Stochastic Battery Discharge in Portable Communication Devices*

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Abstract

The objective of this work is to explore ways in which performance of battery systems can be enhanced through the use of energy-efficient battery management techniques.

The phenomenon of charge recovery that takes place under pulsed discharge conditions is identified as a mechanism that can be exploited to enhance the capacity of a cell in a portable communication device. The bursty nature of many data traffic sources suggests that data transmissions in communication devices may provide natural opportunities for charge recovery. We model the data source as a stochastic process and let the cell discharge be driven by such a process. We use a model of a dual lithium ion insertion cell to identify the improvement to cell capacity that results from the stochastic discharge. The insight from this study leads us to

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propose discharge shaping techniques that tradeoff energy efficiency with delay in the required current supply.

Introduction

As the popularity of radio communication equipments increases, the reliability and energy capacity of batteries has become a critical issue. Indeed, a greater battery capacity means a longer run time of the terminals, and therefore it is a crucial factor in the success of a product. Due to the disparity in the rate of technological advance in batteries and in portable communication equipments markets, software/hardware solutions have to be explored to improve the battery performance.

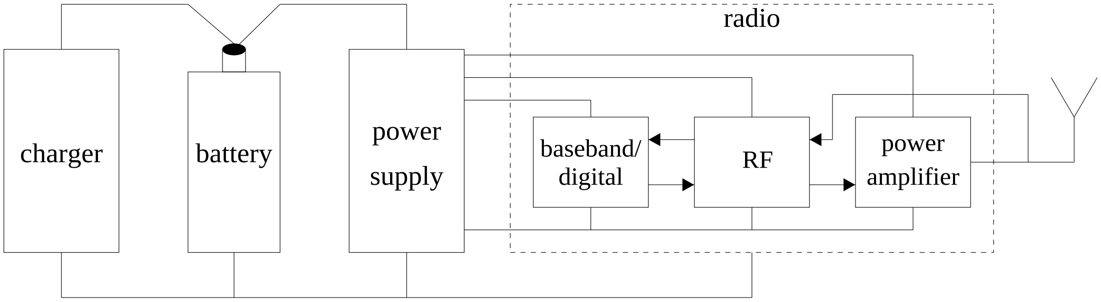

Figure 1: Building blocks of a portable communication device.

A simplified view of a portable radio device is shown in Figure 1, where the *radio* part consists of a baseband/digital section, a RF (Radio Frequency) section and a power amplifier, each of which requires a different power supply [1]. Typically the baseband and RF sections consume a constant level of power but the power amplifier draws a much greater amount of power during the traffic transmission over the radio channel. The power supply unit is a rechargeable battery, typically a Ni-Cd, Ni-MH, or lithium-based battery system. It is quite obvious that features such as a long lifetime, light weight and a small size are highly desirable. For these reasons, battery management has become a critical issue in portable telecommunication systems.

As shown by experimental tests [2, 3, 4, 5], a greater battery capacity can be obtained by using a pulsed current discharge instead of a constant current discharge. In fact, under a pulsed discharge profile the charge recovery mechanism inherent to secondary storage batteries can be exploited and longer relaxation times translate into a greater capacity delivered by the battery [6].

Several findings [3, 4, 6] quantify the advantages that result from a pulsed current discharge. In [4] LaFollette reports the results of subjecting a bipolar lead-acid cell to current pulses that last for 3 ms followed by a rest period of 22 ms. The drained current was initially equal to 12 A/cm^2 and dropped to 7 A/cm^2 at the end of the sixth impulse. During the first four rest periods, the cell was able to totally recover the initial value of potential.

In batteries characterized by a relatively low conductivity, e.g., lithium-polymer cells [7, 8], pulsed discharge can increase the delivered specific power. Lithium-polymer cells have lightweight and flat formats and fit well in extra-thin cellular phones, but ion diffusion through the conducting polymers is slow and this limits the rate at which current can be withdrawn from a cell. However, in [9] a lithium-polymer cell was discharged at up to 50 mA/cm^2, about fourteen times the typical constant discharge rate, using pulses of 10 ms duration followed by a 50 ms rest period.

These benefits continue to hold if the discharge is composed of pulses superimposed on a constant current [10]. Such discharge patterns are likely in communication devices where the baseband and RF parts need a low constant supply ($40 \div 200$ mA), but load changes (2 A) occur whenever the system passes from the idle to the active state or from receive to transmit

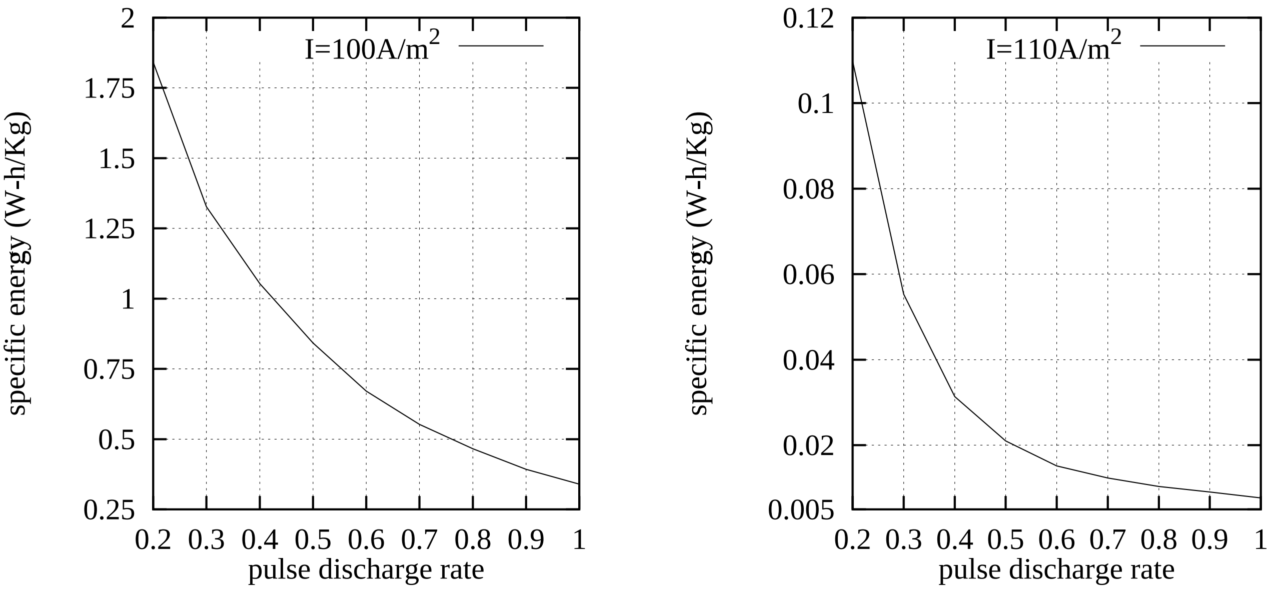

Figure 2: Specific energy versus pulse rate under a Bernoulli driven discharge as the current density drawn off the cell varies.

mode.

In some communication systems, a periodic pulsed discharge is already used in the presence of voice traffic sources. For instance, in GSM every 4.6 ms an impulse of current lasting 576 μs is required to transmit voice traffic over the radio channel, thus a pulse discharge with duty cycle 1:8 is implemented.

Our objective here is to exploit the recovery effect in conjunction with data traffic sources (such as Internet traffic, file transfer, etc.). Data traffic sources are *delay-tolerant* and allow for a much greater flexibility, so that longer relaxation times can be introduced in the discharge process. A data traffic source is modeled as a stochastic process that generates information units, called *packets*, according to a certain probability distribution.

In this paper, we study the actual gain derived under stochastic pulsed discharge of a lithium

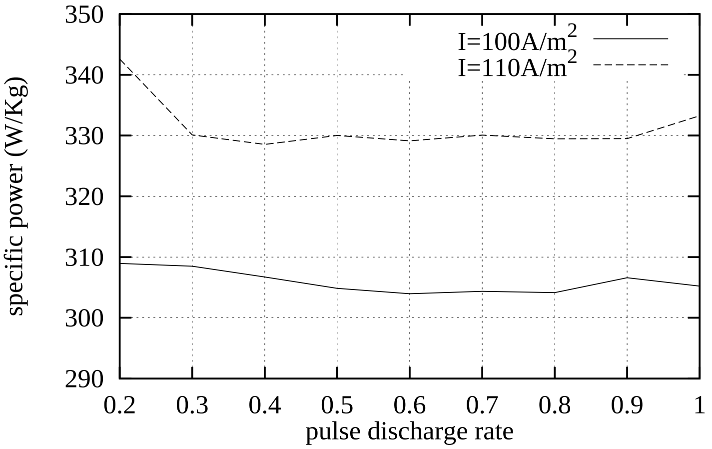

Figure 3: Specific power versus pulse rate under a Bernoulli driven discharge as the current density drawn off the cell varies.

ion cell induced by the packets generation process. Then, we "tailored" the discharge process through a traffic shaping technique. The discharge shaping is performed by delaying a power consuming activity such as the transmission of a packet; in this way, a low rate pulsed discharge is forced and the battery has greater chance to recover.

Pulsed Discharge in Communication Devices

The implementation of Internet-based radio networks needs for high-capacity battery systems to convey large amounts of information to mobile users. Our key idea is to combine the bursty nature of data traffic sources with the recovery effect that takes place in an electrochemical cell: whenever a packet is transmitted over the radio channel a current impulse is drained from the cell, otherwise the cell recovers charge. We discretize the time dimension in intervals 1 ms long, a reasonable value for the duration of the packet transmission. The data traffic source is modeled as a Bernoulli driven process, i.e., at each time interval a packet is generated with probability p. Thus, if we consider to transmit a packet as soon as it is generated, with probability p an impulse 1 ms long is drawn off the cell, while with probability $1 - p$ the cell recovers for 1 ms. During the idle periods the cell potential arises, although as the cell discharges the ability to recover decreases [4]. Eventually, when the cell potential drops below the cut-off value the discharge cycle ends.

Performance of the stochastic discharge described above is studied by considering a dual insertion lithium-ion cell. This was a natural choice since lithium-based batteries are vastly used in portable devices and because of the availability of a program developed by Newman *et al.* [11] that models this cell.

The program, written in Fortran code, numerically solves a detailed model of the cell behavior governed by partial differential equations [12, 13]; the model also includes double-layer capacitance in each electrode. The program was modified to let the discharge of the cell be driven by a stochastic process representing the data packets generation.

Results are obtained for the first discharge cycle of the cell; thus, discharge always starts from a value of positive open-circuit potential equal to 4.3071 V. We considered the cut-off potential equal to 2.8 V and varying values of the current density. This values depend on the particular application we refer to (cellular phone, cordless phone, etc.) and on the technology used to build the electronics of the device. We took for these parameters values that are reasonable for the use in portable communication devices and at the same time avoid excessively long runs of the software program.

Figure 2 presents the behavior of the specific energy derived from the cell as a function of the rate at which the current impulses are drained (p). Two values of current density are considered: I=100 and I=110 A/m^2. As it can be seen, a difference of almost one order of magnitude exists in the amount of energy delivered in the two cases. However, as the pulse discharge rate decreases, the delivered energy dramatically increases for both the values of I. This is due to the fact that as the discharge rate becomes smaller, the chance to recover for the cell significantly grows.

Figure 3 illustrates the behavior of the specific power versus the discharge rate for the same values of current density. The plot shows that the level of specific power per impulse remains roughly constant no matter what discharge rate is used. This is an important result since the electronic circuits used in portable devices require a steady level of power.

These results suggest that an accrue in battery capacity is always possible if a power consuming activity, such as the transmission of a packet, is delayed and a sufficiently low discharge rate is used.

Shaping of the Discharge Demand

In communication networks, data packets may be delivered to the receiving user with fairly large delays without affecting the required traffic quality of service. Therefore, we can shape the discharge demand at the communication device by delaying the packets transmission. Packets, whose transmission is delayed, are stored in a buffer from the time instant of their generation until they are transmitted.

As before, we consider that the packets generation process is Bernoulli distributed with a certain probability p_g that a packet is generated in a time interval 1 ms long. However, now we assume that the discharge process is Bernoulli distributed with probability p_d independent of p_g. We take $p_d < p_g$, i.e., packets are transmitted at a lower rate than their generation rate.

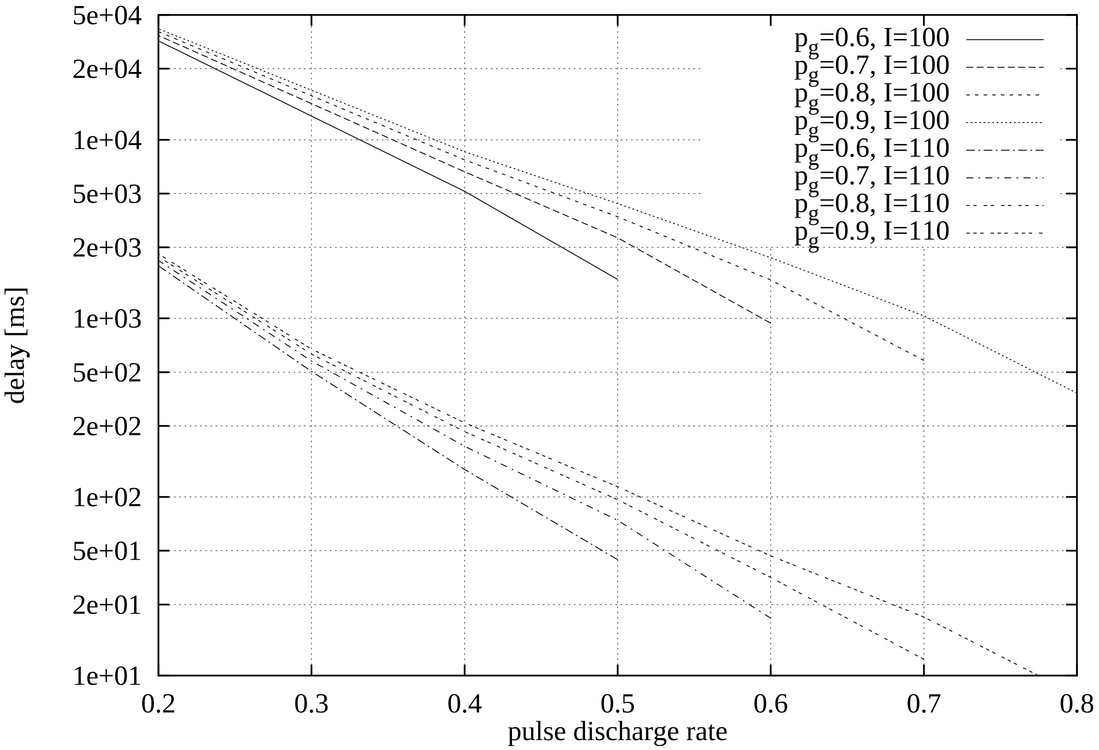

Figure 4: Time delay in power supply when a simple discharge shaping is applied. Both traffic generation and pulse discharge are Bernoulli driven (p_g denotes the traffic generation rate).

Figure 4 shows the average time delay that data packets experience at the communication device as a function of the discharge rate p_g when the generation rate and the drained current density vary. As expected, for a given value of current density the delay becomes larger as the difference $p_g - p_d$ increases. Consider p_g=0.8 and compare the two cases of current density I=100 A/m^2 and I=110 A/m^2: for a discharge rate p_d=0.5, we obtain a delay equal to 3.7 s and 0.1 s, respectively. The gain in specific energy that we achieve is roughly equal to a factor 2 in both the cases; however, the specific energy delivered at the discharge rate p_d=0.5 for I=100 A/m^2 is equal to 0.84 Wh/kg, whereas for I=110 A/m^2 is equal to 0.021 Wh/kg (see Figure 2). It is clear that the fundamental tradeoff here is between energy efficiency and traffic delay.

The maximum acceptable delay depends on the required quality of service of the considered traffic class.

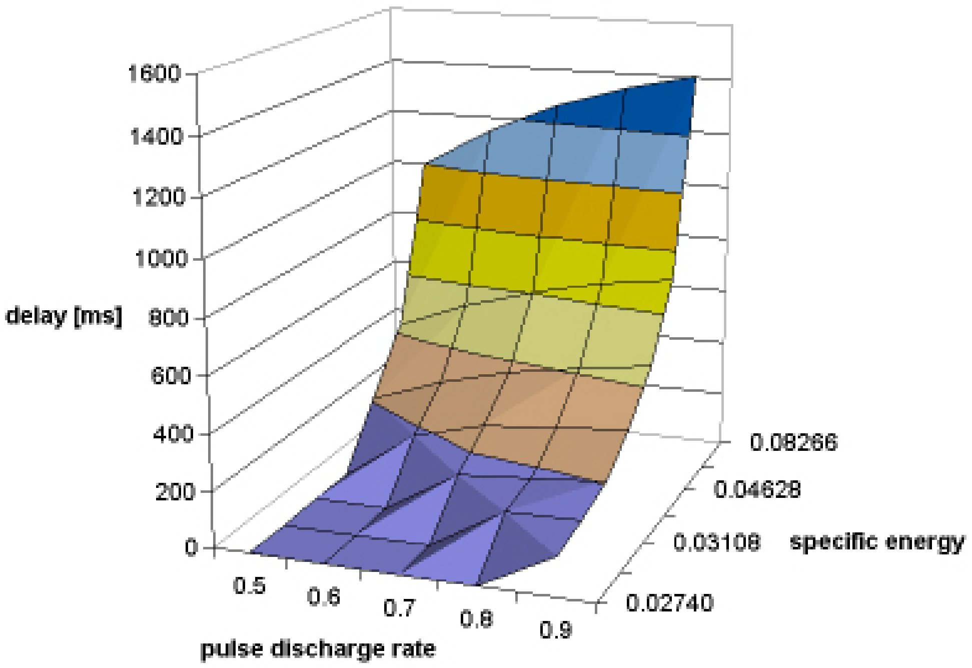

Figure 5: Time delay in power supply as a function of specific energy and traffic generation rate when a discharge shaping with threshold is applied.

Figure 5 presents a three-dimensional plot where the average time delay is derived as a function of the packet generation rate (p_g) and the delivered specific energy when a more complex discharge shaping technique is applied. The current density is taken equal to 110 A/m^2.

In this case, the discharge of the cell is still Bernoulli driven but whenever the cell potential drops below the value of threshold V_t=3.0 V, the discharge process is interrupted and the cell is let recover so that its potential arises again above V_t. Similarly to what we observed before, for a given value of the packet generation rate, the delay grows as the specific energy increases. However, the values of delivered specific energy are significantly greater than those obtained with the previous technique: for p_g=0.8, values of specific energy between 0.0284 and 0.1412 Wh/kg can now be achieved. The price to pay in terms of delay ranges between 0.15 s and 3.7 s. It is worth to notice that for the same generation rate (p_g=0.8) and packet delay (equal to 3.7 s), a higher specific energy is delivered for I=110 Wh/m^2 than for I=100 Wh/m^2 (i.e., 0.1412 Wh/kg and 0.84 Wh/kg, respectively).

Conclusions

Due to the extraordinary market evolution of portable communication devices and the development of Internet data services, a compelling need for high-capacity battery systems exists.

In this paper the recovery effect intrinsic to the electrochemical cells was exploit to increase battery performance in tetherless communication devices. A stochastic pulse discharge was applied in conjunction with bursty traffic and the gain obtained in energy efficiency was shown.

By using discharge shaping techniques, a further improvement is achieved at the cost of an additional delay in providing the required power supply. According to the quality of service constraints that characterize the considered data traffic, a tradeoff between energy efficiency and delay can be found.

Although results were derived only for the dual lithium ion insertion cell, we believe that the benefits of stochastic pulse discharge are enjoyed by any of battery technologies used in portable communication devices. However, additional results for different values of current density, as well as, further investigation of discharge shaping techniques are needed.

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