Ultra Low Power Design

Practical Hints and Pitfalls

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***Abstract* — IOT, wearables, data loggers and new radio applications are creating a growing demand for low power and ultra-low power electronic circuits. This article explains some power saving methods and components as well as some pitfalls one should be aware of when trying to eliminate microamps of current consumption. Last, but not least, some marketing influenced statements are commented from a practical point of view.**

Keywords* — *microcontroller; data logger; battery; coin cell; self discharge; capacitor; leakage current; RTC; sleep mode; EMI; radio; RF; wake up; LoRa; Sigfox; NFC; RFID; WiFi; BTLE; IoT; sensor; energy harvesting; quiescent current; wearables;

I. INTRODUCTION

Since the Internet of Things was identified as *the* future market, almost all manufacturers of electronic components claim (some of) their products are perfectly tailored for low power designs. And some really are. But not only finding the components suited best for a certain application is a challenge, some risks and circumstances often are not as obvious as even experienced developers might believe.

II. WHY “ULTRA” LOW POWER DESIGN?

“Pico Power”, “Nanowatt Technology”, “Deep Sleep Mode”, “Zero Power Oscillator” (not a joke!) are some buzzwords you´ll find in … marketing brochures? Yes, of course, but also in datasheets and technical documents. Where does low power start, where ultra-low power? The simple answer is: it depends.

When the author of this document bought a telephone-fax-machine more than 20 years ago, he was rather shocked by a standby consumption of 9 watts! Just for a telephone, ready to ring on call and print in case of an incoming fax. Not to mention, the time also was displayed on an LCD – a 9 Watts clock, most of the time. It was not a big deal to solder a little circuit disconnecting the complete power line and reconnecting it in case of incoming ringing signal. Material in value of about 5 Euro - electronic shop price - saving electric power worth 10 Euro, every year. And, would the machine still live in case of permanent powering? TV set, HiFi equipment, printer, computer, the “completely” switched off washing machine and many others are standby energy eaters. No surprise that several nuclear power plants are running just to meet standby demand (France: 7.2 TWh per year; USA, GB, Netherlands: around 10% of total domestic power- consumption [Greenpeace 2010]). Meanwhile some regulations have been made to avoid unlimited growth of such waste, but the limits are too high by some magnitudes, compared to what´s technically possible. And, don´t forget the rebound effect! Why do we need laws? Why didn´t marketing people discover *real* energy and money saving techniques much earlier as sales arguments? The knowledge has existed for decades (e.g. watches, hearing aids - see literature list at the end of this article).

III. MICROCONTROLLER BASED ELECTRONICS

Most modern electronic devices are controlled by microcontrollers or microprocessors. This chapter is based on an earlier AVR related article, now more in general and with some additional hints.

A. Microcontroller selection

The decision which MCU to use tends to be more and more CPU architecture independent. Most application firmware is written in C and therefore much less platform specific than former assembler programming. Efficient C compilers are available for all state of the art CPUs. What matters much more are peripherals, development tools, the availability of a wide range of devices in terms of memory size, packages, combinations of peripherals and features etc. Most controller manufacturers offer special “low power” versions. But even many modern standard controllers meet similar low power specifications as such special devices do and may fit into a lot of low power applications, if design is made properly. Costs are another non-technical but real world argument.

What about 8-bit versus 32-bit controllers? Again, it depends: do you need 32-bit computing performance? In fact, there are some very low cost 32-bit controllers out there, but they should be compared to modern (!) 8- or 16-bit MCUs very carefully, if such CPU performance is not required. And, by the way, the real cheap 32-bit MCUs often come with poor peripherals and only a minimum of optional features. In such cases an 8-bit controller not only eats less power, but is better tailored for the targeted application taking in account the advanced peripherals. Further growth of 6% to 8% per year is forecasted for the 8-bit MCU market.

B. Manufacturing process size

The smaller the process, the higher the parasitic losses are due to the leakage current. An 8- or 16-bit controller manufactured in a 130 nm CMOS process can be designed in such a way that all volatile memories keep their contents during the deepest sleep mode, "typically" consuming less than 1 µA. A 32-bit controller based on the same process will be significantly more expensive.

Not only leakage current but also EMI sensitivity will be higher on smaller manufactured devices: to avoid too strong electric fields, the internal supply voltage needs to be lowered, causing less stray immunity. The necessary internal voltage regulator also costs some additional current - and startup time.

C. Clocking

Since the current drawn by CMOS logic is approximately proportional to the clock frequency, there is another opportunity to save power. The 1st idea may be to lower down the clock frequency as far as possible, so that the task just can be done within the given timing restrictions. But it´s not that easy: most applications are a mixture of calculation and information transfers. The latter often are bound to their own time frame, e.g. in case of serial communication with a certain baud rate. In such cases switching the clock frequency can significantly save energy. Whereas the communication will be clocked with the lowest reasonable frequency, during calculating the CPU should be clocked as fast as possible, and then set into sleep mode. Or, if the application doesn´t allow this, the clock should be as slow as possible. This method saves energy compared to a lower frequency clocked CPU which then needs to run for a longer time in active mode, powered by the same supply voltage (see box).

Which system clock source should be used? Especially if sleep modes are required, the 1st choice is the internal RC oscillator, if its sufficiently accurate for the application. If in doubt, compare different controllers. Modern RC oscillator tolerances are round about 2% over the full Vcc and temperature range, often without any recalibration. Hint: If jitter is an issue, ask the manufacturer for suitable specifications. In the past, with chip revision changings sometimes also jitter changed (undocumented). This example, by the way, demonstrates the importance of long term availability of original device versions. If the RC is not sufficiently accurate, check for ceramic resonator, then for crystal. Why? The answer is given by the start-up time values in table 1.

TABLE I. OSCILLATOR TYPES

Oscillator type	Accuracy	Start-up time (cycles)
Quartz crystal	10 to 50 ppm	15000
32 kHz watch crystal	5 to 50 ppm	15000 to 30000
Ceramic resonator	0.5 to 1 %	200 to 1000
RC oscillator	1% (calibrated) to 30 %	6

D. Peripherals

A must-have in modern low power MCUs is the option to switch off peripherals while they are not in use, be it by internal disconnecting from power supply or just by switching off the clock line. It´s worth comparing datasheets regarding this feature.

The implementation of direct communication channels between peripherals is very helpful, not only in terms of power saving, but also in ease of design, performance and safety. Buzzwords are DMA, Event System, Core Independent Peripherals (CIP) and others. This feature allows the CPU to do other jobs w/o interruption, or just to sleep. Any unused peripheral is an additional power parasite.

Modern MCUs allow for selecting, which peripherals to be clocked. A non-clocked CMOS logic circuit only draws little leakage current, whereas "little" depends on the manufacturing process size. A better alternative is to totally disconnect unused peripherals internally from power supply, as practiced on e.g. ATSAML21.

E. Input pins

It is generally known that floating input pins are a no-go. Less is known that the mere compliance with the logic levels 1 and 0 is not sufficient if an extremely low power consumption is to be achieved. Instead, the input level must not deviate more than 0.5 volts from GND or Vcc.

F. Do you need a real time clock?

Many microcontrollers offer an internal RTC with crystal connection pins. This is a bit cheaper than an external RTC module. But there are good reasons for taking an RTC module in account: the most power saving ones just consume 60 to 80 nanoamperes. Some have an RC oscillator option with less accuracy, but still less current consumption of 30 nanoamperes. In addition, such modules are more precise than RTCs with external crystals, which may be shipped with 10 or even 5 ppm accuracy – but they lose a lot after soldering. Also, the circuit needs to be designed carefully, otherwise additional frequency changes may occur as well as oscillator start-up problems, especially in case of high impedance oscillators.

Professional crystal manufacturers know about the characteristics of different MCU types and are willing to assist during circuit design free of charge. Don´t try to measure anything on an RTC oscillator with your standard probe!

G. *A few words about "typical values"*

What marketing influenced datasheets say about "typical values" often is rather useless for designers. As a developer of electronics, intended for mass production you should always take worst case scenarios in account. Here it´s the maximum current that counts, and this value may be an order of magnitude higher than the "typical" one, especially in sleep mode.

Hint: "xx µA per MHz" does NOT mean that the controller consumes xx µA at ONE MHz! If you´re interested in the 1 MHz consumption value, check the datasheet carefully. Usually its significantly more than the µA/MHz value.

H. *Memories*

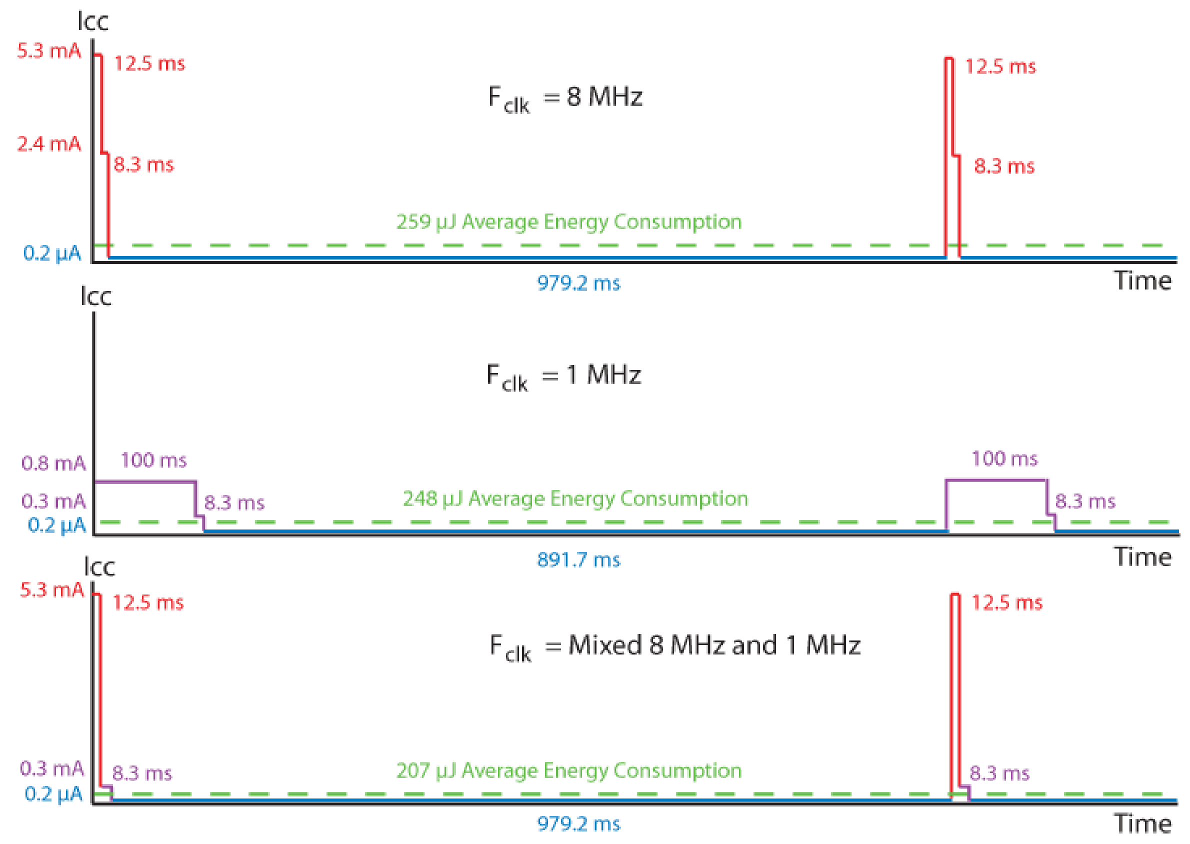
Most MCUs have Flash program memories which can be updated by boot loader mechanisms. If you want to store small data here from time to time, be sure to decide for an MCU with granular memory organization, to avoid overwriting unintended memory space which costs power, writing time (and therefore, additional power) and lifetime. EEPROM usually can be written 10 to 100 times more often than flash. An external EEPROM may be an alternative, especially in case of MCUs without internal EEPROM. Conductive based memory (CBRAM) is another modern technology with 10 to 50 times less writing power consumption, combined with short writing time, X-ray immunity, low voltage capability and very low cost. Recently the number of read-write cycles of CBRAM has increased from 10K to 100K.

I. *Capacitors*

Decoupling capacitors are essential for electronic circuits with active components like MCUs, FPGAs etc. Sometimes not only decoupling is needed but also energy buffering. Standard capacitors may be applicable for low power but not for ultra-low power applications like dataloggers with 10-years battery lifetime. Surely you know that there is a significant leakage current at electrolytical caps. But are you aware that some multilayer ceramic capacitors (MLCC) cause about 5µA leakage current, each [12]?

J. *Supply voltage*

Whereas 5 V still is a standard voltage in many industrial applications, it´s not preferred for most low power devices. The MCU supply voltage obviously depends on the used power source, in most cases re-chargeable or non-re-chargeable batteries. The topic "selecting the right battery" by itself is worth featuring in an own article. Some tips:



DYNAMIC CLOCK SWITCHING IN A REMOTE KEYLESS ENTRY EXAMPLE APPLICATION

This example demonstrates some power saving options on a classical AVR microcontroller w/o special low power features like available on modern Pico Power architectures.

The transmitter spends 98% of its time in power down mode and is activated every second for testing purposes by simulated button-pressing. Power supply voltage is 3 V. The encrypted communication with a base station by radio is done with 9600 baud data rate. The data processing and encryption requires around 100 000 clock cycles. Each transmission consists of 8 bytes.

First, the internal RC oscillator is used at its maximum frequency of 8 MHz, resulting in a total energy consumption of 250 µJ (micro-joules) per transmission. In the 2nd try the frequency is reduced to 1MHz. Thus, power is saved during each transmission, taking a fixed time determined by the baud rate. The MCU also draws less current during mathematical processing, but needs 8 times longer. Now the total consumption is reduced to 248 µJ, a saving of 4% compared to 8MHz. The trick is to perform calculations at 8 MHz and then switch down to 1 MHz during transfer. Now the total power consumption is 207 Micro-Joule, *saving 20% without any hardware modification!*

The *self-discharge* rate of small alkaline cells is somewhat around 5 to 10 µA at room temperature. That means it doesn´t make much sense to struggle for a few µA in such applications.

The typical 1.5 V of *alkaline batteries* is a bit too low for many popular controllers. The easiest way to overcome this disadvantage is using 2 cells in series, if there is enough space left. An alternative is a *DC/DC boost converter*, which saves space and keeps the voltage constantly at e.g. 3V, even when the battery drops down to 0.7 Volt. The losses of the converter are more than compensated by the better utilization of the battery, if the design is well done. On the other hand, such design only is non-critical in case of devices with a mechanical switch. If an event like I/O pin voltage change, temperature change, sound, radio signal or a timer compare match should wake up the system, the controller or another part of the circuit needs to stay continuously sensitive. Here, DC/DC converters must be very power saving with extreme low quiescent current consumption. Even better, the timer resp. external circuit should be a low voltage and (!) low current design, so that the converter can be switched off or disconnected during controller´s sleep mode period.

If a super low quiescence current DC/DC converter still is not an option: there are some controllers on the market, running from just 1.2 Volts or less, thus allowing to power by only one 1.5 V primary cell [11].

On the other hand, if your device needs to be powered by a voltage higher than the allowed Vcc of your controller, it´s worth investing some creativity. Example: 4 primary cells are planned to supply the electronics as well as motors, relays, magnets etc. Their added voltages will drop down from 6 Volts to 3.6 Volts during use. Why not connect the electronics to a *center tap*, providing 3 V down to 1.8 V? This is within the MCU´s specification and renders DC/DC converters or LDOs unnecessary.

The internal resistance of *Lithium Coin* cells is typically in the range of some tens of Ohms. And grows to some 100 Ohms during cell discharge [21]!

Rechargeable batteries never should be discharged under a certain level, depending on battery type (deep discharge). They will never completely recover.

IV. RADIO CONNECTIVITY

A. Radio and IOT

Radio connectivity is much older than IOT. And even radio wearables have been in common use for decades – think about DCF77 based radio watches or hearing aids. Nevertheless, sports and health equipment, remote loggers, building automation and lighting are examples of growing RF markets.

B. Long range radio

The power requirement of radio connectivity depends, amongst others, on transmission power, data rate, frequency range, receiver sensitivity and antenna quality. Long range, i.e. 5 to 30 kilometers, can be achieved with sub-GHz UHF low power transmitters if the data rate is low and transmission is active only during short periods, e.g. for short messages a few times per day. Under these conditions many years of battery lifetime are realistic. The currently most popular and steadily growing standards are *LoRa* and *Sigfox*. Typical applications are remote burglar and vandalism alarm, process control, meteorology, animal locating and many others.

But there is more to it than that: Short wave *WSPR* (weak signal propagation repeat) allows for 20,000 km range – that´s around half the earth – with 100 mW and 1000 km with 10 mW transmission power. The price to pay is a low data rate of one bit per second. But that´s enough for some daily weather data, sent from south pole.

C. Short range radio

Keyless entry, transponders, some bicycle computers are typical shot range applications, making use of “old fashion” long wave radio. DCF77 radio clocks do as well. An advantage of low frequency (LF) is the availability of receivers with current consumption as low as 2 µA when continuously active. WIFI, BTLE, ZigBee are well known standards in ultra-high frequency (UHF) GHz range.

An interesting approach is the combination of both, longwave and UHF technology, based on good old detector principles: a passive detector demodulates the UHF signal, which is modulated with a long wave signal, again ASK modulated with a certain pattern. This signal is forwarded to a wake-up receiver. Only in case of coincidence between the modulated pattern and the configuration of the wake-up receiver, the rest of the electronic circuit will be switched on. Despite being on air permanently, the stand-by receiving current is as low as some 2 µA required by the wake-up receiver. This is one tenth of a percent of usual BT module values [14]!

Summary of "Hardware and Firmware Issues in Using Ultra-Low Power MCUs" by JACK GANSSLE:

This report uses the results of extensive experiments, plus analysis, to prove that most assumptions about designing ultra-low power systems are wrong. Among the most important findings:

- Sleep current is almost irrelevant
- What matters is time spent sleeping...
- ... and contributions of other leaks and drains
- The internal resistance of coin cells increases hugely as the battery is discharged.
- Don't wake up at full speed! Check the voltage as you ramp up frequency.
- Don't use the on-board brown-out reset circuits.
- Droop will trim another 10% or so of battery capacity.
- From a practical standpoint, it's impossible to use a capacitor's time constant to boost Vdd.
- Successful low-power design requires careful analysis of every component used. Even poor decoupling capacitor selection will drain a battery in short order.
- I doubt anyone will get 10 years from a coin cell even with the most careful design practices.

The bottom line is to apply careful engineering judgment to all design decisions.

And test your design. You know the IR will go up as the cell's voltage declines. Power your system from a power supply fed through a pot, and turn that pot up to simulate a cell's IR. Run the system through sleep and wake modes, as well as brown-out-reset, to insure it will still operate correctly even as a battery approaches end of life.

Near field communication (NFC) is useful in many ultralow power applications. To cover different needs, a variety of products are offered.

D. NFC tags

Stand-alone passive tags, compatible to the NFC standards, have long been available. They can be used like other RFID tags, but in addition offer the opportunity for typical NFC applications. Some of these tags feature enhanced cryptography. These should be used when it comes to anti-cloning and manipulation resistant applications.

E. NFC interface devices

These integrated circuits offer NFC connectivity to any electronic device. They are cheap and easy to implement with no need for RF expert knowledge.

An integrated energy harvesting module provides the supply voltage for the chip as well as for the connected controller. This energy is taken from the reader field. Even though only little power can be harvested, it´s enough to re-program a typical microcontroller´s flash memory. Last, but not least such devices often include EEPROM. Not surprisingly microcontrollers with integrated NFC interface are at hand.

The energy harvesting option appears tailor-made for IoT, where energy saving in most cases is a must. A sensos that is only occasionally used can be built without battery and will be powered by the NFC field just during scanning. An example is a humidity sensors within the wall or floor of buildings. Electronic labels with E-paper displays also don´t need batteries. Only during display update energy is needed, which can be taken from the initiator´s field.

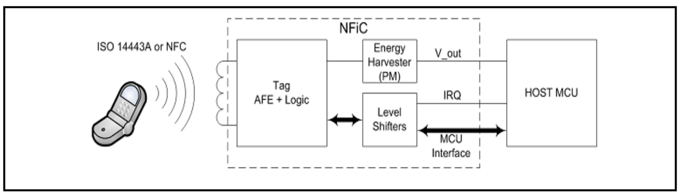


Fig. 1. NFC interface device adds NFCto any electronic product

F. NFC sensor devices

Low power NFC active sensor tags can be used for tracking data like temperature, acceleration (shock), humidity, radiation etc. over months or even years, storing them in non-volatile memory, time stamped by an integrated real time clock (RTC). Such tags integrate most of the components needed for sensor and data logger applications in a single chip. In addition to the NFC interface they provide an internal RTC, EEPROM, analog ADC, temperature sensor and analog sensor interface pins for connecting additional external sensors.

Fig. 2. Integrated circuit for data logging sensors

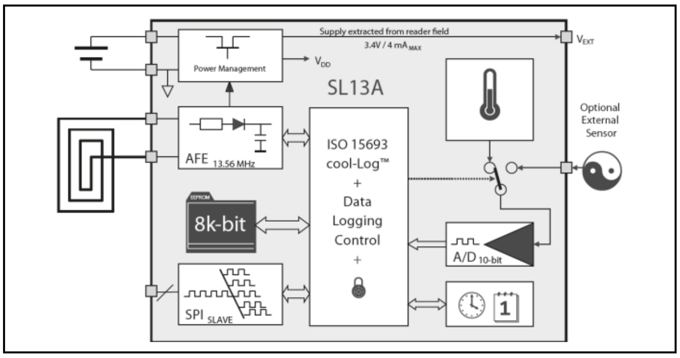


Fig. 3. Proof of genuineness by NFC combined with internet acces via phone

SUMMARY

A lot can be done to reduce power consumption of electronic devices on different levels. Many measures are surprisingly old, but effective, others are surprisingly inefficient. Real ultra-low power circuit design is not trivial.

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