



Optimizing Microcontroller Power Efficiency for Ultra Low Power Designs

*Jukka Eskelinen, tinyAVR Marketing Director
Kim Meyer, FAE*

Summary

The rise of ultra low power applications has changed how developers must approach power optimization. Devices must support single-cell operation, charge/discharge closer to battery thresholds, and be able to control motors and/or high brightness LEDs, all while reducing device form factor and cost. Power management needs to be implemented at all levels, from the processor architecture up through the application layer, with power consumption coordinated across the entire system.

The ATtiny43U provides an optimal platform for developing efficient, single-cell architectures, enabling designers to build compact battery-operated devices at the lowest cost and highest power efficiency. With its integrated boost regulator, multiple current modes, smart battery management capabilities, optimized processor architecture, and extensive low power architectural innovations, designs based on the ATtiny43U can drain cells down to 0.7 V while operating high current LEDs and small motors.

Table of Contents

<i>Introduction.....</i>	<i>2</i>
<i>Efficient Voltage Conversion.....</i>	<i>2</i>
<i>Boost and Low Current Modes.....</i>	<i>3</i>
<i>Smart Battery Management</i>	<i>4</i>
<i>Implementing Power Efficiency at the Application Level.....</i>	<i>5</i>
<i>Selecting an Ultra Low Power/ Ultra Low Voltage MCU</i>	<i>6</i>
<i>Conclusion</i>	<i>10</i>

Introduction

Optimizing power consumption, whether for consumer, industrial, or medical applications, has typically been addressed by reducing active processing time and increasing how long processors can reside in sleep mode. With the rise of ultra low power applications, however, this approach no longer suffices. Trends such as single-cell operation, charging/discharging closer to battery thresholds, and the need to control motors and/or high brightness LEDs, all while reducing device form factor and cost, have changed how developers must approach power optimization.

For devices such as electric toothbrushes, personal media players, remote controllers, wireless sensors, and a wide range of other portable and handheld devices, power management needs to be implemented at all levels of a system. By optimizing power consumption through efficient single-cell voltage conversion, utilizing multiple current modes, introducing smart battery management, and implementing power saving techniques at the application level, power consumption can be coordinated across an entire system.

Efficient Voltage Conversion

Many ultra low power applications are moving to single battery cell architecture in order to reduce device cost, size, and weight, three of the key factors that determine the success of battery-powered portable applications. Oftentimes, the battery is heavier than all of the other components and PCB combined. In addition, standard AA or AAA batteries are typically the single largest component on the PCB. Reducing the power supply to a single cell is attractive because it simplifies battery holder mechanics and results in significantly smaller and lighter overall product construction.

Designing to a single-cell power supply, however, introduces a variety of new challenges for designers. While the voltage from a single battery cell usually ranges from 1.2 V to 1.5 V when fully charged, cells can drop below 1 V while still possessing a substantial amount of usable energy. Even MCUs with a 1.8 V power supply require at least two cells in series to operate and some applications, such as driving high-intensity LEDs with high forward

voltages, require as many as four cells. In order to drive motors, LEDs, and even the processor itself from a single-cell, a regulator is required to boost the available voltage to appropriate levels. Boost regulators, however, can cost on par with an MCU and require as much space on the PCB as well. Additionally, some regulators need to be controlled by an MCU, further complicating design.

The seamless operation of a self-managed integrated boost regulator within an MCU not only avoids most of the cost and space issues related to an external regulator, it can enable the MCU to provide greater draining efficiency than is possible using an external DC-DC converter. For example, the integrated regulator of the ATtiny43U (see Figure 1) is able to boost voltages as low as 0.7 V, allowing discharging to continue closer to the end of a cell's reserves than is supported by other types of implementations. An integrated regulator can also offer superior idle current – 1 μ A (typical) for the ATtiny43U – and automatically start as soon as there is sufficient voltage available (1.2 V indicating a full battery is available or charging is near completion).

In addition, the regulator supports any battery technology, giving designers complete freedom in selecting the optimal battery for a particular application. Battery voltage can range between 0.7V and 1.8 V, enabling developers to use 1.6 V alkaline or Silver Oxide, 1.5 V Li-Ion, 1.4 V Zinc-Air, and 1.2 V NiMH and NiCd, among others.

Boost and Low Current Modes

High current capacity without external drive circuitry is also important for many applications. The boost regulator of the ATtiny43U has the capacity to drive up to 30 mA, enabling direct control of high brightness LEDs and small motors. By being an integrated part of the MCU, the regulator can be optimized to the architecture to maximize efficiency. For example, Figure 2 shows the conversion efficiency of the ATtiny43U for particular load currents based on remaining charge.

As can be seen from the graph, high current operation is less efficient than when running at a lower current. Most high current applications, however, do not need to operate in high current mode continuously. For example, a toothbrush or camera operates its motors only occasionally. If the architecture is locked into a high current mode, then these devices will operate at reduced efficiency even when the device only requires a low current draw; i.e., the regulator will supply low current at the reduced efficiency characteristic of high current.

To preserve efficiency, the MCU needs to be able to support multiple operating modes. Thus, when the device requires high current and tightly regulated V_{cc} , the MCU and regulator will operate in a Regulated Mode. However, when motors or other peripherals are not in use, and the load current drops down to below 0.6 mA, the regulator automatically switches into a Low Current Mode, performing more efficient power conversion.

Additionally, at light or no loads the converter in Regulated Mode will periodically reach its duty cycle low limit. By automatically dropping into Low Current Mode, the converter stops switching and reduces current consumption to a minimum while still remaining active (see Figure 3). Such variation in output voltage occurs when the MCU is in Power Down or consuming little power. In the main mode of operation, Active Regulated Mode, output voltage remains stable within 3V $\pm$ 100mV. Also note that the typical transition voltage changes as the energy in the cell is depleted (see Figure 4). The regulator is an

independent subsystem that requires no active management by the MCU. However, for designers who require more direct control of the boost regulator, certain features can be controlled through software.

As efficiency also depends upon the application, it does not make sense to integrate all of the passives associated with power regulation. For example, while cost is the primary driver for some markets, operating life is tantamount in others. Rather than be forced to use passives optimized for the wrong market driver or that provide decent (but not optimal) response across all applications, developers ideally will be able to select the passive components that provide the right balance for their application. This can be achieved with less than a handful of components (i.e., a single inductor, two by-pass capacitors, and a Schottky diode).

Smart Battery Management

Accurate estimation of remaining power is an important factor in maximizing utilization of available battery charge. Rechargeable batteries, for example, require careful monitoring and charging control within set limits to ensure safe usage and optimum operating life. The more accurately remaining charge can be estimated, the closer these batteries can be charged and discharged to their limits without risk of damaging the capacity of the cell from charging or discharging too deeply.

While finer control of battery charging and discharging means longer operating life because greater cell capacity is accessible, lack of flexibility in this control can severely limit the battery technologies a processor can support. For example, different battery chemistries have different voltage thresholds to which they can be safely charged and discharged. If an MCU has fixed thresholds or limitations in how these thresholds can be configured, this will be reflected as a limitation in the battery technologies the MCU can manage efficiently. As a result, developers may be forced to use a particular battery based on the MCU selected rather than being able to choose the battery technology best suited for the application.

For applications where users must replace batteries, flexibility is critical in being able to support rechargeable cells. Rechargeable cells have significantly different thresholds than their disposable counterparts. If they are drained too far, this can damage their overall charge capacity. The resulting drop in operating life will most likely be perceived as the fault of the device rather than the battery. The ATtiny43U's firmware can monitor the battery voltage using the built-in ADC and decide when to put it in Stop Mode, thus thoroughly draining disposable batteries while ensuring the maximum life of rechargeable cells over multiple recharging cycles.

While automatically shutting down the processor protects rechargeable cells, an abrupt loss of power may not be acceptable from an application perspective. For example, shutting a camera down suddenly will leave the lens exposed and vulnerable. As such, an important component of power management is being able to accurately estimate remaining power. This can be achieved by using the 10-bit ADC of the ATtiny43U to measure the battery voltage at regular time intervals. In this way, the application can have a chance to place devices into a safe configuration before shutdown.

Implementing Power Efficiency at the Application level

Many applications add an MCU as a secondary processor to assist the main host processor. This MCU offloads tasks such as updating the display, monitoring the keyboard, operating small motors, and intelligently managing smart batteries. The advantage of using a second processor is that an MCU can execute these functions with higher power efficiency than an applications processor. For example, an applications processor monitoring a keyboard would need to wake up frequently to perform this task. Alternatively, using an MCU to monitor the keyboard and update the display would enable the applications processor to sleep longer uninterrupted, resulting in substantial power savings as an MCU consumes less power in active mode than an applications processor.

Of course, processing efficiency has a significant impact on power efficiency as well since the more work an MCU can perform each cycle, the sooner it can drop into sleep mode. Increasing clock frequency increases power consumption so more effective MCU architectures will support a dynamic operating frequency as well as execute instructions in a single cycle and automate management of peripherals.

Ultra low power MCUs also require multiple sleep modes. For example, a sensor application may monitor temperature until it exceeds a threshold. Keeping the entire MCU in active mode during monitoring consumes more power than is actually necessary. Support for different sleep modes that allow developers to shut down different parts of the device enable better power conservation (see Table 1).

There are several architectural innovations developers can utilize in the ATtiny43U architecture that increase power efficiency in both active and sleep modes:

True Supply Voltage: While an MCU may accept a single voltage supply, it might have varying internal voltages across its architecture. Such a design methodology introduces power inefficiencies as the dynamic power will be higher than anticipated. When all analog peripherals, Flash, EEPROM, and RAM run at the same voltage, less power is consumed by the device overall.

Minimized Leakage Current: Temperature, supply voltage, and process technology affect leakage current. Rather than modifying an existing architecture to run at a lower voltage, ultra low power MCUs must be created from the ground up with power efficiency in mind, such as how Atmel's picoPower AVR family of microcontrollers were designed.

Low Power Brown-Out Detection (BOD): While zero-power brown-out detectors consume no power, they are also slow to respond and can require a full millisecond to detect a below-threshold voltage, thus leaving the MCU at risk. Alternatively, a "Sleeping BOD" can detect brown-out conditions in 2 microseconds while drawing only 20 μ A. Since no brown-out protection is required when the MCU is in deep sleep modes, a sleeping BOD can be turned off, consuming zero power as well. In this way, developers can have both low power and fast responsiveness.

Digital Input Disable Registers (DIDR): Multiplexing inputs to a peripheral such as an ADC increases design flexibility for low pin-count devices. However, when voltages in the range of $V_{cc}/2$ are applied, the transistors comprising the input buffer will experience

leakage of current. The use of dedicated Input Disable Registers, with one disable bit per analog input, enable developers to disable individual input buffers to prevent leakage.

Clock Gating: Clock gating reduces the toggling frequency of any clock domain. Any clock that is not in use can be gated so that it does not unnecessarily consume power.

Power Reduction Register: While multiple sleep modes simplify power management, they often turn whole blocks of peripherals on or off. Thus, if only one peripheral is in use, several others must also be active. A Power Reduction Register gives developers full control to turn off individual peripheral modules. Disabling one peripheral module can result in a reduction of 5-10% of the total power consumption in active mode and 10-20% when in Idle mode.

Flash Sampling: Traditional Flash is designed to always be enabled while in active mode. At lower clock speeds, however, the Flash read time will be less than the clock period. Flash sampling enables the Flash on the order of 10 ns to sample the array's contents and then immediately disables it, reducing average power consumption.

Fast Wake Up: If a system is slow to wake, it will need to be left in active mode longer to accommodate the added latency to prevent disruption of real-time event processing. Put another way, the faster the MCU can wake, the longer it can stay asleep.

Selecting an Ultra Low Power/Ultra Low Voltage MCU

Developers need to be aware when reviewing specs of different ultra low power MCUs to ensure that equivalent measurements are compared. For example, consider:

- **Efficiency across a range:** Efficiency specs are usually given at an MCU's best measurement (sweet spot) rather than across load current and voltage. The typical operating range of an application may position it along a less efficient curve. Additionally, efficiency must be evaluated across the entire voltage drop of a cell.
- **The safe operating range of a cell:** While an MCU may be able to drain a battery quite low, without sufficient accuracy to measure voltage and temperature, the limits of the cell may be exceeded, resulting in battery damage and shorter operating time. Accuracy is a key factor in determining how much of a battery's energy potential a device can safely exploit.
- **Regulator inefficiency:** An MCU without a boost regulator will have higher efficiency specs because the conversion losses are hidden in the external regulator. Also, for single-cell designs, don't forget to include the cost and design complexity of an external boost regulator if the MCU does not integrate one.
- **The efficiency across a device's entire use profile:** An MCU may have high efficiency when driving high currents, but unless it offers multiple operating modes, it will be less efficient when driving low currents. If an application requires high current capacity on a relative infrequent basis, overall efficiency could suffer as a result.
- **Whether specs were measured with a single or multiple cells:** Certain MCU specs will change, depending upon the number of cells in use. For example, if multiple cells are available, an internal boost regulator can be bypassed, thereby increasing efficiency.

Conversely, listed specs made with multiple cells, such as wake up time, may be lower when only a single cell is used.

- The maturity of the development environment: Achieving ultra low power requires innovation at the architectural level. Ultra low power MCUs based on entirely new architectures often at best offer only marginal design tools that are still under development. With software development one of the most significant cost drivers, the stability, completeness, and capabilities of the design tools play a major role in how efficient developers can manage power consumption, as well as how quickly they can speed time-to-market.

One way to determine how ultra low power a MCU actually is to measure it for yourself. Demo Kits provide an effective means for both testing a MCU's efficiency under real-world operating conditions and exploring its feature set. The ATtinyx3U top module, for example, attaches to the STK600 development board, giving developers full access to the ATtiny43U's capabilities and Atmel's comprehensive suite of proven development tools (see Figure 5). Using the module, developers can test the limits of single-cell operation, profile power consumption while directly driving a high brightness LED, and drive the integrated boost regulator's auto shut-down and power-on features to tune power thresholds to utilize the maximum capacity of cells within safe parameters.

Figure 1. Integrating a boost regulator enables the ATtiny43U to operate from a single cell with voltages as low as 0.7 V, efficiently driving loads up to 10 mA and allowing discharging to continue closer to the end of a cell's reserves compared to other types of implementations.

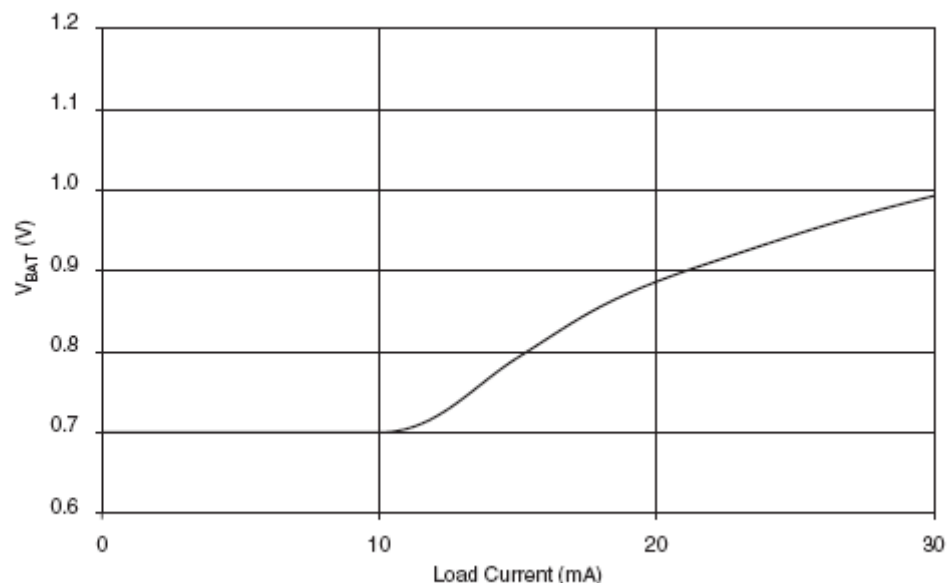


Figure 2. An integrated boost regulator is optimized to its MCU architecture, maximizing conversion efficiency across varying loads and supply voltages. Integrated

regulators also reduce board space requirements and lower overall system cost by eliminating the need for an external regulator.

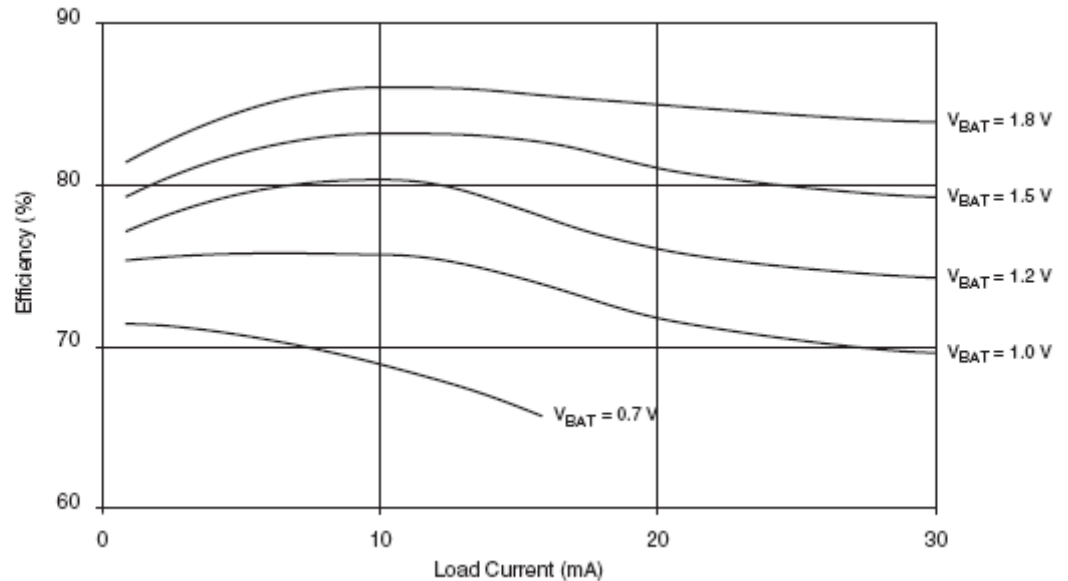


Figure 3. This graph shows typical output voltage patterns of a Boost Converter at various loads. At light or no loads (plotted in green), the switching time (rising voltage) is measured in hundreds of microseconds while idle time (falling voltage) is measured in seconds. Note that such variation occurs when the MCU is in Power Down or consuming little power. In the main mode of operation, Active Regulated Mode, output voltage remains stable within $3V \pm 100mV$ (plotted in red).

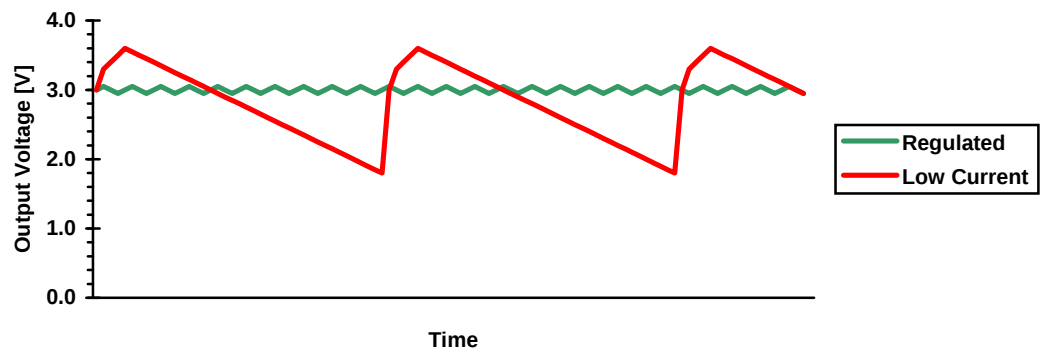


Figure 4. The typical transition range between Active Low Current Mode and Active Regulated Mode is dependent upon the available input voltage and load.

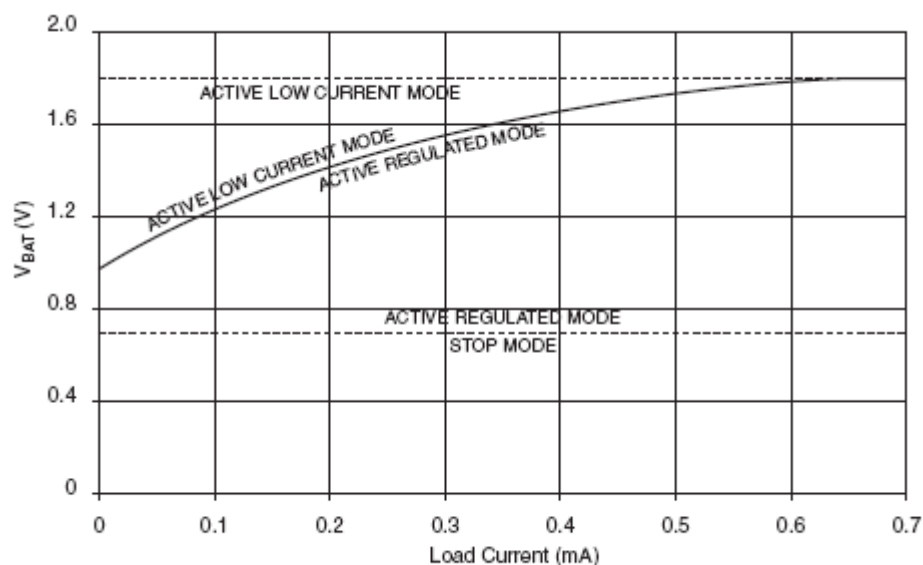


Figure 5. Demo kits such as the STK600 and ATtinyx3U top module enable developers to measure power efficiency under real-world operating conditions. These kits give developers full access to the ATtiny43U's capabilities and Atmel's comprehensive suite of proven development tools, enabling the testing of single-cell operation, power profiling of high brightness LEDs, and tuning of power thresholds to utilize the maximum capacity of cells within safe parameters.



Table 1. Caption: Multiple sleep modes enable developers to place an ultra low power MCU in a variety of reduced-power idle modes when only limited functionality is

needed rather than requiring the entire MCU to operate in a higher power active mode.

Mode of Operation	Condition	Level of Activity	Can Wake Device	Current Consumption
Power Down	$V_{BAT} = 1.2V$	No clocks running. Retains RAM	External interrupt, pin change or Watchdog Timer	5 μA
Idle	$V_{BAT} = 1.2V$	All peripherals run as normal. No code can run	Any peripheral can wake up CPU	0.7 mA
Active	$V_{BAT} = 1.2V$ $f_{CLK} = 4MHz$	Fully active	Already awake	5 mA

Conclusion

Single-cell designs eliminate the payload of extra batteries, typically the heaviest and largest component in ultra low power systems. MCUs integrating an on-chip regulator with configurable modes efficiently bridge the gap between the minimum supply voltage of the MCU and typical output voltages of standard single-cell battery technologies, enabling developers to minimize power consumption based on available load conditions and battery voltage. With only one battery, no external regulator, the ability to drain cells down to 0.7 V, and high current capacity for LEDs and small motors, designers can build compact battery-operated devices at the lowest cost that are truly ultra low power.

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Contact: Jukka Eskelinen, tinyAVR Marketing Director, Finland, Tel: 358-9-4520-820, e-mail: jukka.eskelinen@atmel.com

Kim Meyer, FAE, Finland, Tel: 358-9-4520-820, e-mail: kim.meyer@atmel.com

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