ARM Cortex core microcontrollers

12th Energy efficient operation

Balázs Scherer

Méréstechnika és Információs Rendszerek Tanszék

The importance of power efficiency

- Comparing microcontroller attributes

$$\frac{\text{Computation power}}{\text{Price} \quad * \quad \text{Power consumption}}$$

- The power efficiency not just a microcontroller level thing. System considerations always plays more important role.

Factors influencing power consumption

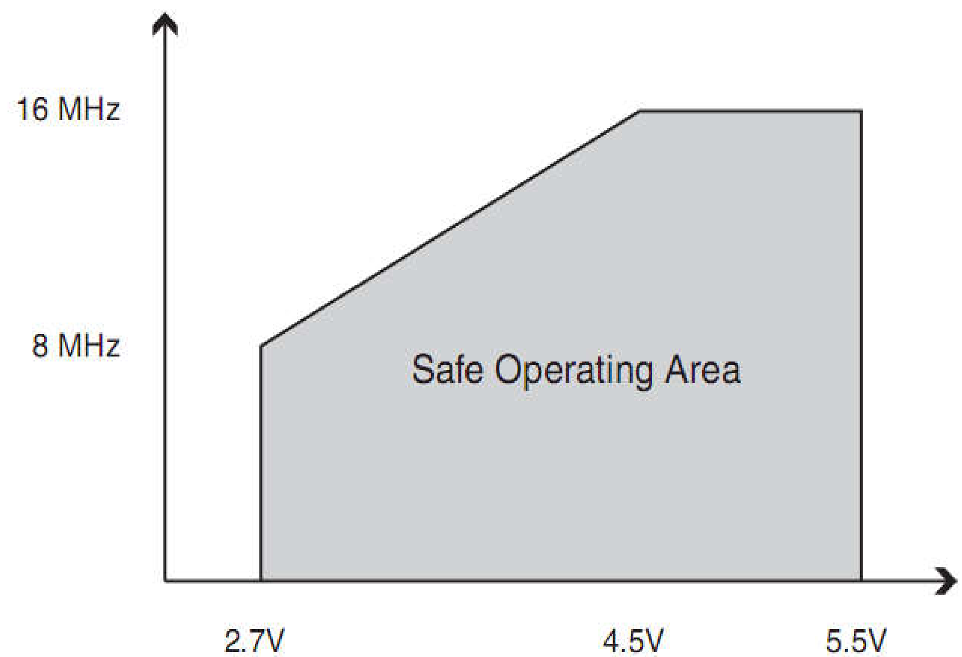
- Factors influencing **microcontroller** power consumption
  - Operating Voltage
  - Power consumption in active mode
    - mW/MHz
  - Usage of power save modes and their effects
  - Wake up times
- Factors influencing **system** power consumption
  - Operating Voltage, and the implementation of the power supply system
  - Power consumption of external components
  - Power switching of external components
  - System level power safe modes

Factors influencing microcontroller power consumption

Operating voltages

Operating voltages
8-bit microcontrollers

- Traditionally there are two lines: general purpose, and low power (L line)
  - General purpose: ~4V – 55V (ATmega128, ATmega1281)
  - L (low power line): 2.7V – 5.5V (ATmega128L, ATmega1281V)
- Maximal operating frequency can depend on voltage level

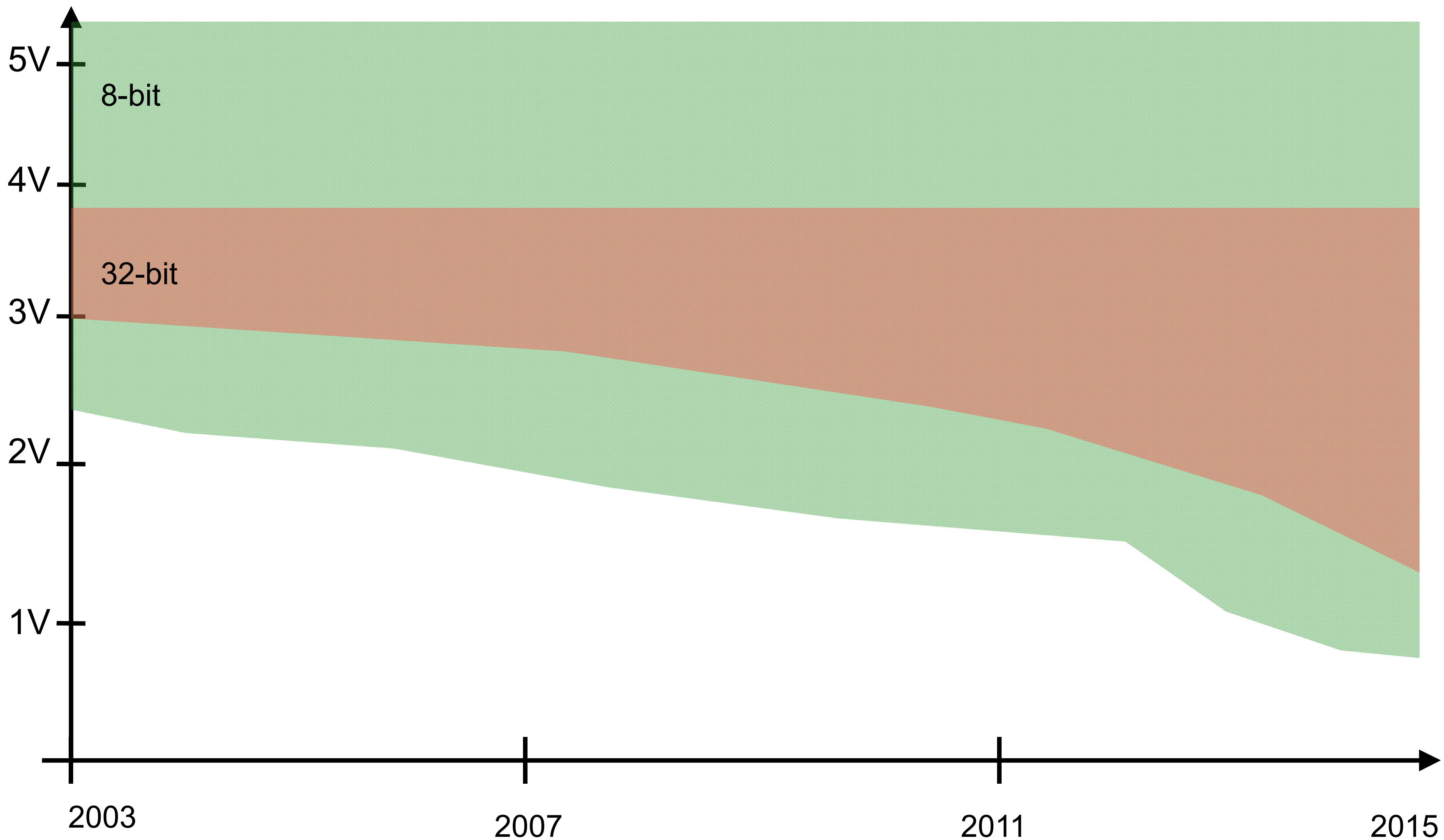


Operating voltages
32-bit microcontrollers

- LPC2106 (2003)
  - Separate core and peripheral voltage
    - 3.3V peripheral (3.0V – 3.6V)
    - 1.8V core

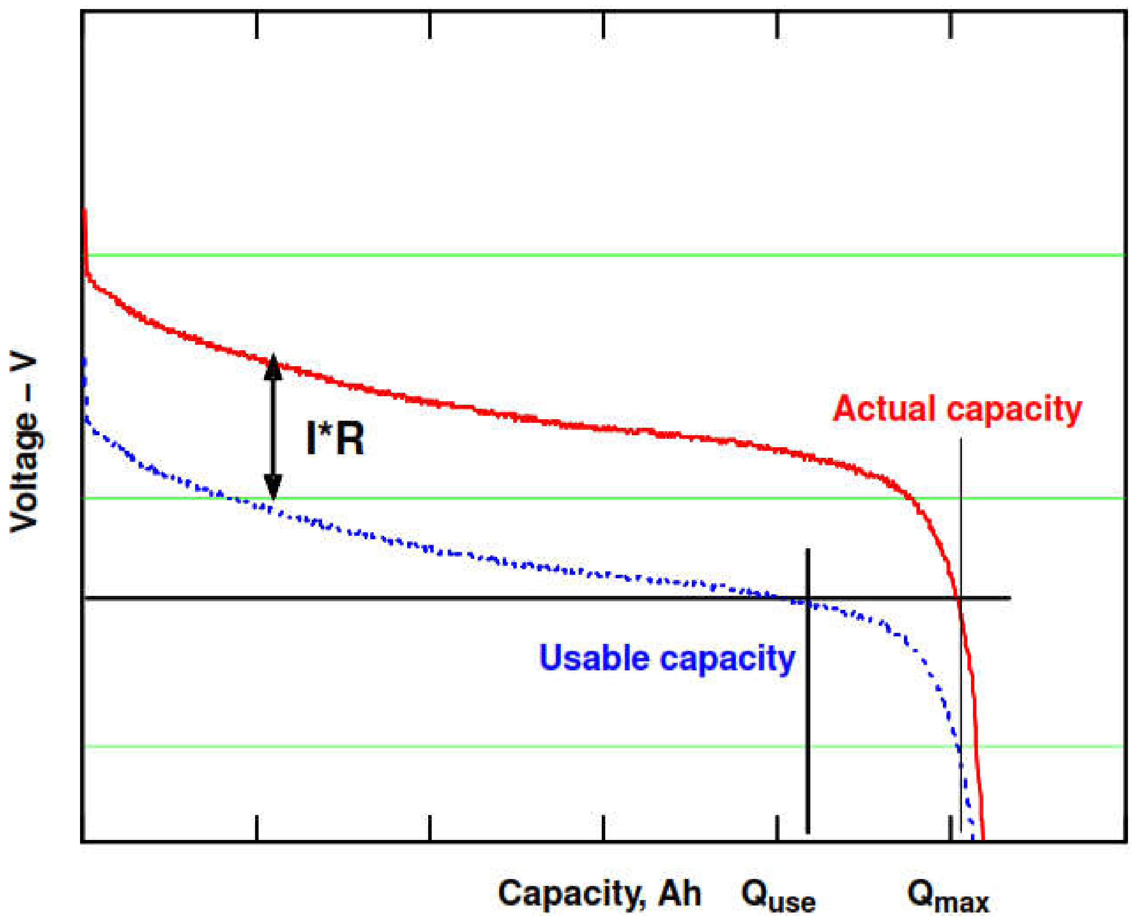
- ARM Cortex M lines: there is no separate power
  - STM32F1xx (2007) 2.0V – 3.6V
  - STM32F2xx (2010) 1.8V – 3.6V
  - STM32F4xx (2013) 1.7V – 3.6V
  - LPC1768 (2009) 2.4V – 3.6V
  - LPC800 (2012) 1.8V – 3.6V
  - EFM32ZG(2014) 1.98V – 3.8V

Change of operating voltage levels



Discharge diagram of an AA battery

- Very typical power source of embedded systems



Discharge diagram of an AA battery

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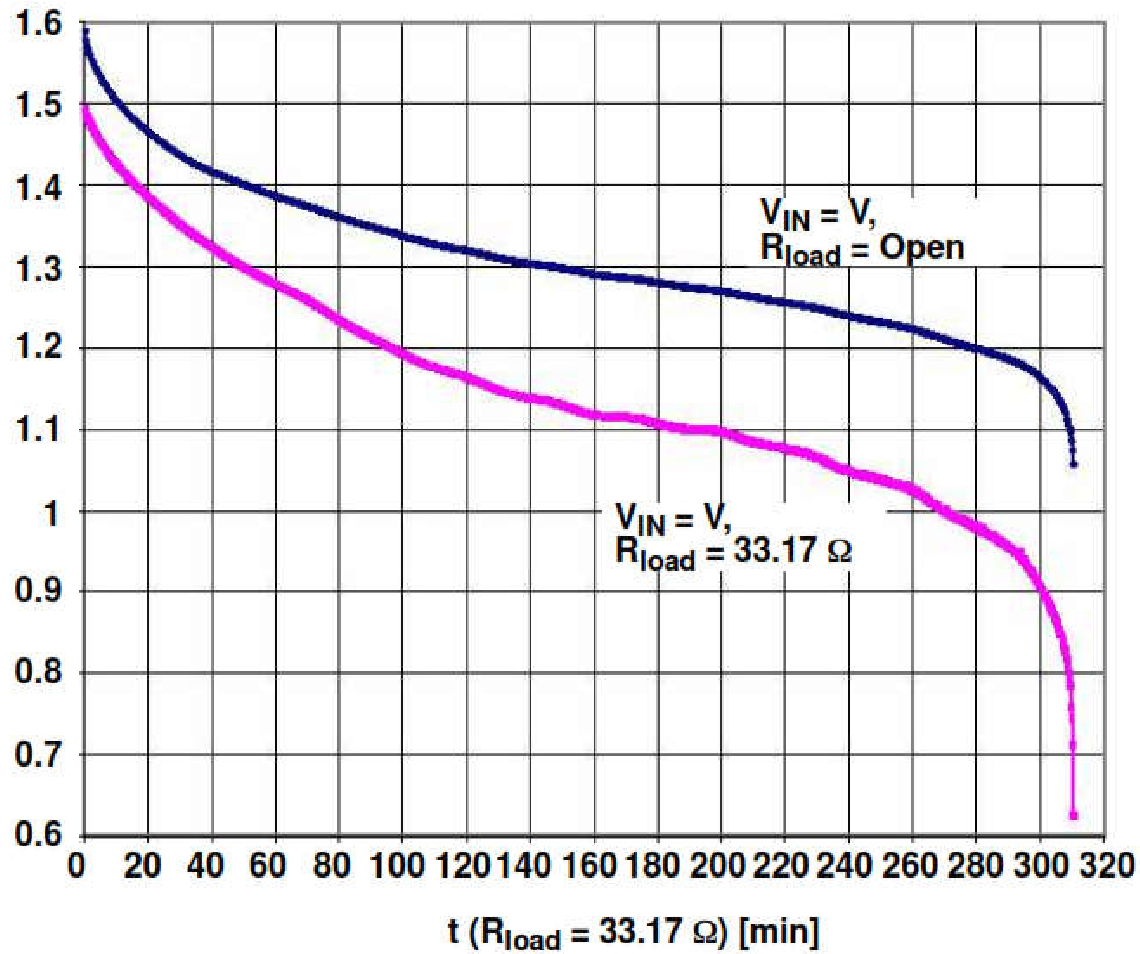
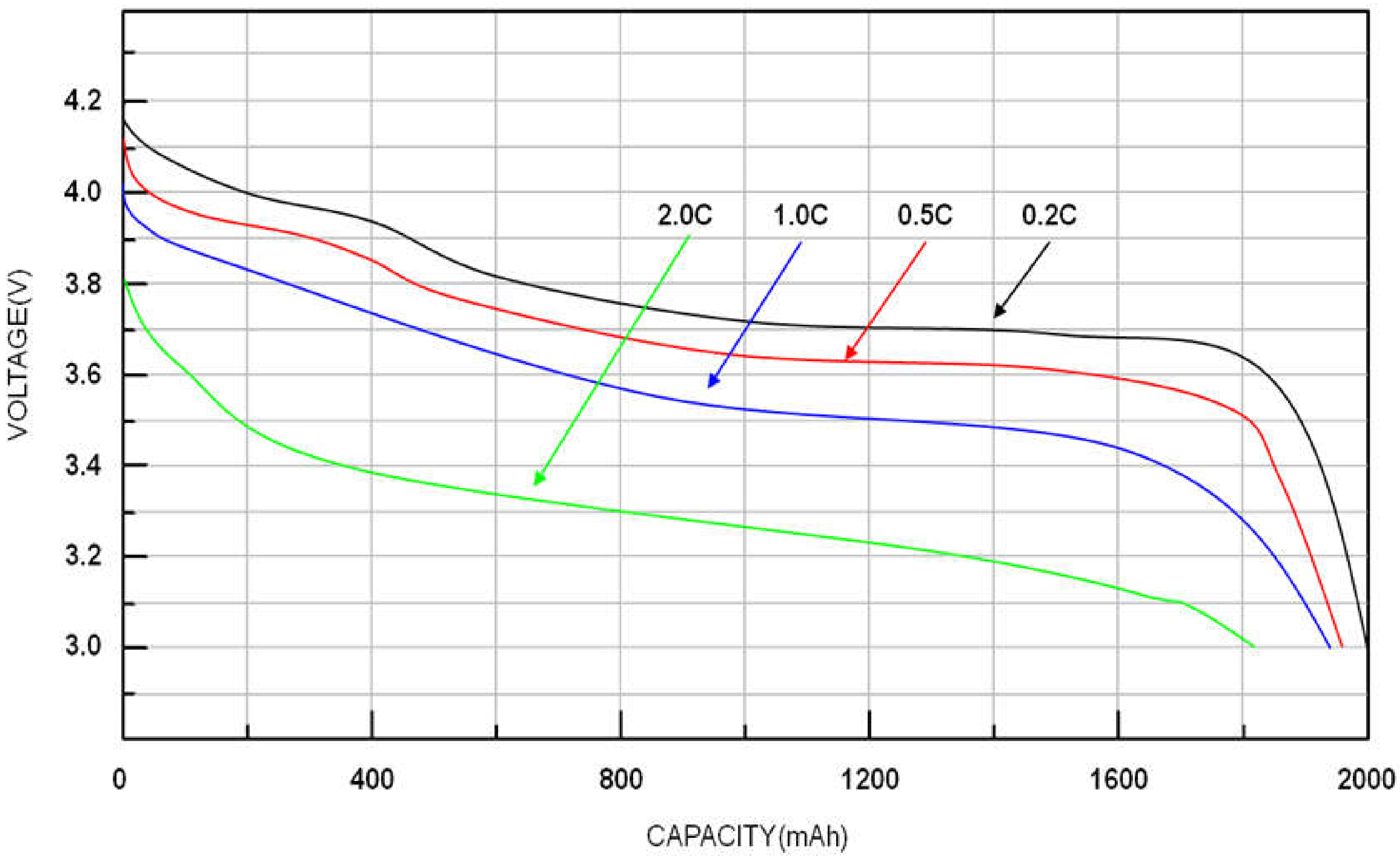


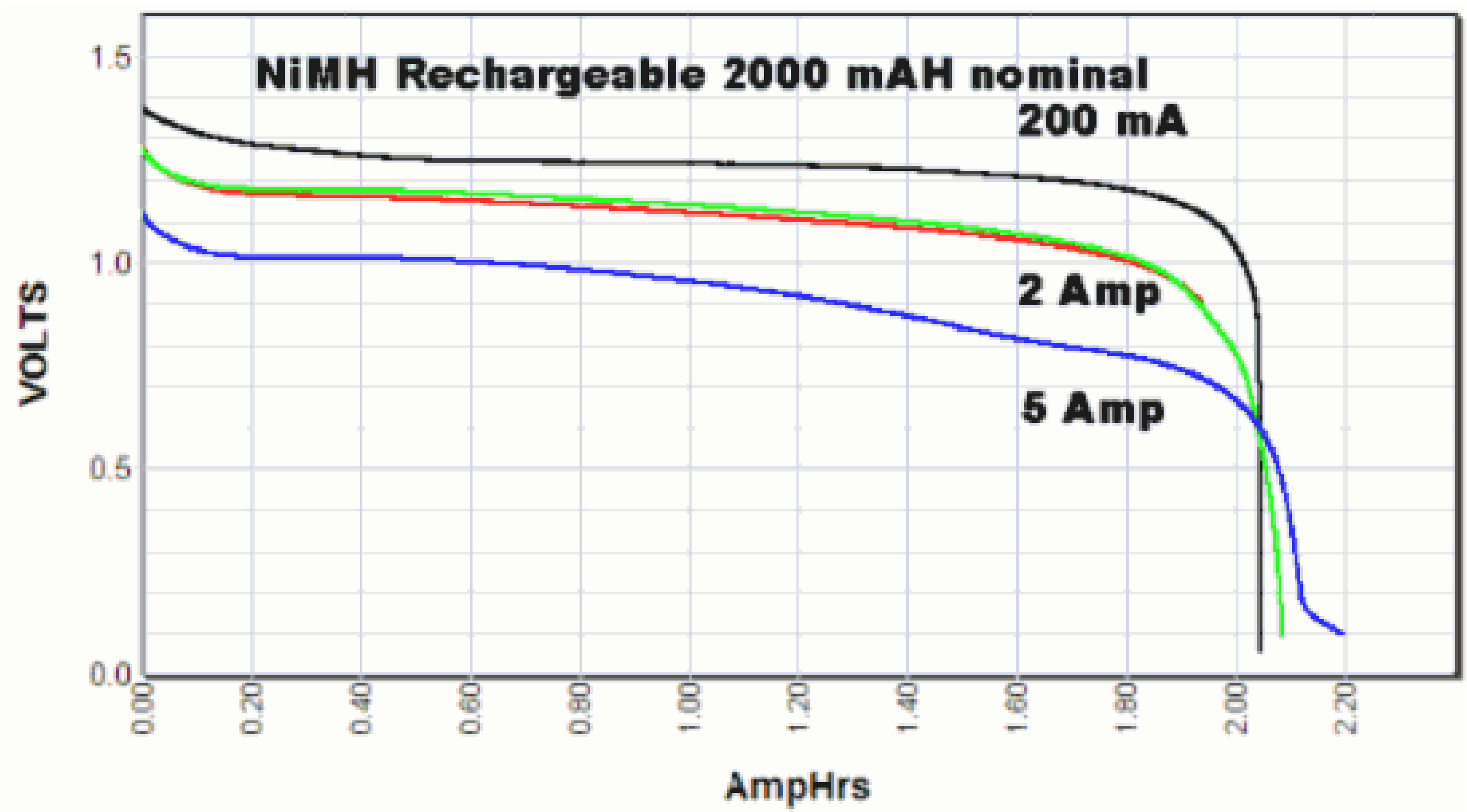
Rechargeable batteries

- Lithium-ion



Rechargeable batteries

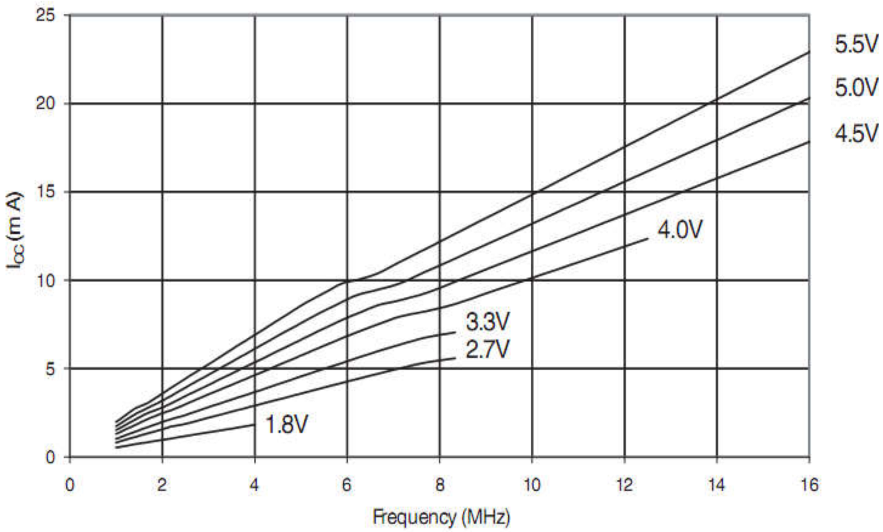
- NiMH



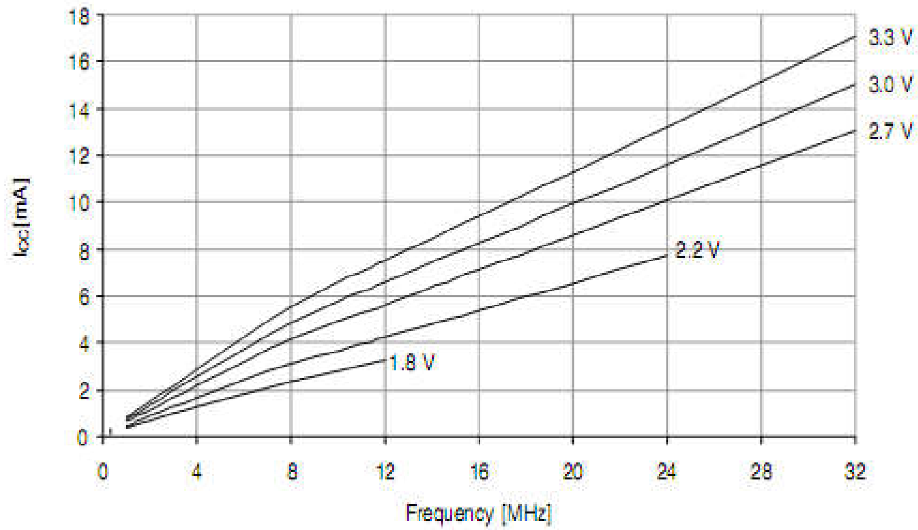
Power consumption in active mode

The influence of Voltage level

- Example of an AVR 8-bit microcontroller



Old line



New line

The influence of ambient temperature

- Example of STM32F4F429

f_{HCLK} (MHz)	Typ	Max(2)		
		T_A = 25 °C	T_A = 85 °C	T_A = 105 °C
180	98	104(5)	123	141(5)
168	89	98(5)	116	133(5)
150	75	84	100	115
144	72	81	96	112
120	54	58	72	85

Active power consumption of *8-bit micros*

Popular lines in μA/MHz

Aktív fogyaztás							
	ATmega1281 (2005)	ATtiny45 (2006)	PIC18F452 (2004)	PIC24F16 (2008)	MSP430G2x	mega128A1 (20	Atmega164A
min. μA/MHz	500	300	500	200 (x2)	220	350	300
max. μA/MHz	1500	1100	1100	360 (x2)	350	500	480

Active power consumption of *32-bit micros*

- 32-bit micros are relatively more efficient at high speed

Aktív fogyaztás								
	LPC2378	STM32F107	STM32F207 (RAM	LPC1113 (LP)	LPC800	EFM32ZG108	EFM32GG990	STM32F429
LowFrek MHz	10	8	30	12	6	10	10	8
LowFrek mA	15	6,6	7	2	0,7	1,2	2,5	3
LowFrek μA/MHz	1500	825	233	166	115	120	250	375
High frek MHz	72	72	120	50	24	24	32	180
High frek mA	63	32	22	7	2,2	2,75	6,4	44
High frek μA/MHz	875	450	183	140	95	115	200	245
High frek Aktív periféria mA	125	66	49,5					98

Active power consumption of *32-bit micros*

32-bit micros are relatively more efficient at high speed

- The Flash acceleration can influence the power cons.

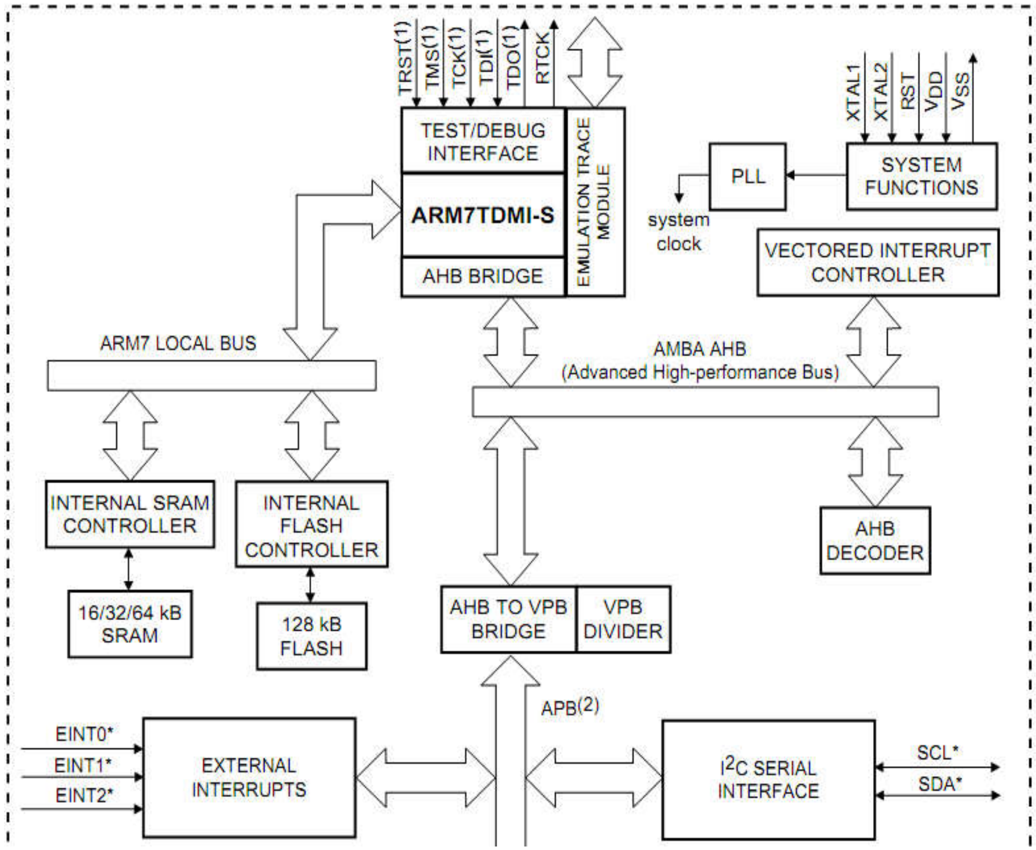
STM32F429 tipikus fogyasztás perifériák lekapcsolva		
Freqvencia	Flash gyorsítással	Flash gyorsítás nélkül
180 MHz	44 mA	57 mA
150 MHz	36 mA	46 mA
120 MHz	25 mA	36 mA
90 MHz	20 mA	29 mA
60 MHz	14 mA	21 mA
30 MHz	8 mA	13 mA
8 MHz	3 mA	5 mA

Aktív fogyaztás								
	LPC2378	STM32F107	STM32F207 (RAM	LPC1113 (LP)	LPC800	EFM32ZG108	EFM32GG990	STM32F429
LowFrek MHz	**10**	**8**	**30**	**12**	**6**	**10**	**10**	**8**
LowFrek mA	15	6,6	7	2	0,7	1,2	2,5	3
LowFrek µA/MHz	**1500**	**825**	**233**	**166**	**115**	**120**	**250**	**375**
High frek MHz	72	72	120	50	24	24	32	**180**
High frek mA	63	32	22	7	2,2	2,75	6,4	44
High frek µA/MHz	**875**	**450**	**183**	**140**	**95**	**115**	**200**	**245**
High frek Aktív periféria mA	**125**	**66**	**49,5**					**98**

Influencing active mode power consumption

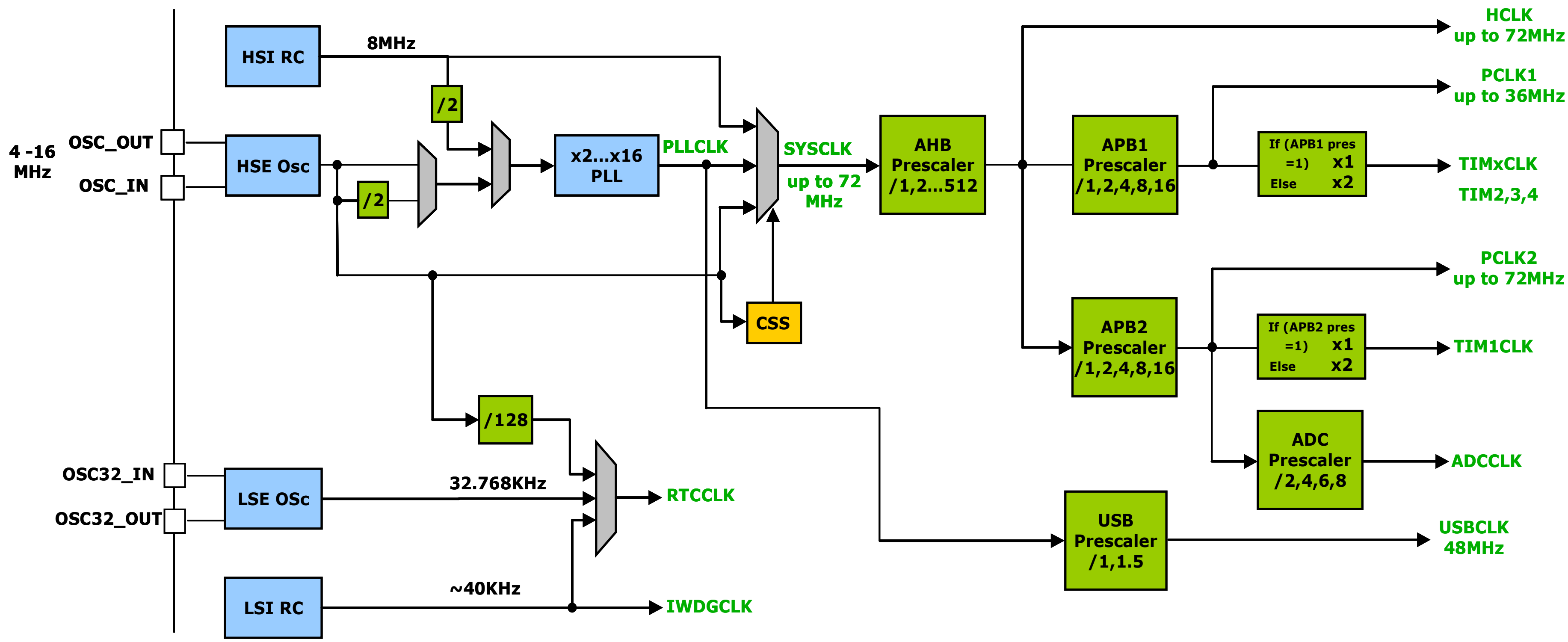
Flash acceleration, peripheral clock tree

- These opportunities present sine the first 32.bit lines
  - Can have an influence of 10%-20%



Flash acceleration, peripheral clock tree

- New ARM cortex generations have more and more detailed clock tree



Switching of peripherals

- Present since the first lines

Table 10. Typical LPC2104/2105/2106/01 peripheral power consumption in Idle mode

Core voltage 1.8 V; T_{amb} = 25 °C; all measurements in mA; PCLK = $^{CCLK}/_{4}$

Peripheral	CCLK = 60 MHz
Timer 0	0.258
Timer 1	0.254
UART 0	0.494
UART 1	0.561
PWM0	0.511
I^2C-bus	0.078
SPI	0.060
RTC	0.109
SSP	0.377

Switching of peripherals

- STM micros start with peripheral clocks switched of after reset

AHB	ETH_MAC	5.2
	OTG_FS	7.7
APB1	TIM2	1.5
	TIM3	1.5
	TIM4	1.5
	TIM5	1.5
	TIM6	0.6
	TIM7	0.3
	SPI2	0.2
	USART2	0.5
	USART3	0.5
	UART4	0.5
	UART5	0.5

	I2C1	0.5
	I2C2	0.5
	CAN1	0.8
	CAN2	0.8
	DAC	0.4
APB2	GPIO A	0.5
	GPIO B	0.5
	GPIO C	0.5
	GPIO D	0.5
	GPIO E	0.5
	ADC1(2)	2.1
	ADC2(2)	2.0
	TIM1	1.7
	SPI1	0.4
	USART1	0.9

Power save modes

Power save modes

- Traditional power save modes

	CPU Clock	Peripheral Clock	Real-Time Clock	Asynchron IT
Run				
Idle / Standby				
Power Safe, *Power Down*				
Power Down, Deep Power Down				

Power save modes
8-bit micros

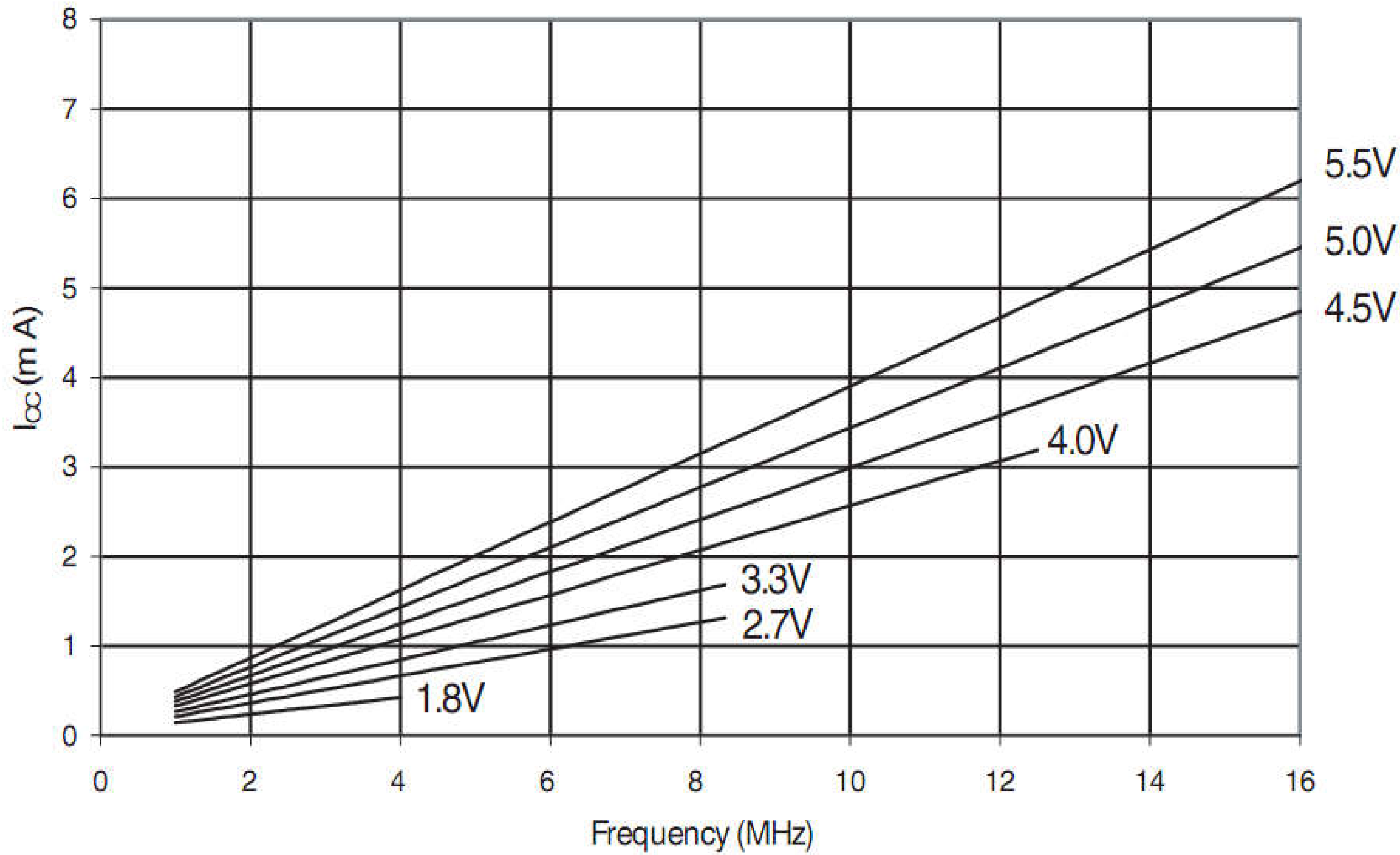
- Example of power save modes of an AVR microcontroller

	Active Clock Domain			Oscillators		Wake-up Sources				
Sleep Modes	**CPU Clock**	**Peripheral and USB Clock**	**RTC Clock**	**System Clock Source**	**RTC Clock Source**	**USB Resume**	**Asynchronous Port Interrupts**	**TWI Address Match Interrupts**	**Real Time Clock Interrupts**	**All Interrupts**
Idle		X	X	X	X	X	X	X	X	X
Power down						X	X	X		
Power save			X		X	X	X	X	X	
Standby				X		X	X	X		
Extended standby			X	X	X	X	X	X	X	

Power save modes

8-bit micros

- **Idle mode** of ATmega1281: 1/3 of active power



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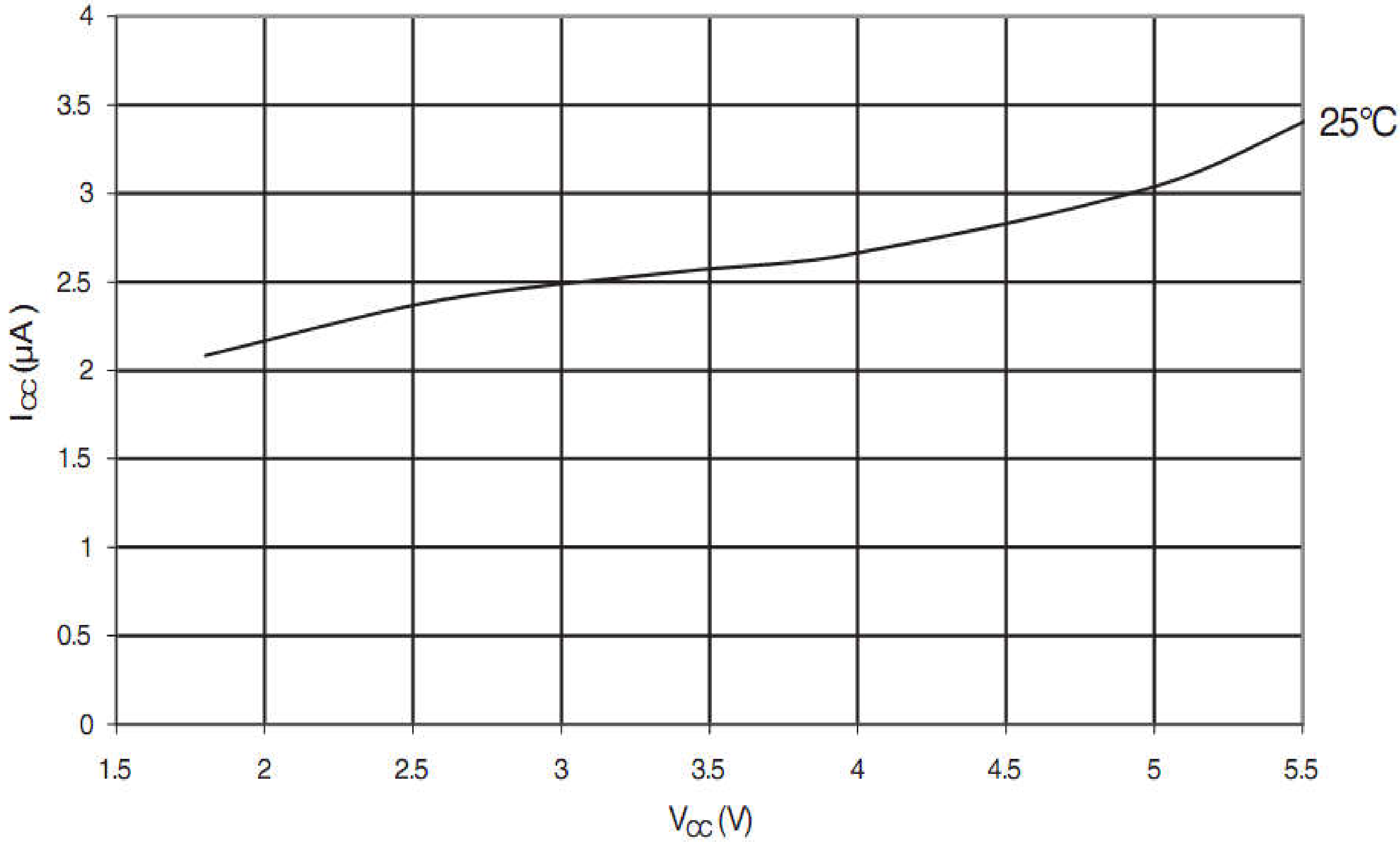
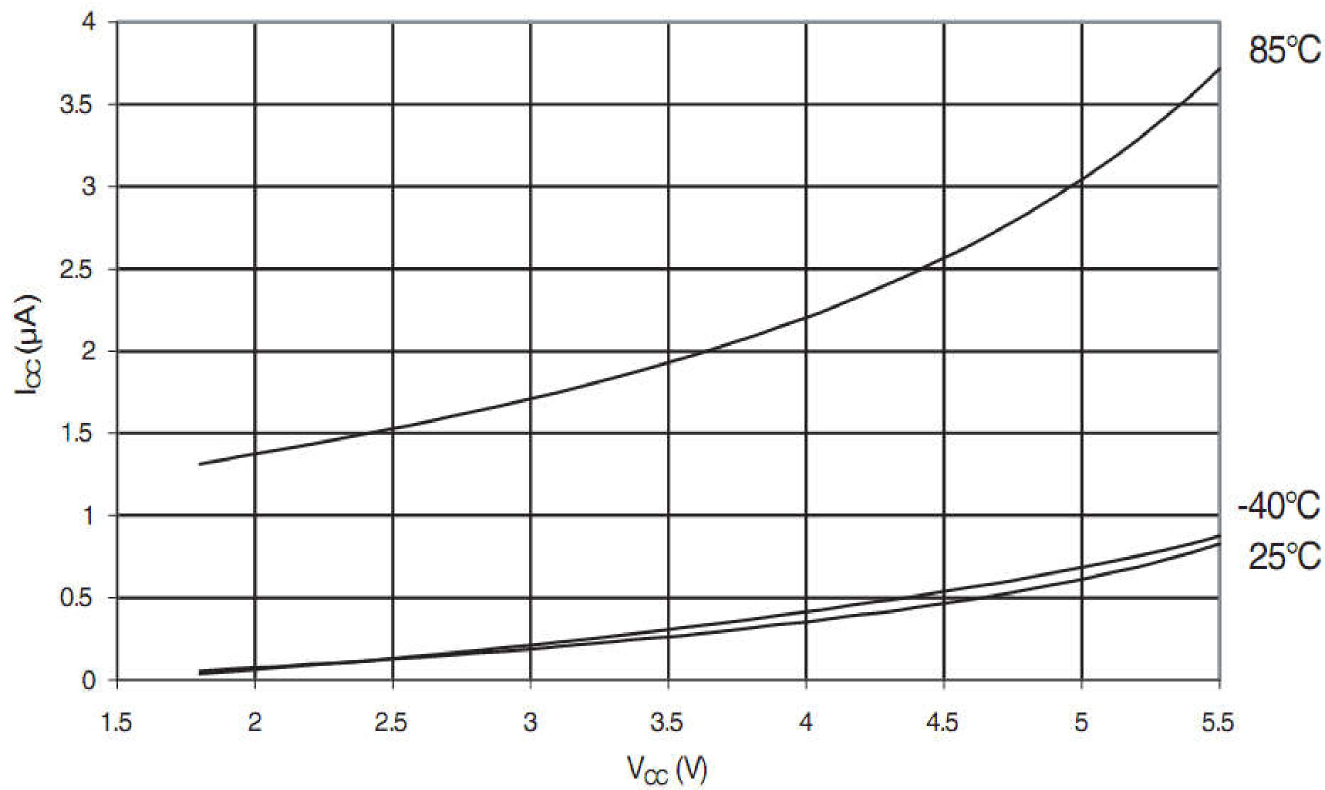
Power save modes
8-bit micros

- **Powersave mode** of ATmega1281
  - Watchdog Timer on: +3μA



Power save modes
8-bit micros

- **Powersave mode** of ATmega1281
  - Watchdog Timer on: +3μA
  - Ambient temperature has a huge effect on it



Power save modes

8-bit micros

- AVR wake up times
  - External cystal

Oscillator Source / Power Conditions	Start-up Time from Power-down and Power-save	Additional Delay from Reset (V_{CC} = 5.0V)
Crystal Oscillator, BOD enabled	16K CK	14CK
Crystal Oscillator, fast rising power	16K CK	14CK + 4.1 ms
Crystal Oscillator, slowly rising power	16K CK	14CK + 65 ms

  - Internal RC

Power Conditions	Start-up Time from Power-down and Power-save	Additional Delay from Reset (V_{CC} = 5.0V)
BOD enabled	6 CK	14CK
Fast rising power	6 CK	14CK + 4.1 ms
Slowly rising power	6 CK	14CK + 65 ms[(1)]

Power save modes
32-bit micros

- The very first line in 2003, the LPC2106
  - Idle mode
    - Processzor stop
    - Peripherals are still on
    - Wake up by any IT
    - **~10 - 20mA**
  - Power down mode
    - Every clock stops
    - Wake up by external IT
    - **10 – 500 μA (Very high and very temperature dependent)**

Power save modes
32-bit micros

- The main source of the problem is the SRAM
  - Main factor in the sleep consumption
  - Power consumption of an 32 kByte SRAM chip
    - Dinamic: 30mA
    - Standby: 2 – 40 μA

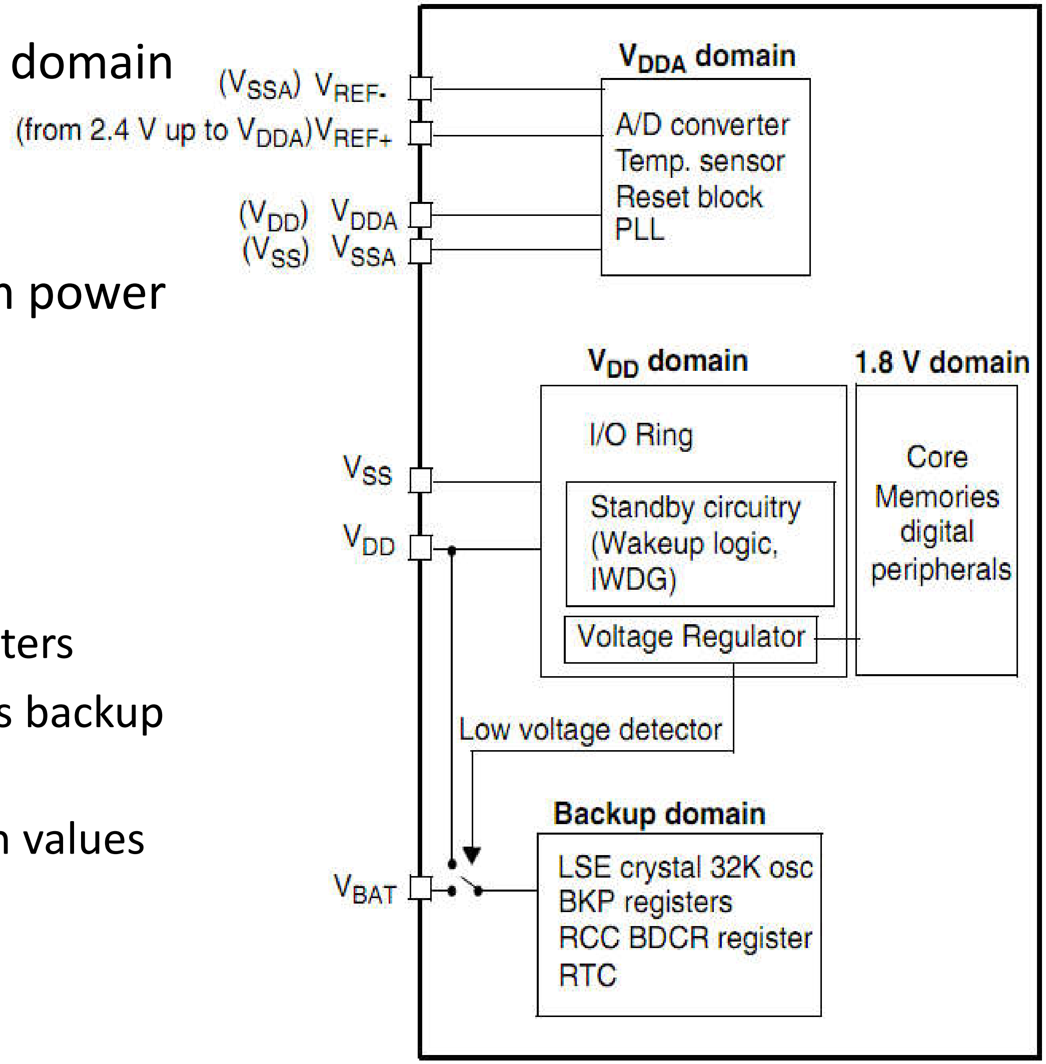
Power save modes of 32-bit micros

- New mode to handle the SRAM problem

	CPU Clock	Peripheral Clock	Real-Time Clock	SRAM	Asynchron IT
Run					
Idle / Standby					
Power Safe					
Power Down					
Deep Power Down					

Power save modes
32-bit micros

- STM32F107 separate battery domain
  - Backup registers
  - RTC functionality
  - Automatic switching from power to batters power source
    - Reset
    - Power control blokk
  - Backup register
    - 42 pieces of 16 bit registers
    - The tamper signal clears backup register values
    - Contains RTC calibration values



Power save modes
32-bit micros

- STM32F107
  - *Sleep mode*
    - Processor core stops (Idle mode in AVR).
    - Wake up in nearly 0 time.
    - Uses the WFI, WFE special instructions of cortex core
  - *Stop mode*
    - Core and peripheral clocks stops, SRAM data preserves its context
    - The Watchdog, internal RTC and their power can remain on
  - *Standby mode*
    - Core and peripheral power domain switch off with their power regulators
    - SRAM is cleared. The power for Watchdog and internal RTC is provided by the battery domain
    - Wake up by the Wake–up pin , Watchdog reset, reset, or RTC interrupt

Power save modes
32-bit micros

- STM32F107 Sleep mode

Symbol	Parameter	Conditions	f_{HCLK}	Max[1]		Unit
				T_A = 85 °C	T_A = 105 °C	
I_{DD}	Supply current in Sleep mode	External clock[2], all peripherals enabled	72 MHz	48.4	49	mA
			48 MHz	33.9	34.4	
			36 MHz	26.7	27.2	
			24 MHz	19.3	19.8	
			16 MHz	14.2	14.8	
			8 MHz	8.7	9.1	
		External clock[3], all peripherals disabled	72 MHz	10.1	10.6	
			48 MHz	8.3	8.75	
			36 MHz	7.5	8	
			24 MHz	6.6	7.1	
			16 MHz	6	6.5	
			8 MHz	2.5	3	

Power save modes
32-bit micros

- STM32F107 Stop and Standby mode

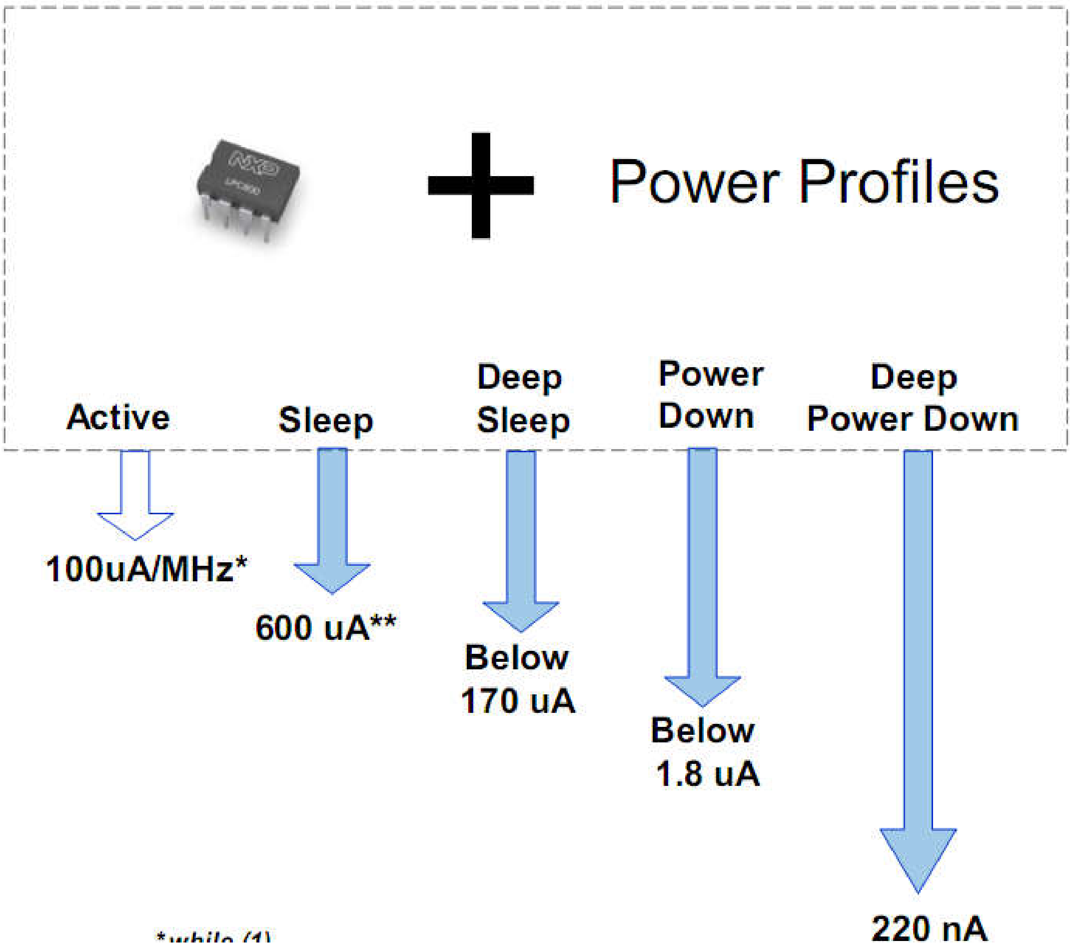
Symbol	Parameter	Conditions	Typ[1]			Max		Unit
			V_{DD}/V_{BAT} = 2.0 V	V_{DD}/V_{BAT} = 2.4 V	V_{DD}/V_{BAT} = 3.3 V	T_A = 85 °C	T_A = 105 °C	
I_{DD}	Supply current in Stop mode	Regulator in Run mode, low-speed and high-speed internal RC oscillators and high-speed oscillator OFF (no independent watchdog)		32	33	600	1300	µA
		Regulator in Low Power mode, low-speed and high-speed internal RC oscillators and high-speed oscillator OFF (no independent watchdog)		25	26	590	1280	
	Supply current in Standby mode	Low-speed internal RC oscillator and independent watchdog ON		3	3.8	-	-	
		Low-speed internal RC oscillator ON, independent watchdog OFF		2.8	3.6	-	-	
		Low-speed internal RC oscillator and independent watchdog OFF, low-speed oscillator and RTC OFF		1.9	2.1	5[2]	6.5[2]	
I_{DD_VBAT}	Backup domain supply current	Low-speed oscillator and RTC ON	1.1	1.2	1.4	2.1[2]	2.3[2]	

Power save modes
32-bit micros

- STM32F107 wake up times
  - External crytal: time for stabilizing is about 2ms
  - Internal RC osc

Symbol	Parameter	Typ	Unit
$t_{WUSLEEP}$(1)	Wakeup from Sleep mode	1.8	µs
t_{WUSTOP}(1)	Wakeup from Stop mode (regulator in run mode)	3.6	µs
	Wakeup from Stop mode (regulator in low power mode)	5.4	
$t_{WUSTDBY}$(1)	Wakeup from Standby mode	50	µs

Power save modes
Cortex M0, LPC800 summary



Low Power Mode	Impact
Sleep	Peripherals and memories are active, core is shut down
Deep Sleep	Peripherals receive no internal clocks. Memories are in stand-by mode. The WWDT, WKT, and BOD can remain active to wake up the system on an interrupt
Power Down	Peripherals receive no internal clocks. The flash memory is powered down. The WWDT, WKT, and BOD can remain active to wake up the system on an interrupt
Deep Power Down	The entire system is shut down except for the general purpose registers in the PMU and the self wake-up timer. All registers maintain their internal states. The part can wake up on a pulse on the WAKEUP pin or when the self wake-up timer times out. On wake-up, the part reboots

Silabs EFM32 power save modes

32 bites micros

- **Energy Mode 0: Run Mode ~ 200uA/MHz**

  Normal active mode

- **Energy Mode 1: Sleep Mode ~ 50uA/MHz**

  CPU clock stops. Peripherals and SRAM working. DMA can move data.

- **Energy Mode 2: Deep Sleep Mode ~ 1.1uA**

  High speed clock stopped. Low clocks speed (32kHz) and asynchron peripherals remain active (LCD driver, Low enegy USART, RTC, Low Energy Sensor Interface, Analog Comparator, GPIO)

- **Energy Mode 3: Stop mode ~ 0.9uA**

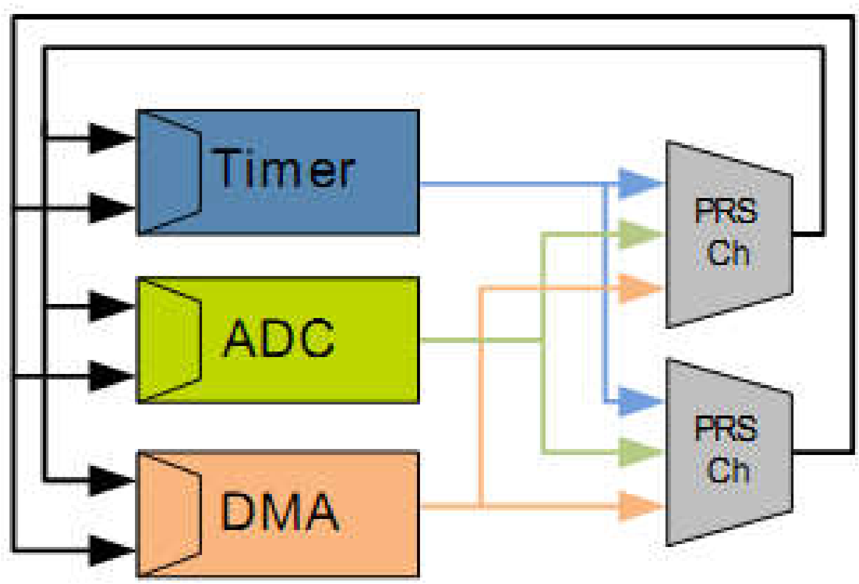
  Clocks are off except the ULFRCO. Some periferals can use ULFRCO (I2C, Watchdog, Analog Comparator, Voltage Comparator, RTC ULFRRCO, GPIO asycron IT)

- **Energy Mode 4: Shut Off Mode ~ 0.4uA with RTC, 20nA without RTC**

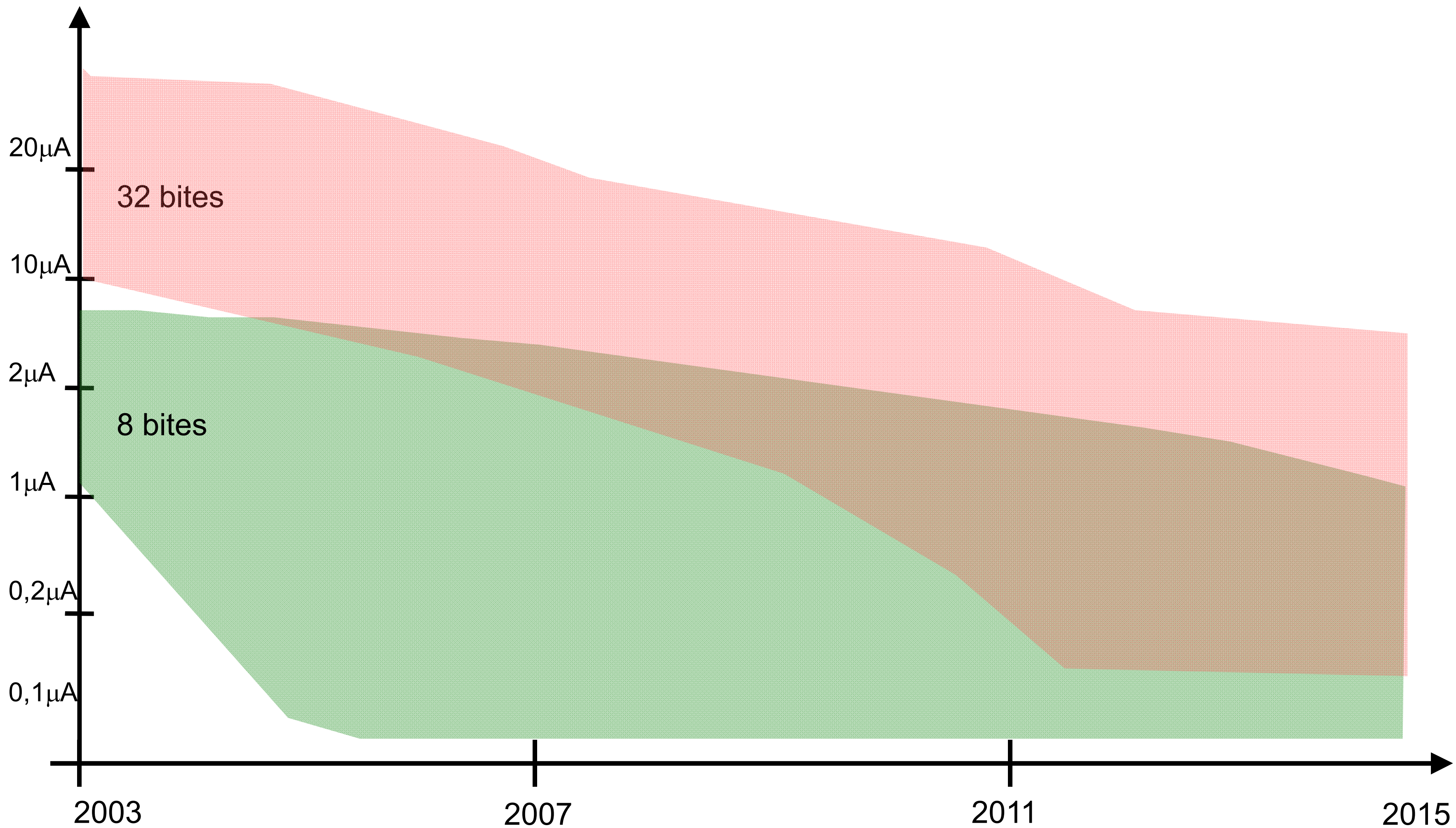
  Everyting stops, wake up to dedicated wake-up pin, or reset. Retention RAM keep context, and Backup RTC can operate.

Silabs EFM32 energia peripheral reflex system

- Enables fast peripheral – peripheral interaction
- “Smart peripheral – peripheral DMA”
- Some features can operate at EM2, EM3 modes



Change of sleep currents



System level energy saveing

Selecting power source

- Selecting battery type
  - Alkaline battery
    - Low self discharge: typicall 5%/year room temperatre (can change to 25%/year at high temperature)
    - Capacity 1500-2000mAh
  - Button batteries, Lithium
    - 3V power 10mAh-200mAh capacity

Selecting power source

- Selecting battery type *cont…*
  - Rechargeable
    - NiMH and NiCd batteries
      - Memory effect
      - Fast self discharge: n%/day
    - Lithium-Ion, LiFePo
      - No memory effects
      - Tolerable self discharge 5–10%/month
      - Questionable operation at low temperature
  - Super capacitans
    - Limited Voltage levels 2V-5,5V
    - Capacitance of 0,1F-10F

Voltage levels

- Is Voltage level change needed?
- Switching DC/DC converters, and it attributes
  - Step-up, Step-down, or combined
  - Efficiency
  - Cost factor
  - Quiescent current
- Linear stabilizers
  - Drop voltage
  - Efficiency
  - Quiescent current
- Integrated power modules

System architecture

- Determining the Active, Passive periods
  - Communication systems should take this into account
- Switching of non active external peripherals
  - High-side
  - Low-side
- Do not let not used pins in floating

Comparison of computation efficiency 8-bit, 16-bit, 32-bit

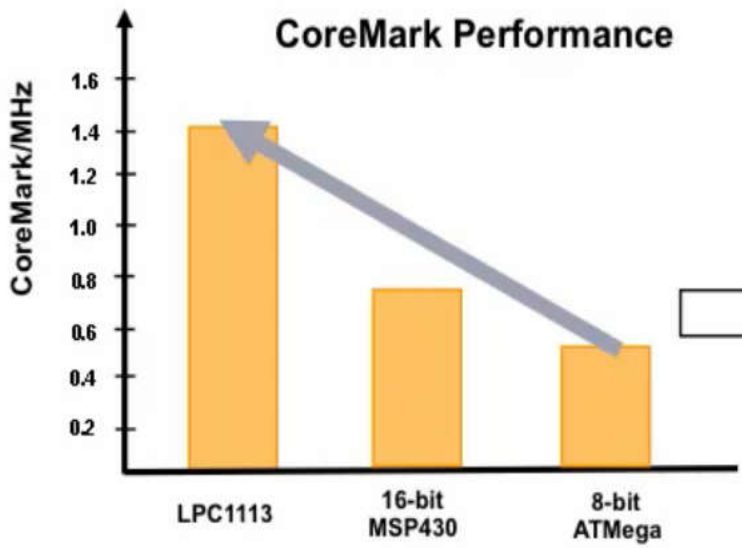
8-bit example		16-bit example	ARM Cortex-M0

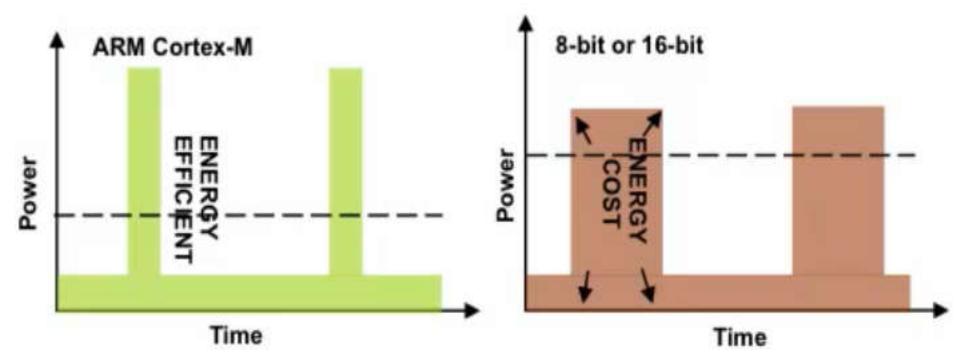
MOV A, XL ; 2 bytes
MOV B, YL ; 3 bytes
MUL AB; 1 byte
MOV R0, A; 1 byte
MOV R1, B; 3 bytes
MOV A, XL ; 2 bytes
MOV B, YH ; 3 bytes
MUL AB; 1 byte
ADD A, R1; 1 byte
MOV R1, A; 1 byte
MOV A, B ; 2 bytes
ADDC A, #0 ; 2 bytes
MOV R2, A; 1 byte
MOV A, XH ; 2 bytes
MOV B, YL ; 3 bytes
	MUL AB; 1 byte
	ADD A, R1; 1 byte
	MOV R1, A; 1 byte
	MOV A, B ; 2 bytes
	ADDC A, R2 ; 1 bytes
	MOV R2, A; 1 byte
	MOV A, XH ; 2 bytes
	MOV B, YH ; 3 bytes
	MUL AB; 1 byte
	ADD A, R2; 1 byte
	MOV R2, A; 1 byte
	MOV A, B ; 2 bytes
	ADDC A, #0 ; 2 bytes
	MOV R3, A; 1 byte
		MOV R1,&MulOp1
		MOV R2,&MulOp2
		MOV SumLo,R3
		MOV SumHi,R4
			MULS r0,r1,r0

Time: 48 clock cycles* **Code size:** 48 bytes		**Time:** 8 clock cycles **Code size:** 8 bytes	**Time:** 1 clock cycle **Code size:** 2 bytes

Computation efficiency and power consumption

- Performing functions faster can results in more time in sleep





http://www.arm.com/products/processors/cortex-m/index.php

Interesting novelties

FRAM based controllers

- Ferroelectric RAM
  - Non volatile memory
  - Requires relatively small amount of power to write
  - Fast write time: idő 125ns (not really fast)
  - Univerzal memory: Data + Code + backup
  - 10^{15} write cycles (can be a problem is some situations)
- Texas Instrumentsnek has a line of these micros introduced in 2011

FRAM based controllers

- TMS430FR line
  - Max. freq: 16-24MHz
  - 4-128kByte FRAM
  - 0,5-2kByte SRAM

Mode	Consumption (Typical)
Active Mode	81.4 µA/MHz
Standby	6.3 µA
Real-Time Clock	1.5 µA
Shutdown	0.32 µA