Designing for Ultra-Low Power with MSP430

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Agenda

• Introduction to Ultra-Low Power
• Looking for Ultra-Low Power Parts
• MSP430 – The Ultra-Low Power MCU
• Low-Power Efficient Coding Techniques
• Summary
Achieving **Ultra-low Power**

- Extended Ultra-low Power standby mode
- Minimum active duty cycle
- Performance on-demand
Ultra-low Power Clock Control

- **LPM0**
  - CPU Off
  - DCO on
  - ACLK on
  - 35uA

- **Active**
  - DCO on
  - ACLK on
  - 250uA

- **LPM3**
  - RTC function
  - LCD driver
  - RAM/SFR retained

- **Stand-by**
  - DCO off
  - ACLK on
  - 0.8uA

- **LPM4**
  - Off
  - All Clocks Off
  - 0.1uA

- **<6us**

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Ultra-Low Power Architecture

Multiple operating modes
- 0.1uA power down
- 0.7uA standby mode
- 250uA / 1MIPS

Modern CPU
Minimum cycles per task

Instant-on stable high-speed clock

Zero-power BOR

- 50nA pin leakage

Intelligent peripherals
Power Consumption in CMOS Designs

• CMOS Inverter:

- Power Consumption of a CMOS Inverter:

\[ P = P_{\text{stat}} + P_Q + P_{\text{dyn}} \]

\[ P_{\text{stat}} = V_{cc} \times I_{LL} \]
\[ P_Q = \beta / 12 \times (V_{cc} - 2U_{Tn})^3 \times \tau / T \]
\[ P_{\text{dyn}} = C_L \times f \times V_{cc}^2 \]
MCU's Digital Supply Current

- AVcc
- AVss
- DVcc
- DVss
- Reset
- CPU Clock

Graph showing waveforms with labels:
- CH1
- CH2

Tek Stop: 50.0MS/s
66 Acqs

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MSP430 Active Mode Supply Current

- MSP430F2131 data sheet [slas439a]:

![Graph 1](image1.png)

**Figure 2.** Active mode current vs $V_{CC}$, $T_A = 25^\circ C$

![Graph 2](image2.png)

**Figure 3.** Active mode current vs DCO frequency

$T_A = 85^\circ C$

$T_A = 25^\circ C$

$V_{CC} = 3\, V$

$T_A = 85^\circ C$

$T_A = 25^\circ C$

$V_{CC} = 2.2\, V$

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## Device, Voltage, Temperature & Clock

<table>
<thead>
<tr>
<th>Device</th>
<th>Voltage</th>
<th>Temperature</th>
<th>Current (µA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSP430F16x LPM3</td>
<td>VCC = 2.2V</td>
<td>TA = -40°C</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TA = 25°C</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TA = 85°C</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TA = -40°C</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TA = 25°C</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TA = 85°C</td>
<td>3.0</td>
</tr>
<tr>
<td>MSP430F20xx LPM3</td>
<td>VCC = 3V</td>
<td>TA = -40°C</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TA = 25°C</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TA = 85°C</td>
<td>0.9</td>
</tr>
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<td></td>
<td></td>
<td>TA = -40°C</td>
<td>0.9</td>
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<td></td>
<td></td>
<td>TA = 25°C</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TA = 85°C</td>
<td>1.6</td>
</tr>
<tr>
<td>LFXT1</td>
<td>2.2V</td>
<td>TA = -40°C</td>
<td>0.7</td>
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<tr>
<td></td>
<td></td>
<td>TA = 25°C</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TA = 85°C</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TA = -40°C</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TA = 25°C</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TA = 85°C</td>
<td>1.0</td>
</tr>
<tr>
<td>VLO</td>
<td>3V</td>
<td>TA = -40°C</td>
<td>0.5</td>
</tr>
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<td></td>
<td></td>
<td>TA = 25°C</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TA = 85°C</td>
<td>1.3</td>
</tr>
</tbody>
</table>

- Die size and # pins
- Family architectures and clock system
P1OUT |= 0x02;  // Power divider
CACTL1 = CARSEL + CAREF_2 + CAON;  // Comp_A on
if (CAOUT & CACTL2)
  P1OUT |= 0x01;  // Fault
else
  P1OUT &= ~0x01;
P1OUT &= ~0x02;  // de-power divider
CACTL1 = 0;  // Disable Comp_A
## Integrated Analog Power Managing

### ADC10

<table>
<thead>
<tr>
<th>$I_{ADC10}$</th>
<th>Operating supply current into $V_{CC}$ terminal (see Note 3)</th>
<th>$V_{CC}$ = 2.2 V</th>
<th>$V_{CC}$ = 3 V</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$f_{ADC10CLK}$ = 5.0 MHz, $ADC10ON = 1$, REFON = 0, $ADC10SHT0=1$, $ADC10SHT1=0$, $ADC10DIV=0$</td>
<td>0.52 mA</td>
<td>0.6 mA</td>
</tr>
<tr>
<td>$I_{REF+}$</td>
<td>Reference operating supply current, reference buffer disabled (see Note 4)</td>
<td>$V_{CC}$ = 2.2V/3 V</td>
<td>0.25 mA</td>
</tr>
<tr>
<td></td>
<td>$f_{ADC10CLK}$ = 5.0 MHz, $ADC10ON = 0$, REFON = 1, REF2_5V = x; REFOUT = 0</td>
<td></td>
<td>0.4 mA</td>
</tr>
</tbody>
</table>

### DAC12

<table>
<thead>
<tr>
<th>$DAC_{12AMPx}$</th>
<th>$DAC_{12IR}=1$, $DAC_{12_XDAT}=0$</th>
<th>$V_{eeREF+}=V_{REF+}=AV_{CC}$; $V_{REF+}=AV_{CC}$</th>
<th>2.2V/3V</th>
<th>μA</th>
</tr>
</thead>
<tbody>
<tr>
<td>$DAC_{12AMPx}=2$</td>
<td>$DAC_{12IR}=1$, $DAC_{12_XDAT}=0800h$</td>
<td>$V_{eeREF+}=V_{REF+}=AV_{CC}$</td>
<td>2.2V/3V</td>
<td>50</td>
</tr>
<tr>
<td>$DAC_{12AMPx}=5$</td>
<td>$DAC_{12IR}=1$, $DAC_{12_XDAT}=0800h$, $V_{eeREF+}=V_{REF+}=AV_{CC}$</td>
<td>$V_{REF+}=AV_{CC}$; $V_{eeREF+}=V_{REF+}=AV_{CC}$</td>
<td>2.2V/3V</td>
<td>200</td>
</tr>
<tr>
<td>$DAC_{12AMPx}=7$</td>
<td>$DAC_{12IR}=1$, $DAC_{12_XDAT}=0800h$, $V_{eeREF+}=V_{REF+}=AV_{CC}$</td>
<td>$V_{eeREF+}=V_{REF+}=AV_{CC}$</td>
<td>2.2V/3V</td>
<td>700</td>
</tr>
</tbody>
</table>

### OA

<table>
<thead>
<tr>
<th>Mode</th>
<th>$V_{CC}$</th>
<th>2.2 V/3 V</th>
<th>μA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast Mode, RRIP OFF</td>
<td>2.2 V/3 V</td>
<td>180</td>
<td>290</td>
</tr>
<tr>
<td>Medium Mode, RRIP OFF</td>
<td>2.2 V/3 V</td>
<td>110</td>
<td>190</td>
</tr>
<tr>
<td>Slow Mode, RRIP OFF</td>
<td>2.2 V/3 V</td>
<td>50</td>
<td>80</td>
</tr>
<tr>
<td>Fast Mode, RRIP ON</td>
<td>2.2 V/3 V</td>
<td>300</td>
<td>490</td>
</tr>
<tr>
<td>Medium Mode, RRIP ON</td>
<td>2.2 V/3 V</td>
<td>190</td>
<td>350</td>
</tr>
<tr>
<td>Slow Mode, RRIP ON</td>
<td>2.2 V/3 V</td>
<td>90</td>
<td>190</td>
</tr>
</tbody>
</table>
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MSP430x11x/12x Basic Clock

R2/SR:

<table>
<thead>
<tr>
<th>Reserved</th>
<th>V</th>
<th>SCG1</th>
<th>SCG0</th>
<th>OSC OFF</th>
<th>CPU OFF</th>
<th>GIE</th>
<th>N</th>
<th>Z</th>
<th>C</th>
</tr>
</thead>
</table>

LFXT1 Oscillator

12pF

OSC OFF

12pF

VCC

SCG0

DCO

Digitally Controlled Oscillator

LFXT1CLK

ACLK

MCLK

CPU OFF

SCG1

SMCLK

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Performance on Demand

- Immediate-stable clock start for reaction to events

**Interrupt**

**DCO**

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**Low Power Mode Configuration**

<table>
<thead>
<tr>
<th>Mode</th>
<th>V</th>
<th>SCG1</th>
<th>SCG0</th>
<th>OSC OFF</th>
<th>CPU OFF</th>
<th>GIE</th>
<th>N</th>
<th>Z</th>
<th>C</th>
<th>Power Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Mode</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>N</td>
<td>Z</td>
<td>C</td>
<td>~250uA</td>
</tr>
<tr>
<td>LPM0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>N</td>
<td>Z</td>
<td>C</td>
<td>~35uA</td>
</tr>
<tr>
<td>LPM3</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>N</td>
<td>Z</td>
<td>C</td>
<td>~0.8uA</td>
</tr>
<tr>
<td>LPM4</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>N</td>
<td>Z</td>
<td>C</td>
<td>~0.1uA</td>
</tr>
</tbody>
</table>

- **Assembler Code Example:**
  ```
bis.w #CPUOFF,SR ; LPM0
  ```
- **C Code Example:**
  ```
_BIS_SR (CPUOFF); // LPM0
  ```
Interrupt Processing

Prior to ISR

ISR hardware - automatically

- PC pushed
- SR pushed
- Interrupt vector moved to PC
- SR is cleared
- IFG flag cleared on single source flags

reti - automatically

- SR popped - original
- PC popped
Low Power Modes In Assembler

```
ORG 0F000h
RESET mov.w #300h,SP
       mov.w #WDT_MDLY_32,&WDTCTL
       bis.b #WDTIE,&IE1
       bis.b #01h,&P1DIR
Mainloop bis.w #CPUOFF+GIE,SR
       xor.b #01h,&P1OUT
       jmp Mainloop
WDT_ISR   bic.w #CPUOFF,0(SP)   reti

ORG 0FFFEh
DW RESET
ORG 0FFF4h
DW WDT_ISR
```
Low Power Modes In C

```c
void main(void)
{
    WDTCTL = WDT_MDLY_32;
    IE1 |= WDTIE;
    P1DIR |= 0x01;

    for (;;)
    {
        _BIS_SR(CPUOFF + GIE);
        P1OUT ^= 0x01;
    }
    #pragma vector=WDT_VECTOR
    __interrupt void watchdog_timer(void)
    {
        _BIC_SR_IRQ(CPUOFF);
    }
}
```

Low Power Modes In C

```
Item1
Item2
PC
SR=0018
```

```
Item1
Item2
PC
SR=0008
```

```
Item1
Item2
PC
SR
```
2xx Basic Clock Module+ with VLO Clock

- VLO provides crystal alternative
- Lower power
- < 500 nano-amp
Interrupts Control Program Flow

UART
RX
TX

9600 baud

100% CPU Load

// Polling UART Receive for (; ; )
{ 
    while (!(IFG2 & URXIFG0));
    TXBUF0 = RXBUF0;
}

0.1% CPU Load

// UART Receive Interrupt
#pragma vector=UART_VECTOR
__interrupt void rx (void)
{
    TXBUF0 = RXBUF0;
}
Software Functions >> Peripherals

100% CPU Load

Zero CPU Load

// Endless Loop
for (;;) {
  P1OUT |= 0x04;  // Set
delay1();
P1OUT &= ~0x04;  // Reset
delay2();
}

// Setup output unit
CCTL1 = OUTMOD0_1;
_BIS_SR(CPUOFF);

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MSP430 ADC10

• 10-bit ADC
• 200ksps+
• Autoscan
• Single Sequence
  Repeat-single
  Repeat-sequence
• Internal/external reference
• TA SOC triggers
• Direct transfer controller (DTC)
Is Timer-Triggered ADC Important?

```
// Interrupt
; MSP430 ISR to start conversion
BIS #ADC12SC,&ADC12CTL0 ; Start conversion
RETI ; Return

CPU cycles
6
5
5
16
```
Why Is Autoscan + DTC Important?

70 cycles/Sample

Fully Automatic

// Software
Res[pRes++] = ADC10MEM;
ADC10CTL0 &= ~ENC;
if (pRes < NR_CONV)
{
    CurrINCH++;
    if (CurrINCH == 3)
        CurrINCH = 0;
    ADC10CTL1 &= ~INCH_3;
    ADC10CTL1 |= CurrINCH;
    ADC10CTL0 |= ENC+ADC10SC;
}

// Autoscan + DTC
_BIS_SR(CPUOFF);
Why Is DMA Important?

// Interrupt
; MSP430 ISR for one output waveform
CPU cycles | DMA clocks
--- | ---
6 | 0
MOV @R5+, &DAC12_0DAT ; Update DAC0
5 | 2
AND #1F, R5 ; Modulo pointer
2 | 0
RETI ; Return
5 | 0
; 18 | 2

; MSP430 ISR for two output waveforms
CPU cycles | DMA clocks
--- | ---
6 | 0
MOV @R5+, &DAC12_0DAT ; Update DAC0
5 | 2
MOV @R5+, &DAC12_1DAT ; Update DAC1
5 | 2
AND #3F, R5 ; Modulo pointer
2 | 0
RETI ; Return
5 | 0
; 23 | 4
Low-Power Peripheral Features

• ADC10 reference buffer automatically controlled
• ADC10, ADC12, SD16 cores automatically controlled
• Auto-scan ADC modes
• Timer-triggered data conversion
• I2C and USCI modules automatically enable clock
• DAC and OA have speed vs. power settings

What can I do without the CPU?
Power Manage External Devices

- OPA with shutdown can be 20x lower total power

0.01uA = Shutdown
20uA = Active

0.06uA = Average

1uA = Quiescent
1uA = Active

1uA = Average
How To Terminate Unused Pins?

• Floating inputs cause additional current consumption!

• Please see last page of chapter 2 in User’s Guide

Vin at P1.0 [V]
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Bytes, Words & CPU Registers

- Use CPU registers for calculations and dedicated variables
- Same code size for word or byte
- Use word operations when possible

<table>
<thead>
<tr>
<th>Instruction</th>
<th>Description</th>
<th>Code/Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>5405</td>
<td><code>add.w R4,R5</code></td>
<td>; 1/1</td>
</tr>
<tr>
<td>529202000202</td>
<td><code>add.w &amp;0200,&amp;0202</code></td>
<td>; 3/6</td>
</tr>
<tr>
<td>5445</td>
<td><code>add.b R4,R5</code></td>
<td>; 1/1</td>
</tr>
<tr>
<td>52D202000202</td>
<td><code>add.b &amp;0200,&amp;0202</code></td>
<td>; 3/6</td>
</tr>
</tbody>
</table>
Effect Of The Constant Generator

- Immediate values **0xFFFF, 0, 1, 2, 4, 8** generated in hardware
- Reduces code size and cycles

**Completely Automatic!**

```
D3E20021       bis.b  #002h,&P1OUT ; With CG
D0F200100021   bis.b  #010h,&P1OUT ; Without CG
```
Interrupt Vector Generator

- TAIV is used to efficiently decode the TIMER_A1 interrupt vector for all other interrupt sources
- Contents is either 0, 2, 4, or 10
- Reading TAIV returns and clears the highest-priority pending interrupt
- Add TAIV to the PC and use a jump-table for TAIV demux
- Using TAIV instead of IFG polling greatly reduces interrupt overhead
C Coding Tips

• Use local variable as much as possible. Local variables use CPU registers whereas global variables use RAM.

• Use bit mask instead of bitfields for unsigned int and unsigned char.

• Use unsigned data types where possible

• Use pointers to access structures and unions

• Use “static const” class to avoid run-time copying of structures, unions, and arrays.

• Avoid modulo

• Count down “for” loops

Get to know your C code and its disassembly!
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Principles For ULP Applications

• Maximize the time in standby (LPM3)
• Use interrupts to control program flow
• Replace software functions with peripheral hardware
• Power manage internal peripherals
• Power manage external devices
• Device choice can make a difference
• Effective code is a must. Every unnecessary instruction executed is a portion of the battery wasted that will never return.
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<td>Video &amp; Imaging</td>
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