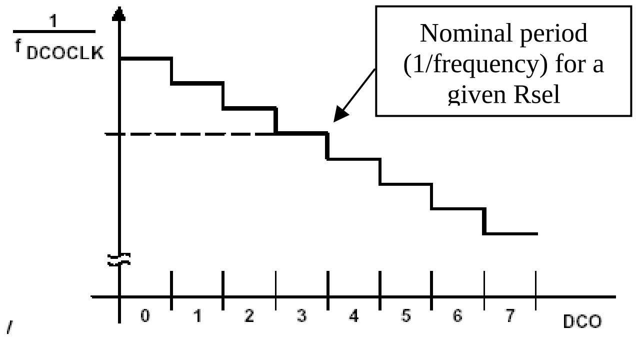
CPE/EE 323 Introduction to Embedded Computer Systems
Homework IV

1(25)	2(25)	3(25)	4(25)	Total
___	___		___	_____

Problem #1 (25 points) Microcontroller MSP430 is using 32KHz crystal connected to LFXT1 Oscillator, 8MHz crystal connected to XT2 Oscillator, and 3V power supply. See **Appendix (pages 6-9)** for necessary information.

Datasheet specifications:

$f_{Rsel+1} / f_{Rsel} = 1.65$,
$f_{DCO+1} / f_{DCO} = 1.12$,
DCOR: use internal R_{osc}



Set the following modes of operation (If the bit can be either 0 or 1, put X):

A. (5 points) processor clock (MCLK) to 8MHz, ACLK to 8KHz, SMCLK to 750 KHz.

BCSCTL1: ____

XT2Off	XTS	DIVA.1	DIVA.0	XT5V	Rsel2	Rsel1	Rsel0

BCSCTL2: ____

SELM.1	SELM.0	DIVM.1	DIVM.0	SELS	DIVS.1	DIVS.0	DCOR

DCOCTL: ____

DCO.2	DCO.1	DCO.0	MOD.4	MOD.3	MOD.2	MOD.1	MOD.0

B. (5 points) processor clock to 840KHz, SMCLK to 420KHz, and ACLK to 32KHz.

BCSCTL1:____

XT2Off	XTS	DIVA.1	DIVA.0	XT5V	Rsel2	Rsel1	Rsel0

BCSCTL2:____

SELM.1	SELM.0	DIVM.1	DIVM.0	SELS	DIVS.1	DIVS.0	DCOR

DCOCTL: ____

DCO.2	DCO.1	DCO.0	MOD.4	MOD.3	MOD.2	MOD.1	MOD.0

C. (5 points) processor clock to 2MHz, ACLK to 32 KHz, SMCLK to 1MHz.

BCSCTL1: _____

XT2Off	XTS	DIVA.1	DIVA.0	XT5V	Rsel2	Rsel1	Rsel0

BCSCTL2: _____

SELM.1	SELM.0	DIVM.1	DIVM.0	SELS	DIVS.1	DIVS.0	DCOR

DCOCTL: _____

DCO.2	DCO.1	DCO.0	MOD.4	MOD.3	MOD.2	MOD.1	MOD.0

D. (5 points) processor clock and SMCLK to 787 KHz and ACLK to 32KHz.

BCSCTL1: _____

XT2Off	XTS	DIVA.1	DIVA.0	XT5V	Rsel2	Rsel1	Rsel0

BCSCTL2: _____

SELM.1	SELM.0	DIVM.1	DIVM.0	SELS	DIVS.1	DIVS.0	DCOR

DCOCTL: _____

DCO.2	DCO.1	DCO.0	MOD.4	MOD.3	MOD.2	MOD.1	MOD.0

E. (5 points) What should be the value of MOD if MCLK needs to be set to **1.5MHz** for the system that doesn't use external oscillators (uses only DCO)? Give values for Rsel, DCO, and MOD. Show how you came up with the result. [*Hint*: use the formula $T=((32-MOD)*T_{DCO} + MOD*T_{DCO+1})/32$]

Problem #2 (25 points) Interrupts

A. (10 points) Let us assume a P2.2 port pin is configured as interrupt request input. Describe all steps involved in handling an interrupt request, from the moment a request is received (rising edge detected on P2.2) until the return from the corresponding interrupt handling routine. Be precise, and describe what is done in hardware and what is done in software.

B. (5 points) What is interrupt nesting? Describe how the MSP430 deals with interrupt nesting.

C. (5 points) What is interrupt selective masking? Describe how the MSP430 deals with selective masking.

D. (5 points) How do we enter and exit low-power modes in the MSP430? Be specific.

Problem 3. (25 points, TimerA, Watchdog Timer)

A. (10 points) Consider the following program. The main program is an infinite loop. The CPU enters a low power mode 3 (CPU, MCLK, SMCLK, and the DCO oscillator are all turned off, ACLK stays on). The WDT interrupt service routine should wake the CPU up every 1000 ms (1s). The CPU then pulses a LED connected at the P1.0 (turns it on, keeps it on for some time, and then turns it off) and then enters the LPM3 mode again. Describe what needs to be done at the beginning of the main routine and what needs to be done in the WDT interrupt service routine. Note: answer in plain English, no code is required. Assume that a watch crystal of 32768 Hz is connected to LFXT1. The watchdog timer taps are 2^9, 2^{13}, 2^{15}. Could you estimate how long the LED will be on?

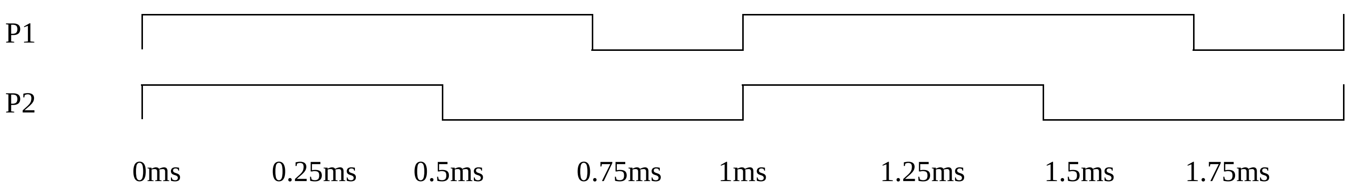
```
void main(void) {
// initialization (put your description below)
//
//
//


  while(1) {
    int i;
    _BIS_SR(LPM3_bits + GIE);           // Enter LPM3
    P1OUT |= 0x01;                      // Set P1.0 LED on
    for (i = 10000; i>0; i--);           // Delay
    P1OUT &= ~0x01;                     // Clear P1.0 LED off
  }
}
#pragma vector=WDT_VECTOR
__interrupt void wdt_isr (void) {
// put your description below

//


}
```

B. (15 points) You would like to generate two pulse-width modulated (PWM) signals P1 (75% of duty cycle) and P2 (50% of duty cycle), with frequency of 1 KHz. Assume that an external high-frequency resonator of 8 MHz is connected on LFXT1. Can you do this using TimerA? If yes, could you describe a TimerA configuration that will carry out signal generation? Note: use English and waveforms to describe your solution.



Problem #4 (25 points) Power, Low power systems

A sensor platform features a microcontroller, a sensor, and a wireless radio interface.

Your application operates with system frequency of 50 Hz, repeating the following sequence. The microcontroller samples an analog signal from the sensor, process the samples, and send the data to the radio chip. The radio then transmits the data to the network coordinator. After the data are sent wirelessly, the system goes into a sleep mode (the sensor, the microcontroller, and radio chip are all in low power mode). Assume that all devices wake up in the active mode when the time comes for the next application cycle, and stay active until the whole application cycle is completed. The radio chip is in the receive mode unless it transmits the data.

From corresponding reference manuals we extracted information about the current drawn by each device when it is in active mode and when it is the low-power mode.

Device	Active mode I [mA] –current	Low-power mode I -- current
Sensor	0.3	3 uA
Microcontroller	5	50 uA
Radio transmit	18	10 uA
Radio receive	20	10 uA

By performing performance profiling of our application we found the following execution times:

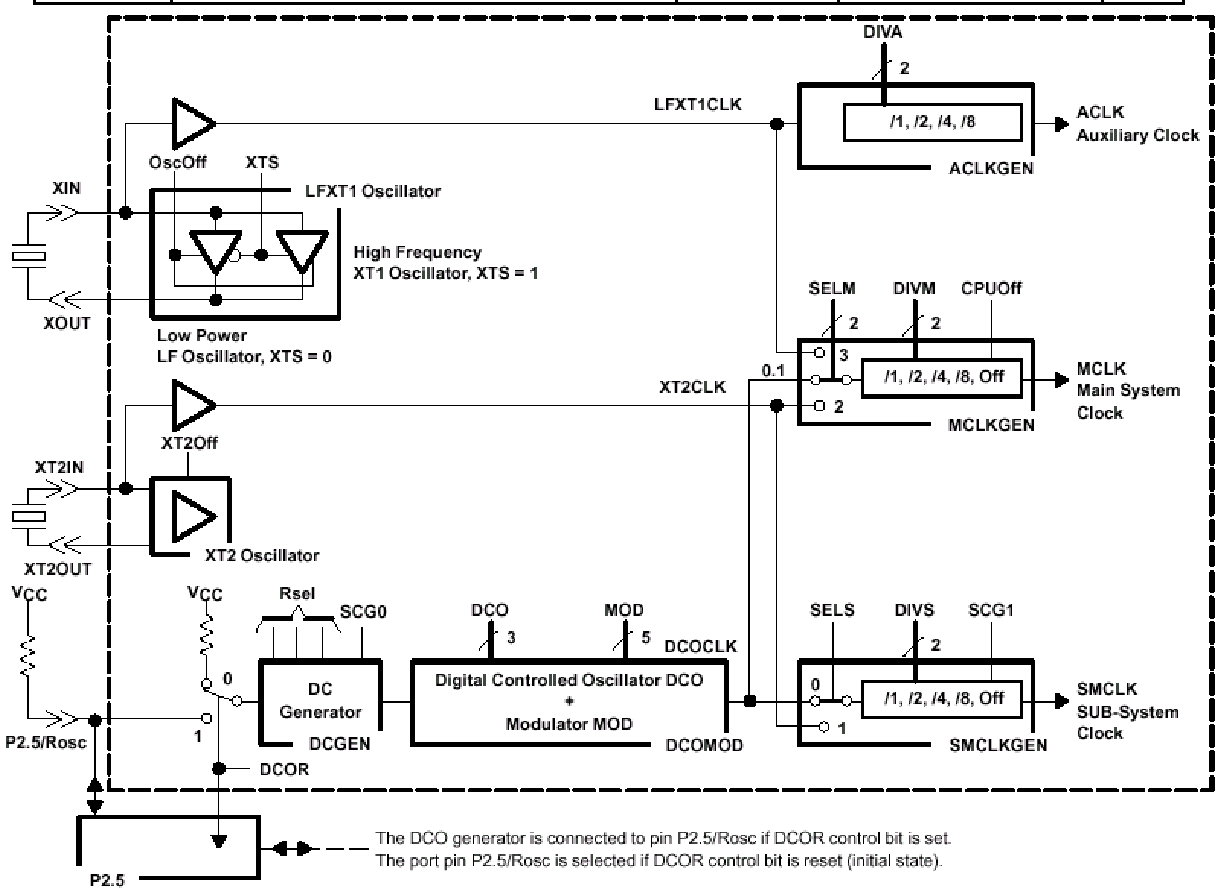
Type of operation	Execution Time
Sample sensor signals	0.2 ms
Process samples	2 ms
Send data to radio	1.8 ms
Radio transmission	2 ms

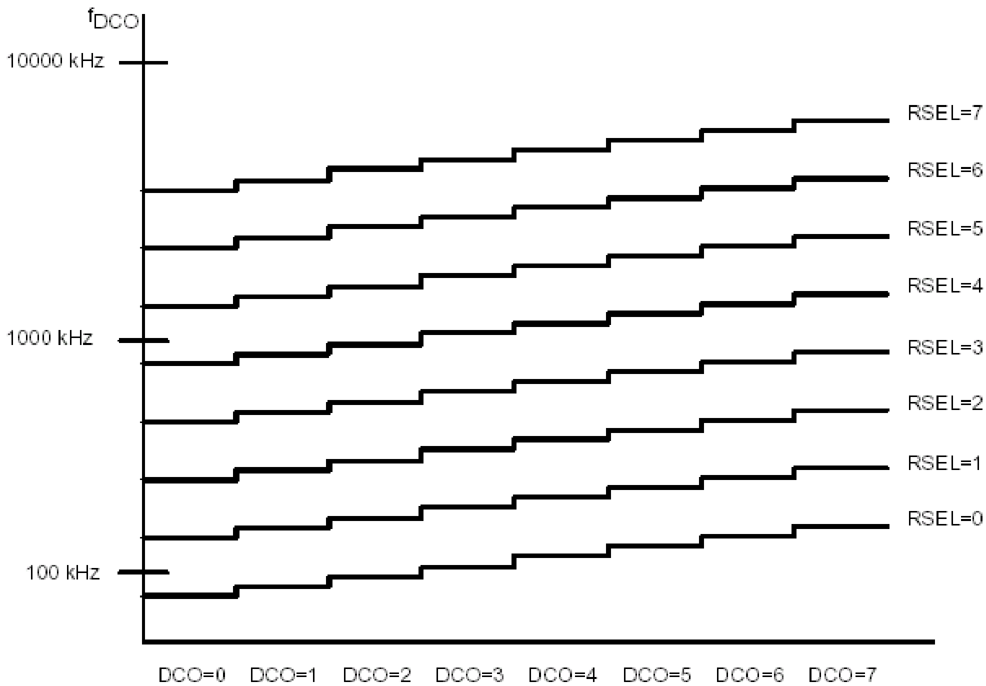
A. (15 points) Calculate the total execution time and the total sleep time during one application cycle. Calculate the average current drawn by the platform while in the active mode (I_{AM}) and in the low-power mode (I_{LPM}). Calculate the total average current drawn by the platform I_{TOTAL}.

B. (10 points) Calculate the total power P consumed (in milliWatts) if we power the platform by two AA batteries (Vsupply = 3.0 V). Determine the system operating time in days if we know that the battery capacity is 2400mAh. How would you further reduce the power consumption and consequently extend the operating time of the given system? Explain.

Appendix

PARAMETER	TEST CONDITIONS		MIN	NOM	MAX	UNIT
$f_{(DCO03)}$	R_{sel} = 0, DCO = 3, MOD = 0, DCOR = 0, T_A = 25°C	V_{CC} = 2.2 V	0.08	0.12	0.15	MHz
		V_{CC} = 3 V	0.08	0.13	0.16	
$f_{(DCO13)}$	R_{sel} = 1, DCO = 3, MOD = 0, DCOR = 0, T_A = 25°C	V_{CC} = 2.2 V	0.14	0.19	0.23	MHz
		V_{CC} = 3 V	0.14	0.18	0.22	
$f_{(DCO23)}$	R_{sel} = 2, DCO = 3, MOD = 0, DCOR = 0, T_A = 25°C	V_{CC} = 2.2 V	0.22	0.30	0.36	MHz
		V_{CC} = 3 V	0.22	0.28	0.34	
$f_{(DCO33)}$	R_{sel} = 3, DCO = 3, MOD = 0, DCOR = 0, T_A = 25°C	V_{CC} = 2.2 V	0.37	0.49	0.59	MHz
		V_{CC} = 3 V	0.37	0.47	0.56	
$f_{(DCO43)}$	R_{sel} = 4, DCO = 3, MOD = 0, DCOR = 0, T_A = 25°C	V_{CC} = 2.2 V	0.61	0.77	0.93	MHz
		V_{CC} = 3 V	0.61	0.75	0.90	
$f_{(DCO53)}$	R_{sel} = 5, DCO = 3, MOD = 0, DCOR = 0, T_A = 25°C	V_{CC} = 2.2 V	1	1.2	1.5	MHz
		V_{CC} = 3 V	1	1.3	1.5	
$f_{(DCO63)}$	R_{sel} = 6, DCO = 3, MOD = 0, DCOR = 0, T_A = 25°C	V_{CC} = 2.2 V	1.6	1.9	2.2	MHz
		V_{CC} = 3 V	1.69	2.0	2.29	
$f_{(DCO73)}$	R_{sel} = 7, DCO = 3, MOD = 0, DCOR = 0, T_A = 25°C	V_{CC} = 2.2 V	2.4	2.9	3.4	MHz
		V_{CC} = 3 V	2.7	3.2	3.65	
$f_{(DCO47)}$	R_{sel} = 4, DCO = 7, MOD = 0, DCOR = 0, T_A = 25°C	V_{CC} = 2.2 V/3 V	$f_{DCO40} \times 1.7$	$f_{DCO40} \times 2.1$	$f_{DCO40} \times 2.5$	MHz
$f_{(DCO77)}$	R_{sel} = 7, DCO = 7, MOD = 0, DCOR = 0, T_A = 25°C	V_{CC} = 2.2 V	4	4.5	4.9	MHz
		V_{CC} = 3 V	4.4	4.9	5.4	
$S_{(Rsel)}$	$S_R = f_{Rsel+1} / f_{Rsel}$	V_{CC} = 2.2 V/3 V	1.35	1.65	2	
$S_{(DCO)}$	$S_{DCO} = f_{DCO+1} / f_{DCO}$	V_{CC} = 2.2 V/3 V	1.07	1.12	1.16	
D_t	Temperature drift, R_{sel} = 4, DCO = 3, MOD = 0 (see Note 30)	V_{CC} = 2.2 V	–0.31	–0.36	–0.40	%/°C
		V_{CC} = 3 V	–0.33	–0.38	–0.43	
D_V	Drift with V_{CC} variation, R_{sel} = 4, DCO = 3, MOD = 0 (see Note 30)	V_{CC} = 2.2 V/3 V	0	5	10	%/V





7.5 Basic Clock Module Control Registers

The Basic Clock Module is configured using control registers DCOCTL, BCSCTL1, and BCSCTL2, and four bits from the CPU status register: SCG1, SCG0, OscOff, and CPUOFF. User software can modify these control registers from their default condition at any time. The Basic Clock Module control registers are located in the byte-wide peripheral map and should be accessed with byte (.B) instructions.

Register	Short Form	Register Type	Address	Initial State
DCO control register	DCOCTL	Read/write	056h	060h
Basic clock system control 1	BCSCTL1	Read/write	057h	084h
Basic clock system control 1	BCSCTL2	Read/write	058h	reset

7.5.1 Digitally-Controlled Oscillator (DCO) Clock-Frequency Control

DCOCTL is loaded with a value of 060h with a valid PUC condition.

DCOCTL 056h

7							0
DCO.2	DCO.1	DCO.0	MOD.4	MOD.3	MOD.2	MOD.1	MOD.0
rw–0	rw–1	rw–1	rw–0	rw–0	rw–0	rw–0	rw–0

MOD.0 .. MOD.4: The MOD constant defines how often the discrete frequency f_{DCO+1} is used within a period of 32 DCOCLK cycles. During the remaining clock cycles (32–MOD) the discrete frequency f_{DCO} is used. When the DCO constant is set to seven, no modulation is possible since the highest feasible frequency has then been selected.

DCO.0 .. DCO.2: The DCO constant defines which one of the eight discrete frequencies is selected. The frequency is defined by the current injected into the dc generator.

7.5.2 Oscillator and Clock Control Register

BCSCTL1 is affected by a valid PUC or POR condition.

BCSCTL1 057h

7							0
XT2Off	XTS	DIVA.1	DIVA.0	XT5V	Rsel.2	Rsel.1	Rsel.0
rw–(1)	rw–(0)	rw–(0)	rw–(0)	rw–0	rw–1	rw–0	rw–0

Bit0 to Bit2: The internal resistor is selected in eight different steps.
Rsel.0 to Rsel.2 The value of the resistor defines the nominal frequency.
The lowest nominal frequency is selected by setting Rsel=0.

Bit3, XT5V: XT5V should always be reset.

Bit4 to Bit5: The selected source for ACLK is divided by:

DIVA = 0: 1
DIVA = 1: 2
DIVA = 2: 4
DIVA = 3: 8

Bit6, XTS: The LFXT1 oscillator operates with a low-frequency clock crystal or with a high-frequency crystal:

XTS = 0: The low-frequency oscillator is selected.
XTS = 1: The high-frequency oscillator is selected.

The oscillator selection must meet the external crystal's operating condition.

Bit7, XT2Off: The XT2 oscillator is switched on or off:

XT2Off = 0: the oscillator is on
XT2Off = 1: the oscillator is off if it is not used for MCLK or SMCLK.

BCSCTL2 is affected by a valid PUC or POR condition.

BCSCTL2 058h	7							0
	SELM.1	SELM.0	DIVM.1	DIVM.0	SELS	DIVS.1	DIVS.0	DCOR
	rw–(0)	rw–(0)	rw–(0)	rw–(0)	rw–0	rw–0	rw–0	rw–0

Bit0, DCOR: The DCOR bit selects the resistor for injecting current into the dc generator. Based on this current, the oscillator operates if activated.

DCOR = 0: Internal resistor on, the oscillator can operate. The fail-safe mode is on.

DCOR = 1: Internal resistor off, the current must be injected externally if the DCO output drives any clock using the DCOCLK.

Bit1, Bit2: The selected source for SMCLK is divided by:

DIVS.1 .. DIVS.0 DIVS = 0: 1
DIVS = 1: 2
DIVS = 2: 4
DIVS = 3: 8

Bit3, SELS: Selects the source for generating SMCLK:
SELS = 0: Use the DCOCLK
SELS = 1: Use the XT2CLK signal (in three-oscillator systems) or
LFXT1CLK signal (in two-oscillator systems)

Bit4, Bit5: The selected source for MCLK is divided by:

DIVM.0 .. DIVM.1 DIVM = 0: 1
DIVM = 1: 2
DIVM = 2: 4
DIVM = 3: 8

Bit6, Bit7: Selects the source for generating MCLK:
SELM.0 .. SELM.1 SELM = 0: Use the DCOCLK
SELM = 1: Use the DCOCLK
SELM = 2: Use the XT2CLK (x13x and x14x devices) or
Use the LFXT1CLK (x11xx and x12xx devices)
SELM = 3: Use the LFXT1CLK