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Benchmark – ULPBench debunked

Which microcontroller is really energy-efficient and suitable for ultra-low-power applications? The ULPBench benchmark developed by the EEBMC consortium is meant to shed light on the matter. Unfortunately, realistic conditions are often missed out. In a unique project of its kind, DESIGN&ELEKTRONIK looked at things again. Result: The ULP story must, in part at least, be newly written.

BY FRANK RIEMENSCHNEIDER

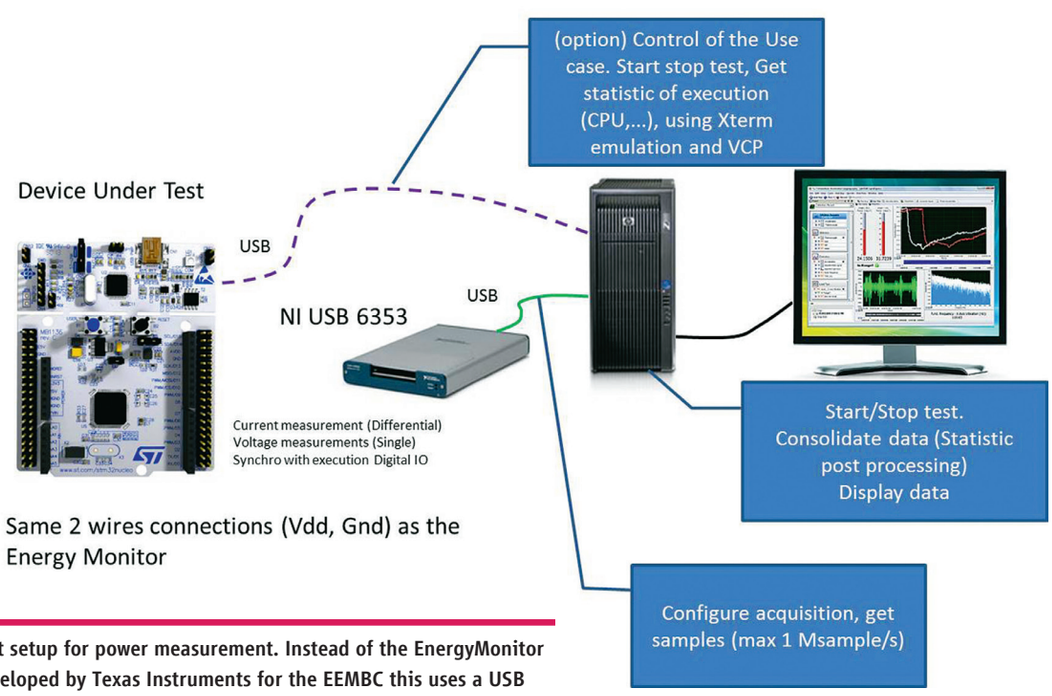

Figure 1: Test setup for power measurement. Instead of the EnergyMonitor developed by Texas Instruments for the EEMBC this uses a USB 6353 from National Instruments.

ULPBench takes a two-prong approach. Firstly there are different tests with common workloads for comprehensive measurement of microcontroller efficiency, and portable across 8-bit, 16-bit and 32-bit microcontrollers (MCUs). With the focus on real-world applications, the low-power modes of the examined MCUs are used, and the effects of active and low-power operation are analyzed. Secondly there is the socalled EEMBC EnergyMonitor, consisting of an energy monitor board and ULPBench software. The functionality of this EnergyMonitor is such that the ULPBench core profile software runs on the MCU, i.e. the device under test (DUT). The source texts of the ULPBench core profile software are included in EEMBC delivery (directories: benchmarks, workloads, TES, platforms).

Fixed on 3.0 V and 25°C

The first problem with ULPBench is its fixation on a supply voltage of 3.0 V, although most ULP controllers can be operated down to 1.8 V. It does not take much imagination to picture that with a dropping supply voltage the power consumption also drops, and higher ULPBench values can be expected.

The second problem of ULPBench is its fixation on a best case ambient temperature, as a rule 25°C, in which producers determine their values and in which the EEMBC also certifies them. But when you think that a smart meter, for example, generates temperatures between 50 and 60°C, and some industrial applications maybe 80 or 85°C, the ULPBench value presented on the EEMBC website can only be accepted with restrictions.

Finding ULPBench between 3.0 and 1.8 V

As a first step DESIGN&ELEKTRONIK determined ULPBench values for lower supply voltages. The heart of measurement hardware (*Figure 1*) was a USB 6353 from National Instruments, specified as follows:

- 32 analog inputs; 1.25 MSample/s with one channel, 1.0 MSample/s multichannel; 16-bit resolution; ±10 V
- Four analog outputs; 2.86 MSample/s; 16-bit resolution; ±10 V
- 48 digital I/Os
- Four 32-bit counters/timers for PWM, encoder, frequency, event counter, etc

The software was developed by means of NI's Signal Express [1], offering more than 850 functions for signal measurements, filters and time/frequency transforms. Being an event-controlled system, programs can be controlled by user interaction on a mouse, keyboard, etc. Extra to that, Signal Express is compatible with all LabView add-ons for special applications or hardware integration. The simple contacts with the MCU board to be tested can be seen in *Figure 2*, the measurement workshop in *Figure 3*. The board is connected by the same two-wire interface as in the case of the EEMBC EnergyMonitor.

Tests at 3.0 V showed a maximum deviation of 5% from values measured with the EnergyMonitor, in concrete terms a ULPBench score of 158.9 for the MSP432 in DC/DC converter mode compared to 152.5 by the EnergyMonitor. For most of the controllers the difference was between 0.1 and 2%. These deviations do not detract from the objective of measuring the pattern of energy efficiency over supply voltage, and determining how far you can reduce supply voltage in the first place before a controller no longer works properly.

The results

Table 1 shows the ULPBench values measured for the following controllers:

- STMicroelectronics: STM32L433, STM32L0
- Texas Instruments: MSP432 DC/DC, MSP432 LDO, MSP430FR5969 FRAM, MSP430FG4618 Flash
- Silicon Labs: EFM32 Wonder Gecko, Giant Gecko, Pearl Gecko, Zero Gecko
- Atmel: SAML21 rev A, rev B LPEFF On, rev B LPEFF Off
- NXP: Kinetis KL27Z
- Microchip: 16-bit PIC24FJ64GA202

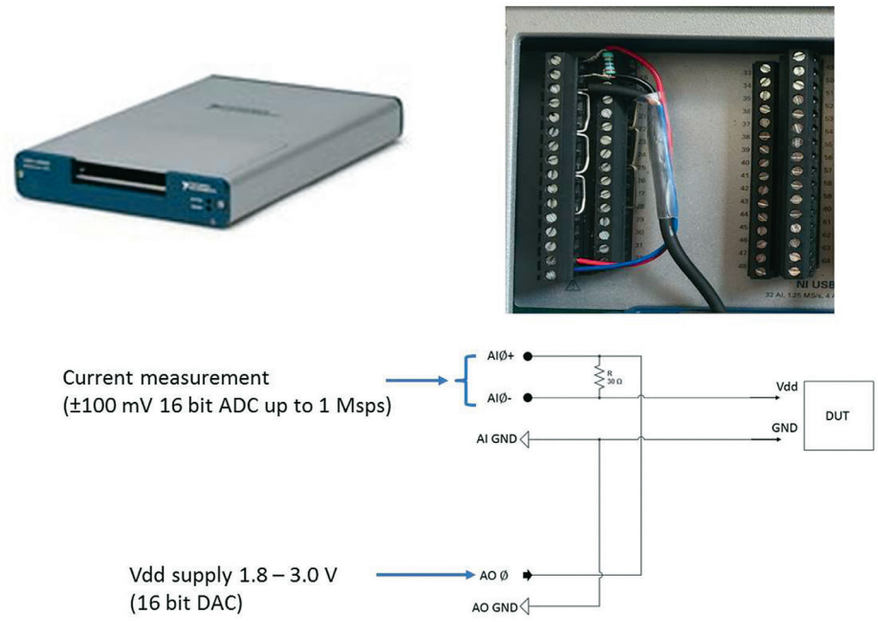

Figure 2: The test circuit for current consumption is adequately simple – the correlating voltage is picked off a 30-Ω resistor.

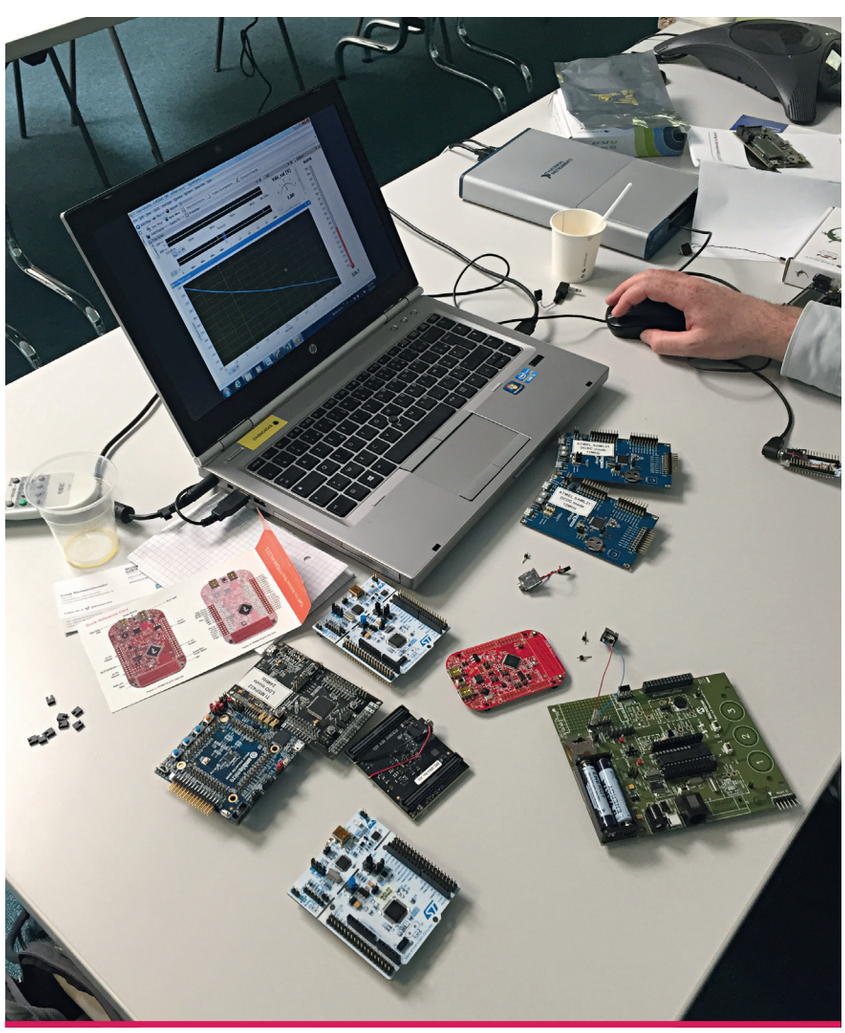

Figure 3: ULPBench measurement workshop.

V_{DD} (V)		3.0	2.9	2.8	2.7	2.6	2.5	2.4	2.3	2.2	2.1	2.0	1.9	1.8
STM32L433		172.58	180.54	188.44	198.01	208.42	217.35	229.34	242.14	254.97	270.26	287.25	305.97	325.78
STM32L476		149.48	156.87	164.72	172.42	181.03	188.82	199.23	209.81	223.32	234.01	246.85	261.45	280.15
SAM21L21	Rev A	147.08	155.30	163.00	168.57	174.90	180.16	186.21	196.25	202.28	211.46	220.41	229.81	240.11
STM32L0		129.99	135.74	140.92	147.47	154.84	161.04	167.41	175.93	184.55	192.99	203.35	214.75	226.67
SAM21L21	Rev B LPEFF Off	127.00	136.00	142.24	148.49	154.88	161.71	167.20	172.78	180.89	189.28	199.71	207.31	215.79
MSP432	LDO	117.88	124.17	128.40	134.88	140.59	147.09	154.45	161.41	169.42	178.64	188.03	197.58	208.82
Kinetis KL27		79.77	83.27	84.30	87.97	92.30	96.41	100.43	104.78	108.82	113.94	119.97	126.09	133.56
MSP430FR5969		120.50	125.17	129.96	135.25	140.73	146.50	152.89	159.41	167.06	175.17	184.07	194.32	n.A.
PIC24FJ64GA202		70.84	73.93	77.42	80.56	83.70	87.18	90.84	95.11	99.69	104.15	110.39	121.84	n.A.
SAM21L21	Rev B LPEFF On	137.33	142.68	151.43	154.00	158.41	167.06	170.95	178.39	183.21	187.16	186.01	n.A.	n.A.
EFM32 ZeroGecko		98.01	103.63	108.65	113.99	118.49	124.19	129.99	136.51	142.59	149.79	157.06	n.A.	n.A.
EFM32GiantGecko		58.68	61.55	64.33	67.02	70.01	73.46	76.91	80.42	84.51	88.73	94.14	n.A.	n.A.
MSP430FG4618		32.00	34.00	36.00	37.60	40.00	42.00	45.00	48.00	50.00	53.00	57.50	n.A.	n.A.
Apollo		329.92	339.30	354.95	367.05	382.94	395.18	410.63	436.62	459.51	472.42	n.A.	n.A.	n.A.
EFM32PearlGecko		106.25	110.44	112.29	113.51	114.85	115.82	115.63	119.31	122.33	127.06	n.A.	n.A.	n.A.
EFM32 WonderGecko		74.59	79.21	82.91	86.44	90.01	94.02	98.27	102.81	107.80	113.42	n.A.	n.A.	n.A.
MSP432	DC/DC	153.99	161.97	166.60	171.85	178.00	183.00	190.11	193.05	199.68	n.A.	n.A.	n.A.	n.A.

Table 1: ULPBench results of investigated microcontrollers at a glance. Not all MCUs can be operated down to 1.8 V. »n.A.« means that ULPBench code is no longer executed correctly at this voltage.

Ambiq Micro: Apollo

STM32L433 with ARM Cortex-M4 achieved the biggest increase of all ULPBench values over voltage: From 172.58 at 3.0 V to 325.78 at 1.8 V means in absolute terms 153.2 points more and the highest scores under 2.1 V. STM32L0 with ARM Cortex-M0+ boosts from 129.99 to 226.67 points, meaning #4 in the low-voltage range.

There was an interesting phenomenon to observe in the Atmel SAM21L21, likewise with an ARM Cortex-M0+ CPU: While a rev A chip comes in at scores between 147.08 and 240.11, that is no longer the case for rev B: To at all scale down to 1.8 V, a bit called LPEFF in the voltage regulator must be set to »0«. The greatest efficiency is not then achieved, which, as can be seen from the *Table*, means that ULPBench results are below the officially published values. The voltage regulator produces maximum reliability if the bit is set to »1«. Below 2.1 V (2.5 V according to the data sheet) the controller no longer functions however.

Less convincing, given the marketing presence of the company Energy Micro acquired by Silicon Labs (»The world's most energy-friendly microcontrollers«), were all families looked at with ARM Cortex-M0+ (Zero Gecko), Cortex-M3 (Giant Gecko) and Cortex-M4 (Pearl Gecko, Wonder Gecko). Not just scaling at reduced supply voltage, the absolute values too plainly trail the ARM competition. And things quit entirely below 2 V, with Wonder and Giant Gecko calling it a day below 2.1 V already – presumably because of the identical TSMC 180 nm fabrication process.

Modest results (in absolute terms), compared to the front of the field, are also registered by the NXP Kinetis KL27 with Cortex-

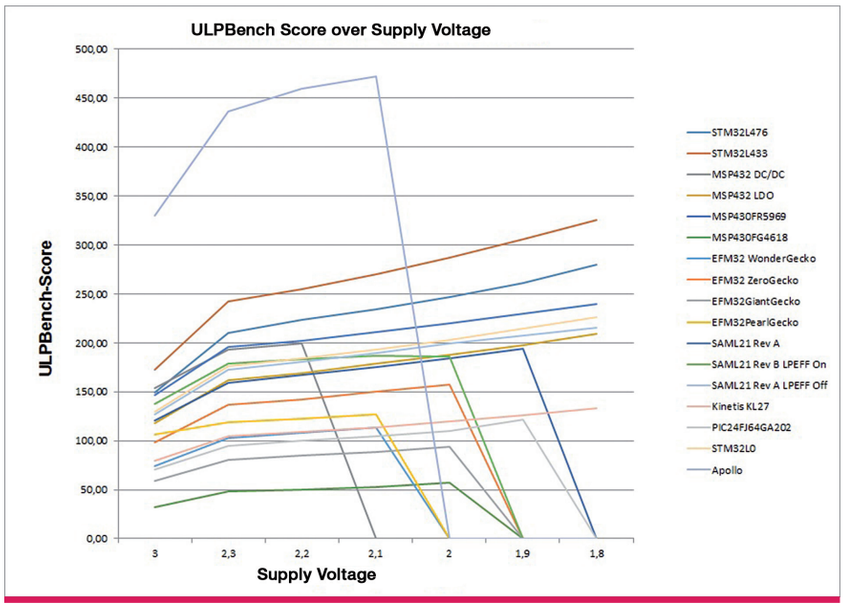

Figure 4: Graphic display of an extract from the measured results. Between 3.0 and 2.2 V ULPBench values for all models increase more or less linearly (see table).

M0+ and Microchip PIC24 with proprietary 16-bit CPU. These scale down to 1.8 V (NXP) or 1.9 V (Microchip), achieving respectable growth rates at least in percentage terms.

Texas Instruments fielded three candidates, whereby caution is called for in the case of the MSP432 with ARM Cortex-M4. If you operate it with a DC/DC converter, it may achieve comparatively good ULPBench values, but 2.2 V is the end of the line – you cannot go lower. If you want to use the whole voltage band down to 1.8 V, you need to operate it with a linear regulator, thus reducing the ULPBench score straight away by almost 25%, and putting it much behind other Cortex-M4 controllers.

From the 8-bit contingent came the MSP430 in a version with FRAM memory and conventional flash. Although the FRAM version was even slightly better than the MSP432 in LDO mode, the flash MSP430 turned out to be the overall loser of the investigation: A ULPBench score of 32 (3.0 V) to 57.5 (2.0 V bottom limit) is below the STM32F433 by a factor of 5 for example.

In addition to the more or less conventional chips there was an outlier upwards: The Ambiq Micro Apollo MCU works in sub-threshold mode, i.e. transistors switch below the actual threshold voltage [2] – a technology that established producers examined decades back but were not able to implement laboratory results in mass production. How the startup managed to overcome the evident fabrication hurdles with natural variations in threshold voltage is not known, but the ULPBench results: Figures range from 329.9 at 3.0 V to 472.42 at 2.1 V, below which the chip goes into reset.

Figure 4 shows an extract from *Table 1* as a line graph, the focus being on the range below 2.3 V to point out which controller can (still) be operated at what supply voltage.

A legitimate question would be why we did not include the RL78 from MCU market leader Renesas. The answer is simple: Try as we might, we just could not get ULPBench code to run on it.

The temperature challenge

The second problem of ULPBench is its fixation on a best case ambient temperature, as a rule 25°C, in which producers determine their values and in which the EEMBC also certifies them. But when you realize that a smart meter, for example, generates temperatures between 50 and 60°C, and some industrial applications maybe 80 or 85°C, the ULPBench value presented on the EEMBC website can only be accepted with restrictions.

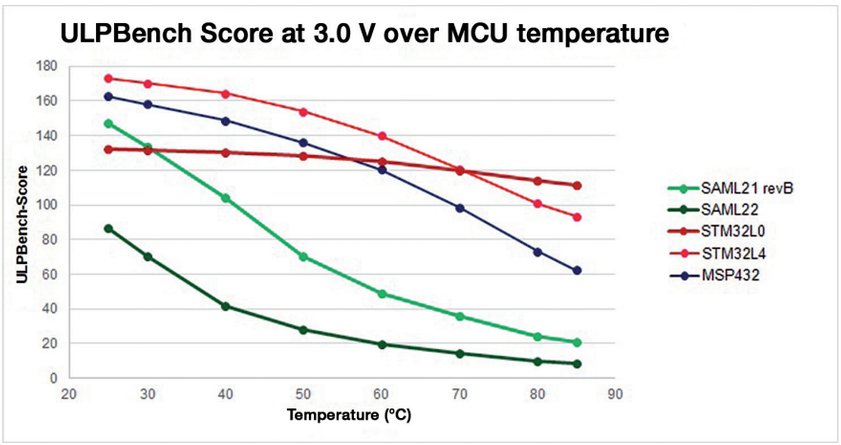

Figure 5: ULPBench results over temperature for 3.0 V supply voltage.

So in a climatic chamber of STMicroelectronics we looked at how ULPBench develops when ambient temperature is increased. The time at our disposal to work in the climatic chamber was limited, and we could not put all controllers through their paces that we had examined in. So we concentrated on two MCUs each from ST and Atmel, plus the MSP432 from Texas Instruments, and the sub-threshold Apollo controller from Ambiq Micro.

Even before embarking on the tests it was obvious that energy efficiency would go down as temperature went up – the question was just by how much. That has mainly to do with the fabrication process. *Figure 5* shows the pattern of the ULPBench value from 25 to 85°C for a supply voltage of 3 V. What strikes you is the temperature stability of the STM32L0 with an ARM Cortex-M0+, fabricated by a proprietary 110-nm ULP process. While the STM32L0 trails behind its competitors in 90-nm and 65-nm processes because of the higher power consumption in active mode (#4 at 25°C), the others suffer from the exponential increase of leakage currents at higher temperatures. At ambient temperatures barely over 70°C already, the STM32L0 edges them out.

Also worth noting is the response of the two Atmel controllers. Their ULPBench curve drops markedly compared to ST and TI at just slightly increased temperature, stabilizing then more at higher temperature. The MSP432 and the STM32L4, on the other hand, remain relatively stable up to 50°C, ready for the bigger fall-off at then higher temperatures.

In *Figure 6* the scale was squeezed somewhat compared to *Figure 5* to fit in the high-flying Apollo from Ambiq Micro. The drop in ULPBench value over temperature is dramatic, at 85°C the almost 200 point lead on the STM32L0 at 25°C has shrunk to little more than 30 points. Even worse is the realization that Ambiq Micro itself for the measured rev 3

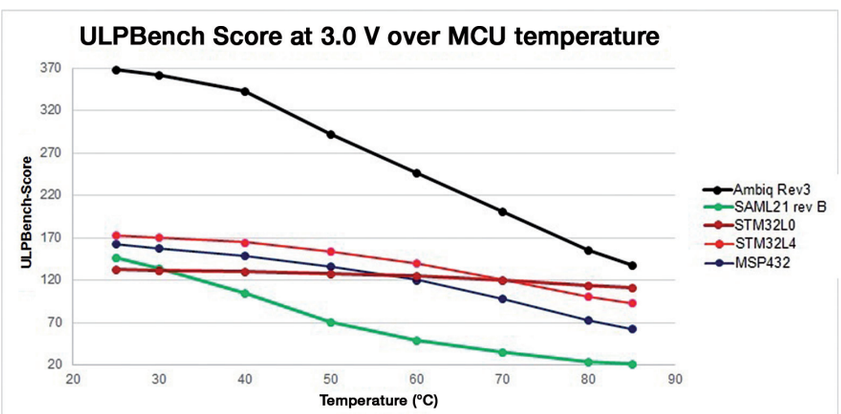

Figure 6: ULPBench results over temperature for 3.0 V supply voltage with Ambiq Micro MCU.

16.21 Device Errata and Design Considerations

16.21.1 Apollo Device Errata

The section describes silicon errata for the Apollo MCU device related to operating temperature range, IO master functionality, ADC, and the PDR threshold. The errata listed below apply to devices with the following part numbers: APOLLO512-KBR, APOLLO512-KCR, APOLLO256KBR, APOLLO256-KCR, APOLLO128-KBR, APOLLO128-KCR, APOLLO064-KBR, and APOLLO064-KCR.

16.21.1.1 Operating Temperature Range

16.21.1.1.1 Errata Details & Impact

Revision A3 Apollo MCU devices are only guaranteed to operate within the -10°C to 60°C temperature range. This range is less than the one shown in the Apollo MCU datasheet of -40°C to 85°C.The reduced range is required to guarantee operation as process and voltage vary in revision A3, in addition to temperature.

16.21.1.1.2 Workaround

Customers must use Apollo revision A3 within the reduced temperature range of -10°C to 60°C.

16.21.1.1.3 Resolution

A new silicon revision now in production (A4), expands the operating temperature range to the expected values of -40°C to 85°C.

Figure 7: Errata sheet of Ambiq Micro Apollo MCU states a restricted temperature range.

only guarantees operation in the temperature range –10 to +60°C (errata sheet, *Figure 7*). We suspect that fabrication for operation below the threshold voltage simply produced too many variations of precisely this, so you no longer had stable switching of the transistors with increasing temperature. It took until rev 4 to achieve the temperature range of –40 to +85°C stated in the data sheet. But this was at the cost of drawbacks described later, and for lesser ULPBench values than measured here with rev 3.

Subsequently the measurements were repeated, reducing the supply voltages to their possible minimum. For all benchmark candidates that meant 1.8 V, except the Apollo MCU, which needs a minimum of 2.1 V. *Figure 8* shows the results: The higher the temperature, the smaller is the margin of Ambiq Micro. Even if we apparently had luck with the measured rev 3 chip, and this had worked without problems to 85°C, you must not forget that Ambiq Micro only released it for up to 60°C.

Improvements for the worse in Ambiq Micro Apollo rev 4

In rev 4 Ambiq Micro then released the –40 to +85°C temperature range specified in the data sheet. But there were further amendments, and not exactly to the benefit of the customer. Seemingly the fabrication process had to be altered for the higher temperature variance so that power consumption increased especially in sleep mode, now resulting in 35 µA/MHz instead of 34 µA/MHz (rev 3) in active mode too. For deep-sleep mode without realtime clock and 8 KB RAM data retention 143 nA are stated for both rev 3 and rev 4. But the figure with realtime clock increased from 198 nA to 419 nA, so you can figure 55 nA (rev 3) for realtime clock alone or 276 nA (rev 4). If you then also take the value for deep-sleep mode plus RAM retention (193 nA), you arrive at 386 nA (rev 3) or 469 nA (rev 4) for deep-sleep mode plus realtime clock plus RAM retention.

Furthermore, with rev 4 the wiring of the

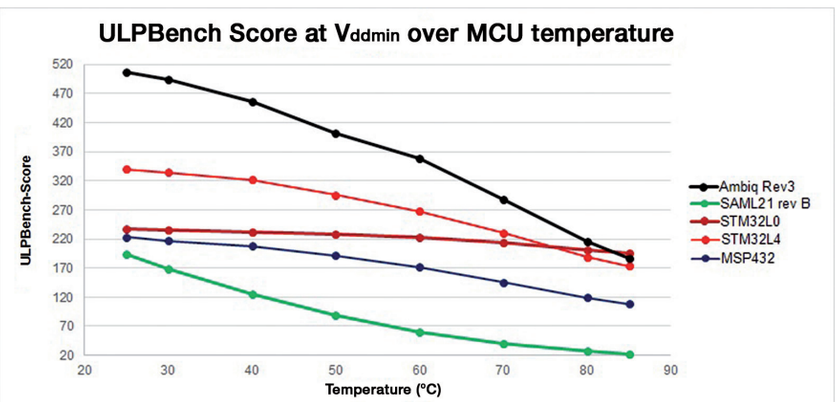

Figure 8: ULPBench results over temperature for 1.8/2.1 V supply voltage.

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MCU, or concretely of a down-converter, must be altered so that, as shown in *Figure 9*, the capacitance C3 is increased from 1 µF to 2 µF – to smooth voltage ripple says Ambiq Micro. This converter is used for the core, flash memory, SRAM and analog/digital periphery. Thus, with a higher capacitance, a higher peak current than in rev 3 is to be expected. Last but not least, in rev 4 the transition from deep-sleep mode to active mode increases from 20 µs to maximally 43 µs, meaning it has more than doubled for worst case.

All three amendments ultimately lead to lesser energy efficiency of the MCU (which we were unable to measure lacking rev 4 silicon). But to be fair you must say that for certain operating points (supply voltage not less than 2.1 V, and relatively low temperatures) unmatched ULPBench scores should be recorded.

Silicon Labs – data sheet and truth

Given the surprisingly poor results for the Gecko MCUs from Silicon Labs, we took a closer look. First clues came already from the official documents. For the Giant Gecko in low-power mode EM1 on 3.0 V supply voltage and 14 MHz clock frequency, the stated current consumption increased between rev 1.10 and rev 1.30 by 48% from 56 to 83 µA/MHz. In EM2 mode the current consumption at 85°C even increased by 50% from 4.0 to 6.0 µA, with the values for all temperatures of rev 1.10 including complete RAM and CPU retention also stated. For rev 1.30, however, only one RAM block is activated – so in the boundary conditions of rev 1.10 (RAM fully active) even higher current consumption can be reckoned with.

Especially worth stressing are actual deviations from data sheets and real measurements (*Table 2*). Such deviations of as much as 935% are immense of course, and not at all to be justified when a developer relies on data sheet figures in the search for an MCU to work their application.

The competition shows that it can work differently, praise going to TI with the MSP432 for instance. Stated for 24 MHz and 3.0 V in active mode with DC/DC converter you read 2200 µA, and we measured

2210 µA – a deviation of less than 0.5% from what the data sheet tells you.

Getting back to Silicon Labs: With the Pearl Gecko rev B too there are some considerable differences between what should be and what is. But at least they are named in an errata sheet: In EM2 mode with 32 KB SRAM for 3.3 V and DC/DC conversion 2,48 µA are consumed instead of 1.4 µA, in EM3 mode likewise for 3.3 V no less than 2.1 µA instead of 1.1 µA.

But Silicon Labs is not alone with its deviations, even if not so extreme. As already pointed out, rev B of Atmel SAM21-MCU does not exhibit the same ULPBench values as rev A. Here too the data sheet provides an explanation: In standby mode the current consumption for 25/85°C without realtime clock climbs from 0.9/10.5 to 1.2/20.7 µA, with realtime clock from 0.94/11 to 1.4/20.8 µA.

Operating mode	EFM32GG995 Datasheet	Measurement using Starter kit	Deviation vs. Datasheet in %
EM0 (48 MHz aktive)	219 µA/MHz	290.0 µA/MHz	+ 32.4 %
EM1 (48 MHz aktive)	80 µA/MHz	100.2 µA/MHz	+ 25.3 %
EM2 (32 KB SRAM, with/without real time clock), 2 µs wake-up time	1.1/0.8 µA	1.67/1.46 µA	+51.8/+82.5 %
EM3 (32 KB SRAM, without real time clock), 2 µs wake-up time	0.8 µA	1.12 µA	+40 %
EM4 with/without real time clock, 163 µs wake-up time	400/20 nA	587/207 nA	+46.8/+935 %

Table 2: Deviations from data sheet and real measurements on Silicon Labs EFM32 Giant Gecko MCU.

What else stands out

Caches are a popular subject for discussion. Atmel for example measures when the READMODE register of the NVM controller is set to »1«, i.e. the cache is working in a low-power mode. Here a wait state is inserted for each cache miss, meaning that the ULPBench score drops at clock frequencies beyond about 12 MHz. The MSP432 does not have a cache at all, for which reason its benchmark scores drop (but not until 24 MHz), and the STM32L4 even manages to hang on until 80 MHz thanks to its ART.

ART (adaptive realtime), known from F2, means that theoretically it is possible to work even up to 168 MHz without wait states to process code from flash memory. In practical terms ART only works if the cache does not have to be constantly reloaded from flash because of numerous leaps in code. In this case all statements are pure theory, but in small benchmarks like CoreMark or ULPBench with sequential code ART can of course really demonstrate its strengths.

Another question was why the Texas Instruments MSP432, with all the prerequisites (IP, ULP fabrication) for a spot at the top, did not finish up front. One reason could be the comparatively high peak turn-on currents, measured at 6.8 (DC/DC) and 6.56 mA (LDO), which the competition clearly outperforms (Atmel SAM21 < 2 mA, STM32L47x 3.2 mA, Ambiq Micro Apollo 4.7 mA). Plus, transition from LDO to DC/DC operation is relatively long at 10 µs.

If in doubt – measure yourself

For an engineer looking for an energy-efficient microcontroller data sheets are only a limited aid because they only state current demand at a few operating points that, depending on the manufacturer, are more or less close to reality or distanced from it. If you want to design a smart meter for example, and aim for a low supply voltage in environments from 50 to 60°C of the operated MCU, you will not get out of measuring yourself.

Marketing slides are promising the world's most energy-friendly microcontrollers, the most energy-efficient microcontrollers in industry, or the controllers with the lowest current demand – and then at the best are just mid-fielders when we compare them. ■

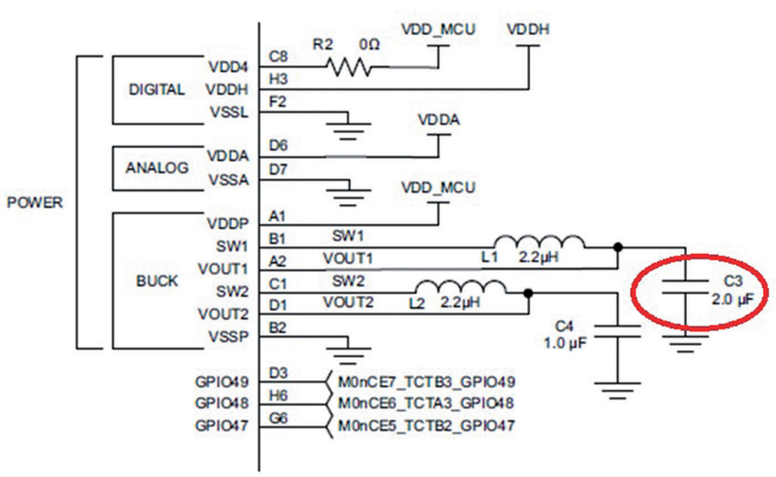

Figure 9: Down-converter 1 in the Apollo MCU must be wired with a 2-µF capacitance from rev 4.

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Literature

[1] Signal Express from National Instruments: http://bit.ly/2eU27Se

[2] Ambiq Micros Apollo-MCUs: http://bit.ly/2eU0KTr