_N decreases. In addition, for a fixed α_N, smaller values of G_p are obtained as the gap between T and N becomes larger.

More interestingly, Fig. 3 shows that for any α_N, G_p approaches its lowest value as q increases, no matter what N is used. This finding reveals that traffic shaping may be a more significant determinant of battery life than N, the initial charge stored in the cell, and α_N, the recovery capability coefficient. When we deal with a more bursty traffic, viz., the Poisson arrival process, higher values of G_p are obtained as shown in Fig. 4. Here, we assume a Poisson arrival process with rate equal to q,

$$a_i = \frac{q^i e^{-q}}{i!} \quad (5)$$

where the time slot duration has been taken equal to 1.

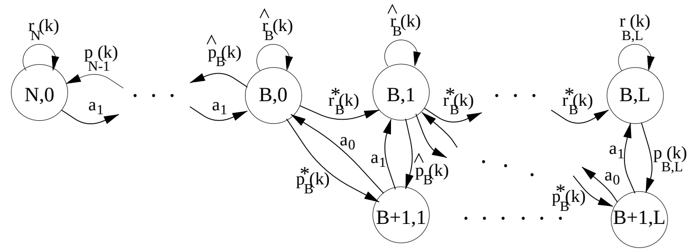

Fig. 5. Markov chain representing the cell discharge driven by Bernoulli arrivals when the leaky bucket technique is implemented.

III. Leaky Bucket Technique Applied to Cell Discharge

We now apply to the cell discharge the *leaky bucket* technique [10] in order to obtain G_p equal to 1 for any value of N, α_N, and traffic load. Our idea is to interrupt the drained current and let the cell recover whenever the cell state of charge drops below a certain threshold. In this way, the maximum number of packets, corresponding to the value of the theoretical capacity, could be more clearly approached.

Let us denote the state of charge chosen as threshold by B. Then, the quantity $M = N - B$ corresponds to the size of the token buffer in the leaky bucket algorithm. Whenever the cell reaches state B, the packet transmission is stopped and packets arriving at the system are queued in a data buffer. We denote the data buffer size by L and assume that L is large enough to guarantee a packet loss probability equal to zero. As soon as a recovery takes place, the cell gains a charge unit; then, if the queue is not empty, a packet is transmitted. Thus, whenever there are queued packets, the cell charge can be at most equal to $B + 1$. We consider as state variables the sum of the number of tokens (i.e., the charge units available in the cell) and the number of queued packets [10]. The modified Markov chain representing the cell discharge is shown in Fig. 5 in case of Bernoulli arrivals. For k=0, ... , T we have

$$\hat{r}_B(k) = \frac{r_B(k)a_0}{p_B(k) + r_B(k)} \;\; ; \; r^*_B(k) = \frac{r_B(k)a_1}{p_B(k) + r_B(k)}$$

$$\hat{p}_B(k) = \frac{p_B(k)a_0}{p_B(k) + r_B(k)} \;\; ; \; p^*_B(k) = \frac{p_B(k)a_1}{p_B(k) + r_B(k)}$$

$$r_{B,L}(k) = \frac{r_B(k)}{p_B(k) + r_B(k)} \;\; ; \; p_{B,L}(k) = \frac{p_B(k)}{p_B(k) + r_B(k)} \; . \quad (6)$$

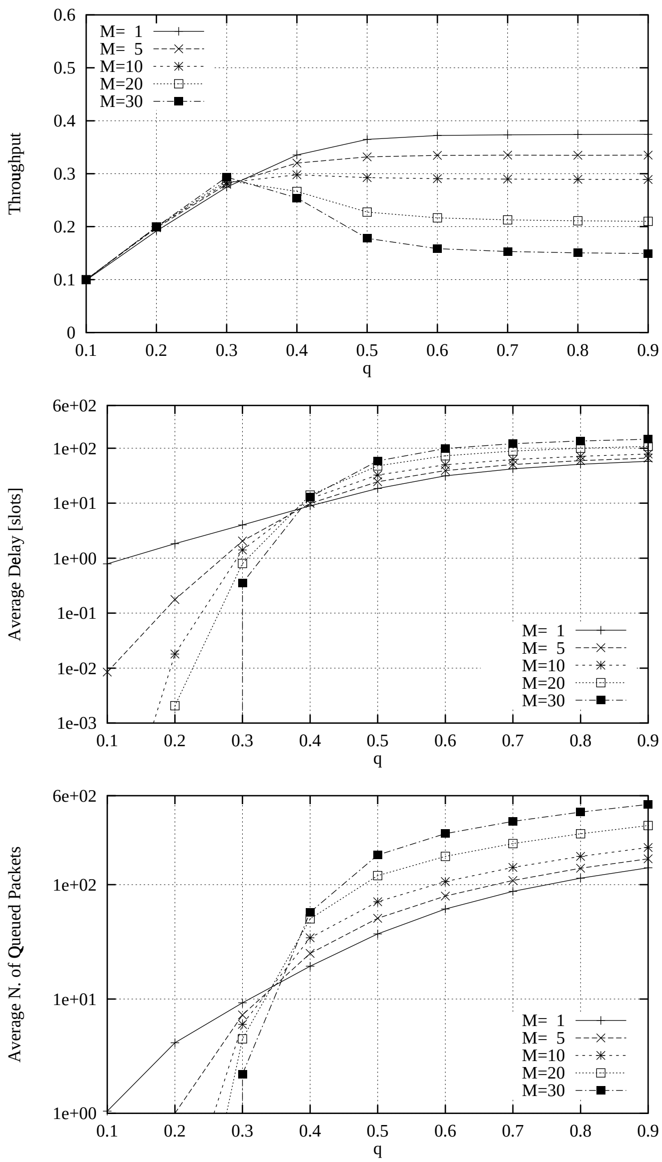

Fig. 6. Bernoulli arrivals: Cell performance as function of q for α_N=0.05, T=100, and M varying.

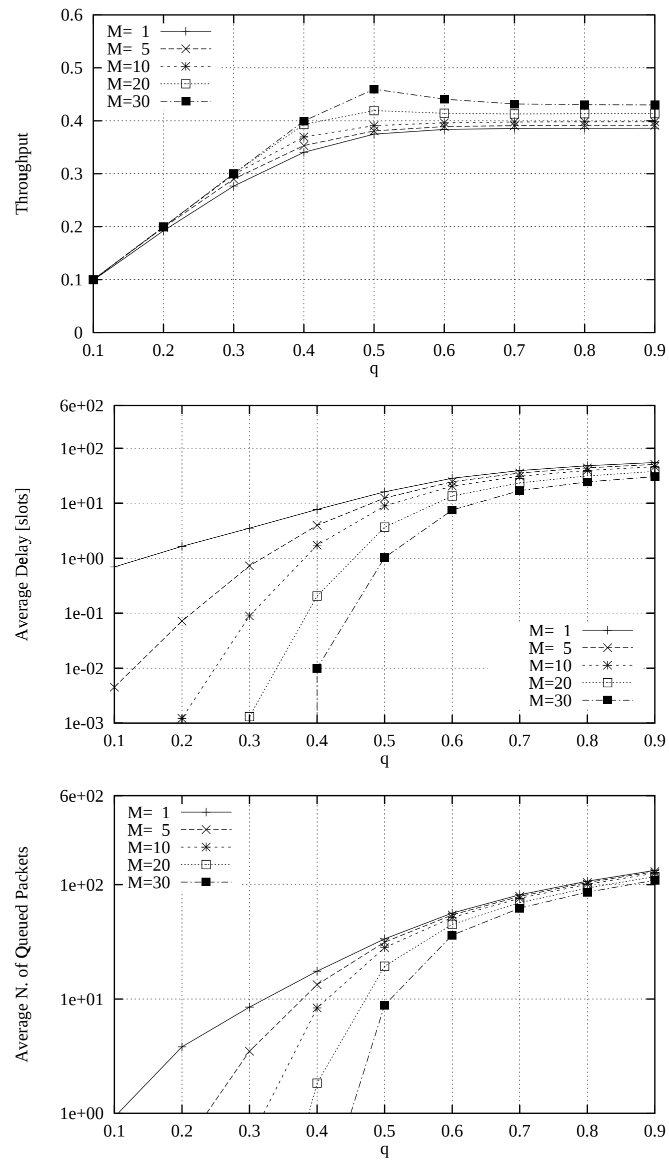

Fig. 7. Bernoulli arrivals: Cell performance as function of q for α_N=0.001, T=100, and M varying.

Results are derived by simulation in terms of throughput, mean packet delay conditioned to being actually transmitted, and average number of the queued packets that will not be transmitted. Results show that by properly selecting M, performance can be optimized as the characteristic parameters of the cell and the packet arrival process change.

Plots obtained in case of Bernoulli arrivals and T=100 are presented in Figs. 6 and 7 as α_N and M vary. From Fig. 6 it can be seen that for α_N=0.05 better results are obtained for low values of M, while Fig. 7 shows that for smaller values of α_N, performance improves as M increases. Indeed, when α_N assumes significant values, the recovery probability greatly reduces as the cell status of charge decreases; thus, if the threshold M is taken close to N the recovery is more likely to occur. From Figs. 6 and 7 it can be also seen that for both the values of α_N and for any value of M, the average packet delay increases when high values of the mean packet arrival rate are considered. In fact, in order to let the battery recover properly, the delay introduced between the arrival of a packet and the time instant of its transmission has to be greater. Moreover, when high values of M are considered, the throughput decreases as q accrues. This is due to the fact that as soon as the discharge process starts, the cell status of charge quickly reaches the threshold B. At this point, the recovery probability is low and the time to wait before being able to resume the packet transmission becomes large; thus, the time period needed to drain from the battery the total number of available charge units increases. As expected from what we observed before, the degradation of the throughput is more evident for greater values of α_N. Finally, it is intuitively clear that the average number of queued packets grows as the mean packet arrival rate and the discharge process duration increase.

Similar curves are obtained in case of Poisson arrivals. Fig. 8

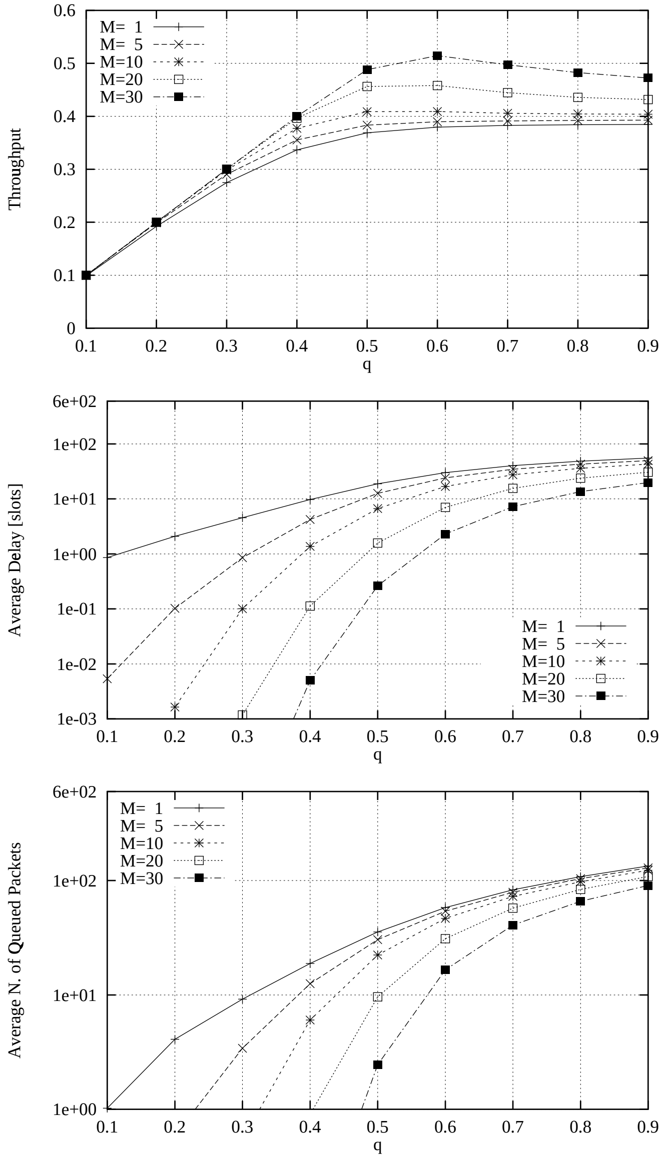

Fig. 8. Poisson arrivals: Cell performance as function of q for α_N=0.001, T=100, and M varying.

shows results for α_N=0.001 and T equal to 100. Results improve as M increases; however, it must be $M < N$ and larger values of M imply greater values of the initial charge N. Comparing Fig. 7 to Fig. 8, it can be seen that for large values of M (namely: 20, 30) the cell performance improves in case of Poisson arrivals since the arrival process is more bursty. Indeed, for a given value of the average packet arrival rate, a greater burstiness allows the cell to benefit of a longer rest time period between two successive arrivals and the diffusion mechanism is better exploited.

IV. Conclusions

The paper presented a model of the single cell taking into account the recovery effect. Results derived using the proposed model show the actual benefits of the pulsed discharge. Then, the leaky bucket technique was applied to the discharge process to take the most of the benefit deriving from the cell recovery. The delivered battery capacity was maximized at the cost of introducing a delay in the packet transmission. It was shown that the system performance can be optimized by selecting the proper size for the token bucket according to the cell recovery characteristics.

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