Battery-Driven Dynamic Power Management

Luca Benini
Università di Bologna

Giuliano Castelli

Alberto Macii

Riccardo Scarsi
Politecnico di Torino

Battery lifetime extension is a primary design objective for portable systems. We introduce the concept of battery-driven dynamic power management, which strives to enhance lifetime by automatically adapting discharge rate and current profiles to battery charge state.

The activity of several components in a computing system is event-driven. For example, the activity of display servers, communication interfaces, and user interface functions is triggered by external events, and it is often interleaved with long, idle periods. An intuitive way to reduce average power dissipated by the whole system consists of shutting down resources during periods of inactivity. In other words, one can adopt a dynamic power management (DPM) policy that dictates how and when various components should be shut down according to a system's workload. Workload-driven DPM can be very effective, thanks to sophisticated policies, based on complex computational models (such as Markov chains) proposed in the recent literature.[1]

We observe, however, that minimum average power is not always the objective when designing battery-operated, mobile applications. Rather, what really matters for this kind of system is ensuring long battery lifetime. Average power reduction and battery lifetime extension may be numerically far apart.[2] This implies that optimizations for minimum average power may not be equally effective in extending battery lifetime, and vice versa. Our work moves from the assumption that taking battery's charge state into account while managing the system helps in maximizing the time of operation of portable devices.

We describe several DPM policies specifically tailored to battery lifetime maximization. In particular, we introduce a class of closed-loop policies, whose decision rules used to control the system operation state are based on the observation of a battery's output voltage (which is related, nonlinearly, with the charge state). This is in contrast with open-loop solutions that reach decisions about component shutdown independently from battery voltage measurement.

Open-loop policies are normally simpler, but less effective, than closed-loop ones; they represent a viable option when cost constraints prevent the use of a voltage sensor on the battery terminals. On the other hand, the distinguishing feature of closed-loop policies is that they control system operation based on the observation of both system workload and battery output voltage. As a consequence, they can dynamically adapt a component's shutdown scheme to the actual battery charge state.

Battery properties

From the system designer's point of view, the physical properties of interest in a battery are output voltage and battery capacity. In an ideal battery, the voltage is constant over a complete

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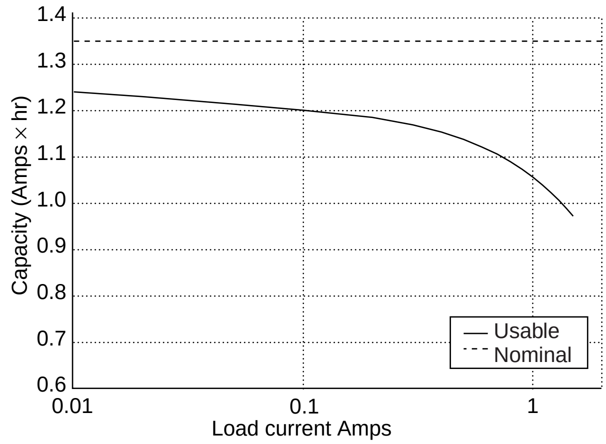

Figure 1. Capacity variation as a function of load current.

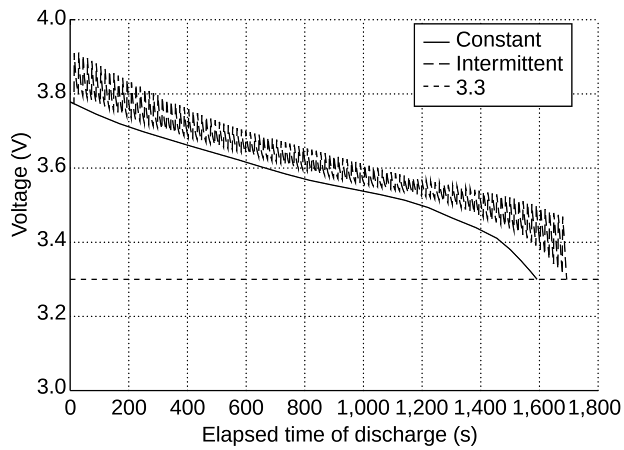

Figure 2. Continuous compared with intermittent discharge.

discharge cycle, and it drops to zero when the battery is fully discharged. In practice, however, voltage decreases as the time of discharge increases. As a matter of fact, a battery is considered exhausted when its output voltage falls below a given voltage threshold (such as 80% of the nominal voltage). This behavior motivates the adoption of DC-DC converters for voltage stabilization when batteries are used to power up digital systems.

Beside this, two additional factors differentiate real batteries from ideal power supplies that are at the basis of the battery-based DPM technique:

- the effective capacity of a battery depends on the discharge current, and
- a battery can recover some of its deliverable charge when it is given some rest.

We illustrate these two effects through experimental evidence, rather than by rigorous construction and derivation of mathematical models representing electrochemical phenomena. Readers may refer to the vast, specialized literature for more information.[3]

The data we present have been obtained through event-driven simulation of the system-level, discrete-time model of a lithium-ion battery.[2] Such a model guarantees an average error in estimated lifetime of 0.52% with respect to a circuit-level, continuous-time model.[4,5] The latter, in their turn, have proven to be within 15% from measured data under a large variety of loading conditions.

Capacity versus discharge current

At higher currents, a battery is less efficient in converting its chemically stored energy into available electrical energy. This fact is pictorially shown in the diagram of Figure 1, where the capacity of the battery is plotted as a function of the average current load. The plot is relative to a battery of nominal capacitance of 1.35 Amp/hr (solid line). We observe that, for increasing load currents, the battery capacity progressively deviates from the nominal value (dashed line).

Charge recovery

A battery can recover some of its deliverable charge if discharge periods are interleaved with rest periods (periods in which no current is drawn). This is shown in Figure 2, where the output voltage of the battery is plotted under two discharge profiles: a constant current load (solid line) and an intermittent current load (dashed line).

Both the constant current and the intermittent current, while on, have the same discharge rate. In addition, the off time of the intermittent discharge is not shown in the plot. Then the *x*-axis represents the actual elapsed time of discharge, and it is proportional to the actual usable capacity of the battery. Note that, in the plot, the constant line at 3.3 V represents the voltage level under which the battery is regarded as exhausted.

The implications of nonideal battery discharge phenomena have been analyzed by several authors in the recent past.[2,6,7] Martin showed how the nonlinear dependency of battery capacity from discharge current should be taken into account when setting the frequency of operation of a battery-powered motherboard.[6] Pedram et al. analyzed the supply voltage and speed setting for maximizing the lifetime-performance product.[7] These approaches can be applied at design time, but they do not investigate the potential of runtime, battery-conscious, dynamic power management. Wu et al. proposed a dual-battery power management policy that switches between a low discharge rate (high-capacity) cell and a high-rate (lower capacity) cell depending on the load current absorbed by the system.[8] No previous work, to our knowledge, has addressed the monitoring of battery output voltage for lifetime maximization.

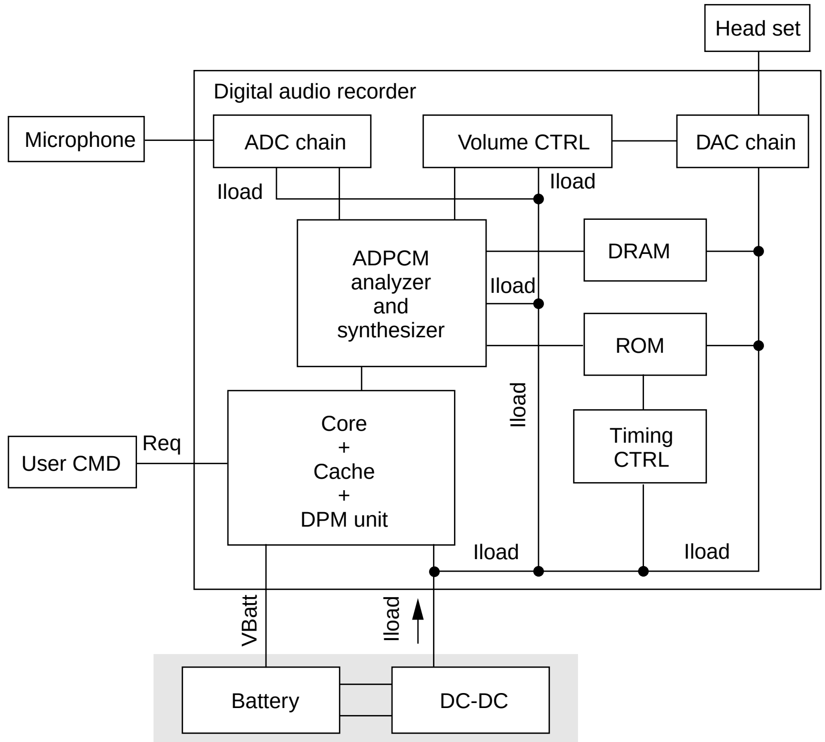

Figure 3. Block diagram of the Oki digital audio recorder.

Battery-driven DPM policies

In general, DPM policies target the maximization of battery lifetime by controlling the system operation mode (or its components). Power-managed systems must be able to operate in different states, which trade off performance for power consumption. We can distinguish between reduced-performance, low-power active states, and inactive, quiescent states. When the system is idle, the power management can force a transition to a quiescent state. The consequences for such a transition are latency and power. Generally, there is a delay and energy cost for activating a system in quiescent state. Even if the system is not idle, in some cases it can be forced into a state where it operates with lower performance and with reduced power.

Case study: a digital audio recorder

To illustrate battery-driven DPM, we consider the system-level description of a digital audio recorder, whose block diagram, shown in Figure 3, is similar to a commercially available product by Oki (Oki Silicon Solutions Company, MS87V1021, http://www.oki.co.jp/semi/english/ms87v102.htm) System components, can be power-managed through signals issued by a DPM unit in accordance with the selected DPM policy.

The digital audio recorder consists of a core processor with 8 Kbytes of cache and a DPM unit, 128 Kbytes of dynamic RAM (DRAM), 64 Kbytes of ROM, an adaptive differential pulse code modulator (ADPCM), a volume controller (Volume CTRL), a timing controller (Timing CTRL), an analog-to-digital conversion block (ADC chain), and a digital-to-analog conversion block (DAC chain). External to the system are the battery subsystem, which includes the DC-DC converter, a block (User CMD) that emulates the input commands provided by the user, a microphone (MIC), and a head set (Head set).

The system can operate in five different states:

- Off: The system is completely turned off and consumes no power.

Table 1. Energy cost per state transition.

	RawSound (mJ)	FineSound (mJ)
Off	49.5	99.0
Sleep	11.5	29.7
Idle	2.0	4.1

Table 2 Latency cost per state transition.

	RawSound (mJ)	FineSound (mJ)
Off	150	200
Sleep	70	100
Idle	40	60

- Sleep: The system is in sleep state and absorbs a current of 15 mA.
- Idle: The system is idle and absorbs a current of 220 mA.
- RawSound: The system plays low-quality sound and absorbs a current of 460 mA.
- FineSound: The system plays high-quality sound and absorbs a current of 790 mA.

When the system moves from one of the quiescent states (such as Off, Sleep, and Idle) to one of the active states (such as RawSound and FineSound), it consumes some additional energy, as summarized in Table 1.

Obviously, transitions between states introduce some latency penalty, as shown in Table 2.

A typical usage of the system consists of an alternate, aperiodic sequence of active (playing sound) and idle (silence) intervals. When no DPM policy is implemented, the system automatically enters the Idle state as soon as the FineSound state is left (that is, playing has terminated). From there, it can either go to the Off state, upon explicit request of the user, or go back to the FineSound state, if playing should resume. Notice that states Sleep and RawSound are never entered when the system runs in normal (that is, not power-managed) mode.

Open-loop, time-out policy

We first consider a simple open-loop time-out policy. When the system stops playing, it immediately enters the Idle state; it waits there for a first time-out, T_1, then it transitions to the Sleep state. After a second time-out, T_2, if the system is still quiescent, it is transitioned to the Off state. Clearly, this policy aims at increasing battery lifetime by reducing the current absorbed by the system while it is not playing (states Sleep and Off are less current-demanding than the Idle state), but also by reducing the overhead due to transitions from Sleep and Off states to FineSound (these states are not entered until time-outs have expired).

Notice that for the open-loop time-out policy just discussed, state RawSound is not used. The duration of the time-out for each quiescent state is set to the break-even time (the minimum time spent in a quiescent state to amortize the energy spent in transitioning in and out of it). It was shown that this time-out choice is two-competitive (it can be outperformed by at most a factor of two by an oracle policy with complete knowledge of the future).[9] The time-out policy is workload-driven and does not take into account battery characteristics.

Closed-loop policy

The simplest closed-loop policy is threshold-based. It aims at maximizing battery lifetime by lowering the quality of the sound when the battery is almost discharged. If the battery is fully charged, the system is kept in the FineSound state. When the battery's output voltage falls below a threshold V_{th} the system is forced into the RawSound state until the battery is fully discharged. The rationale for this policy is to provide graceful degradation of system performance as the battery discharges. Clearly, the choice of V_{th} is critical for trading off sound quality with battery lifetime.

We have adopted the quality factor Q as the quality metric. Q is defined as the ratio between the time the system is in the FineSound state T_{Fine} and the total time of operation $T_{\text{Fine}} + T_{\text{Raw}}$. In symbols:

$$Q = \frac{T_{\text{Fine}}}{T_{\text{Fine}} + T_{\text{Raw}}}$$

To capture the tradeoff between battery lifetime and sound quality, we define metric P:

$$P = NLT \times Q$$

where *NLT* is the normalized battery lifetime. The optimal value V^*_{th} that maximizes P depends on both system and battery characteristics. A complete exploration of the tradeoff curve is provided in the following section.

It is important to notice that the time-out and the voltage threshold policy are not mutually exclusive, and they should be applied together for best results. The hybrid policy exploits quiescent intervals in the workload, but it also trades off quality of the sound for battery lifetime.

Policies for dual-battery systems

Modern portable appliances, such as laptop computers and cellular phones, can accommodate two batteries in the same case. The batteries are normally used following a sequential scheme: the second battery starts operating (that is, supplies the current) only when the first battery is totally discharged.

It was shown earlier that electrochemical cells could recover some amount of deliverable charge if they are allowed to rest after a period of high-current discharge. This behavior can be fruitfully exploited in a dual-battery system by adopting power management schemes where the two batteries alternate in providing current to the load. In this way, the battery temporarily disconnected from the load can recover, while the other one powers the system.

We study several open- and closed-loop policies for dual-battery power management. The baseline for the comparison is a dual-battery system where batteries are discharged in sequence.

Open-loop switching policy. A simple open-loop policy switches between one battery and the other with a fixed frequency f_{sw}. With this policy, which we call Policy 1, the lifetime of the system depends on f_{sw}. For very low values of f_{sw}, each battery is drained for a long time with the full current load. The discharge behavior tends to the limiting case of $f_{sw} = 0$, in which the two batteries are discharged in sequence, one after the other. As f_{sw} increases, although the discharge behavior of the two batteries is less predictable, it is reasonable to expect a lifetime increase thanks to the recovery effect just mentioned.

This conjecture is confirmed by the experimental results reported in the Experiments section, which also includes a detailed study for locating the most suitable value of f_{sw}. In principle, we would like to choose a value $f_{sw} \rightarrow \infty$, because the discharge behavior would tend to be that of a single battery with double capacity. However, experiments have shown that values of f_{sw} higher than a few tens of a Hertz would only marginally impact lifetime extension. In addition, at a high f_{sw}, the behavior of the selector circuit that alternatively connects the batteries to the DC-DC converter may become a critical issue.

Closed-loop policies. A simple closed-loop policy can be obtained by setting a voltage threshold, as in the single-battery case. As soon as the output voltage of the battery system (that is, the output voltage of the battery currently connected to the load) drops below threshold V_{th}, the system is transitioned to the RawSound state, until full discharge. The main shortcoming of this scheme, which we call Policy 2, is that it does not take into account the charge recovery of the batteries during the rest period. Even if a battery output voltage drops below V_{th} while the battery is fully loaded, it may rise back to a value higher than the threshold while the battery is unloaded. Hence, the simple threshold-based scheme may transition the system into RawSound too early, thereby reducing the quality of sound.

This limitation of the basic closed-loop policy can be overcome if we adopt a slightly more complex switching scheme, called the sequel Policy 3. More specifically, we propose a policy with three regions of operation. In the first region, the switching between the two batteries has constant frequency, and the state of operation is FineSound. The second region is entered when the output voltage of one battery first reaches V_{th}. The state of operation is still FineSound, but switching between batteries is voltage-controlled. When the output voltage of the loaded battery reaches V_{th}, it is disconnected from the load (to give it some recovery time). The second region is exited when the output voltage of the battery temporarily disconnected from the load does not increase beyond $V_{th} - \Delta V$ during the recovery time. In

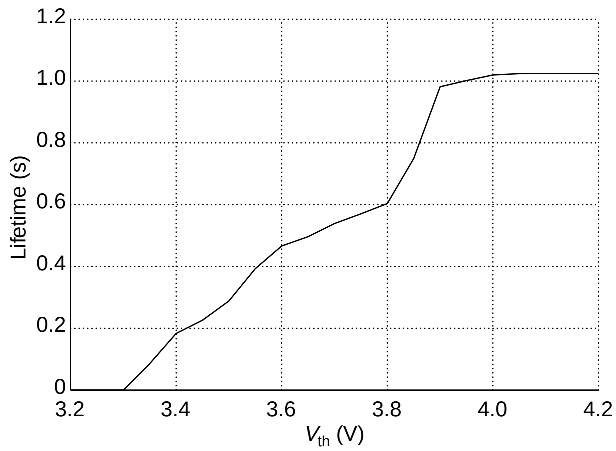

Figure 4. Normalized battery lifetime (NLT) compared with V_{th}.

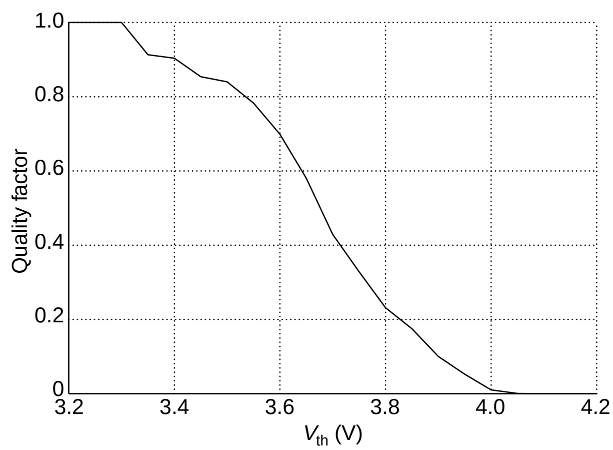

Figure 5. Quality factor (*Q*) compared with V_{th}.

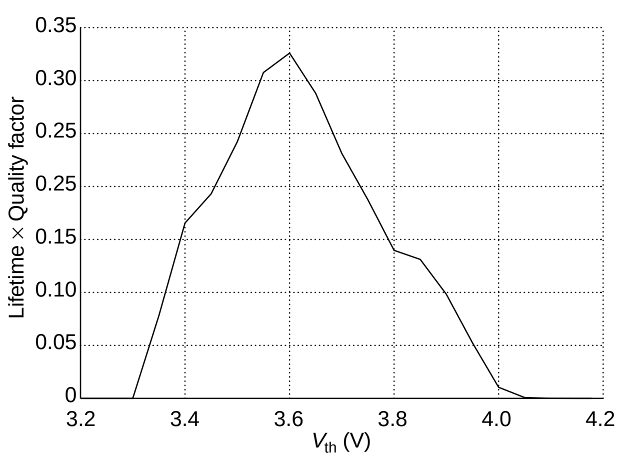

Figure 6. P compared with V_{th}.

the third region, the fixed frequency-switching scheme is restored, and the system is transitioned into the RawSound state until both batteries are fully discharged.

The closed-loop policies we've discussed are clearly orthogonal to the time-out policy we used in the context of single-battery systems. As such, they can be applied altogether to synergically enhance lifetime.

Experiments

To collect all the experimental data, we have applied to the system inputs a workload consisting of an input trace corresponding to typical digital audio recorder use over a time period of approximately 2.5 hours. Therefore, playing and pause intervals of different duration are interleaved in an uncorrelated fashion, and are sometimes followed by shutdown commands issued directly by the user (which force the system to the Off state).

Single-battery system

The open-loop, time-out policy is the first solution we have tested. It extends battery lifetime from 9,650 to 10,917 seconds (that is, by approximately 14%). Application of the closed-loop policy first requires the identification of the threshold voltage, V_{th}, that discriminates between system operation in FineSound and RawSound. Figures 4, 5, and 6 show normalized battery lifetime (NLT), quality factor Q and product, $P = \mathrm{NLT} \times Q$ of these two quantities as functions of V_{th}.

As expected, NLT increases monotonically as V_{th} increases, while Q decreases, still monotonically but with a different shape and slope. Therefore, the product curve exhibits a maximum value for $V_{th} = V^{*}_{th} = 3.6V$. We used this value of V_{th} in the implementation of the battery-driven, closed-loop policy.

When the closed-loop policy is applied in isolation, such as with the time-out policy disabled, a lifetime extension of 22% has been obtained (11,754 seconds against 9,650). As we have already noted, the two policies are not mutually exclusive. Actually, they are very effective if they are combined together. Lifetime extension has gone up to 16,008 seconds, that is 66% higher than the non-managed case. Values of the quality factor are acceptably high (0.679499 for the closed-loop policy alone and 0.698903 for the combined policy).

Clearly, a different choice of the threshold voltage would change both battery lifetime and quality factor. Moving towards higher values of V_{th} would imply a longer battery duration at the cost of reduced sound quality. The opposite would occur by decreasing the threshold voltage. This is demonstrated in Table 3, in which lifetime (in seconds) and Q are reported for different values of V_{th}, namely, $V_{th} = 3.6$ V (or V^*_{th}), $V_{th} = 4.0225$ V and $V_{th} = 3.4275$ V.

We observe that, if the time-out policy is disabled, the difference in lifetime extension between cases $V_{th} = 3.4275$ V and $V_{th} = 3.6$ are almost negligible, while the quality factor is much higher. This indicates that the choice of the optimal value of V_{th} is not always advisable in practice.

Table 3. Lifetime and quality factor for different V_{th}.

	Without time-out policy		With time-out policy	
V_{th}	LT	Q	LT	Q
3.4275 V	10,571	0.892231	14,951	0.888409
3.6V	11,754	0.679498	16,008	0.698903
4.0225 V	16,486	0.250451	22,091	0.197222

Dual-battery system

The first set of experiments performed on dual-battery policies assesses the lifetime extension that can be achieved by switching between two batteries with fixed frequency f_{sw}. Battery lifetime for different values of f_{sw} is shown in the semilogrithmic diagram of Figure 7. The plot clearly indicates that the battery-switching scheme results in sizable lifetime extensions for a range of switching frequencies. When f_{sw} is very low, the two batteries are discharged in sequence, and lifetime is minimum. This corresponds to the scheme currently adopted by commercially available appliances that contain two batteries. As f_{sw} increases, lifetime increases as well, until a diminishing return is reached. Most of the lifetime benefits are obtained by switching between batteries with $f_{sw} \approx 0.1$ Hz. Observe that, in order to isolate the effect of f_{sw} on lifetime, the curve of Figure 7 has been determined by loading the battery with a constant current, instead of the usual trace of operation. In particular, the current load we applied corresponds to that absorbed by the system when running in the FineSound state.

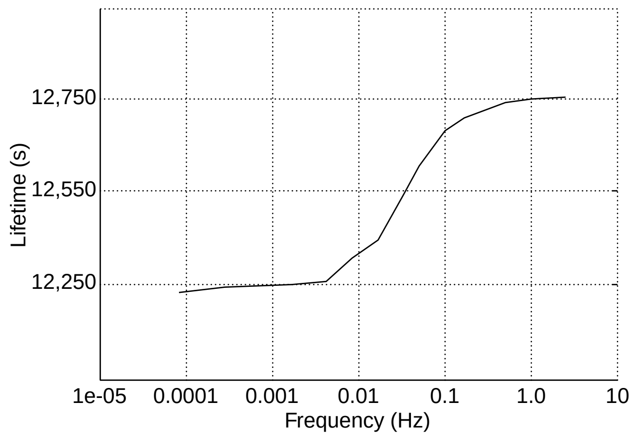

Figure 7. Battery lifetime compared with f_{sw}.

Table 4. Lifetime and quality factor for different dual-battery policies.

Policy	LT (sec)	LT (%)	Q	Q (%)
Policy 1	29,378	—	1	—
Policy 2	31,669	7.79%	0.7046293	– 29.54%
Policy 3	31,535	7.34%	0.7077156	– 29.23%

A second set of experiments was performed to test the effectiveness of the closed-loop policies presented. The switching frequency was set to $f_{sw} = 0.1$ Hz, and the time-out policy was enabled to achieve maximum lifetime extensions (Table 4).

The open-loop policy (Policy 1) with $f_{sw} = 0.1$ Hz, used as a baseline for comparison, has maximum quality, because the system never enters the RawSound state. The first closed-loop policy (Policy 2), with a voltage threshold set to $V_{th} = 3.6$ V, aggressively trades off quality for lifetime extension, while the second closed-loop policy (Policy 3) slightly improves quality with a small penalty in lifetime.

The results demonstrate that dual-battery switching policies effectively increase lifetime, even when no quality loss can be tolerated. Furthermore, closed-loop policies can trade off quality losses for sizable lifetime extensions.

Battery-driven power management opens new opportunities for lifetime extension in portable systems. We have proposed several open-loop and closed-loop policies that increase battery lifetime by taking into account battery characteristics. Our experiments have also shown that battery-oriented power management can work synergically with traditional workload-driven DPM to achieve further lifetime increase.

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For questions regarding this article, please contact Luca Benini at phone + 39 051 209 3782 or e-mail lbenini@deis.unibo.it.

Luca Benini received the Dr. Eng. degree in electrical engineering from Università di Bologna, Italy, and the MS and PhD degrees in electrical engineering from Stanford University. He is an Assistant Professor at Università di Bologna and a visiting professor at Stanford University. He also holds a position as visiting scientist at the Hewlett-Packard Laboratories, Palo Alto, Calif. His research interests are in all aspects of computer-aided design of digital circuits, with special emphasis on low-power applications.

Giuliano Castelli received the Bachelor degree in physics in 1996, from the Faculty of Natural, Physics and Mathematics Science of the University of Trieste. Since October 1998 he has been with the Computer Science Department of Politecnico di Torino, where he is currently a PhD student. His research interests are in design, construction, and optimization of models of digital systems powered with batteries.

Alberto Macii received the Dr. Eng. degree in computer engineering from Politecnico di Torino, Italy, where he is working towards his PhD degree in computer engineering. His research interests include several aspects of the development of algorithms, methods, and tools for low-power digital design.

Riccardo Scarsi received the Dr. Eng. degree in electrical engineering from Politecnico di Torino, Italy, where he is working towards his PhD degree in computer engineering. His research interests include several aspects of the development of algorithms, methods, and tools for low-power digital design.