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Spec No: 001-34542

Spec Title: SENSING - OPTICAL PULSOMETER WITH PSOC(R) - AN2158

Sunset Owner: M Ganesh Raaja (GRAA)

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Sensing - Optical PulsOmeter With PSoC®

Author: Victor Kremin
Associated Project: Yes
Associated Part Family: CY8C24xxx, CY8C27xxx
Software Version: PSoC® Designer™ 5.1 SP1.1
Associated Application Notes: AN2041, AN2042, AN2152

AN2158 describes the Optical PulsOmeter. PulsOmeters can be used in the medical sector during sport tests for pulse-rate monitoring, or embedded in various sports training equipment. The PulsOmeter can transmit both raw optical pulse wave signals and measured pulse rate values to the PC, which allows the device to be used for illness diagnostics and pulse rate logging.

Introduction

Pulse rate measurement is very important in a mixture of medical applications, sports training, and to elements of an active live style. Various techniques that can be used to measure pulse rate and possible approaches include:

- Mechanical methods, which convert the vessel rippling into electric signals using a strain or pressure sensor. Piezoelectric sensors are typically used in these applications, but the sensor position is very sensitive to the vessel location or vessel displacement. Conventional tonometers use the air gland, which is relatively large and not practical for long-term use.

- Pulse rate electrical signal detection methods, which require placement of two or more electrodes on the skin for electric impulse reception. Electrodes are held in place using self-adhesives or flexible straps. To make pulse rate monitoring more comfortable during training, the electrodes and a micropower wireless transmitter are placed on a flexible waistband in many commercial products. Recent research has reported contact-less electric heart rate monitoring by measuring the radiated electromagnetic field with a supersensitive receiver. This technique is very expensive today and needs “clear” room for practical use.

- Optical pulse measuring methods, based on human tissue light absorption level modulation by changing blood capillary filling via heart activity. This method yields more than simple pulse rate measurement. The light modulation curve analysis is an efficient way to diagnose respiratory system activity and detect illness. Measuring the difference in light absorption in infrared and red bands allows determination of blood oxygen saturation level.

The light absorption modulation method has been used in the proposed PulsOmeter. The PulsOmeter sensor consists of the infrared LED and the photodiode. The sensor can be located different places on the human body: finger, arm, hand, or ear lobe. In such designs, the light path is different depending on sensor location. When the sensor is placed on opposite sides of the finger or ear lobe, the photodiode receives the through-passing light; the received signal is large enough and can be easily amplified and processed. When sensor diodes are located on the same arm or finger side, the photodiode receives the diffused signal. The diffused signal is weak and contains noise introduced by various external light sources such as sun, bulb and fluorescent lamps. Careful signal processing should be applied in this case to obtain reliable PulsOmeter operation. The developed PulsOmeter supports any of the above described sensor locations using a combination of hardware and software signal-processing methods.

The PulsOmeter technical specifications are given in Table 1.

Table 1. PulsOmeter Specifications

Item	Item Value
Pulse Measurement Method	Optical, using light absorption modulation via capillary filling pulsations.
Power Supply Voltage	3.3 V
Power Consumption	35 mA
Measured Pulse Range	30 - 300 beats per minute.
Measurement Error	4%
Measurement Time	7-9 pulse intervals or 30/60 s, depending selected method.
Pulse Calculation Methods	Measuring time interval between adjacent beats or calculated number of beats during fixed time interval.
Display Type	Multifunctional graphic LCD, 48x84 pixels resolution.
Service Features	• Two pulse calculation methods. • Automatic measurement starting when pulse beat signal detected. • Last measurement data hold. • Minimum and maximum pulse estimation. • Beat signal level in bar-graph representation for finding optimal position for sensor. • Separate LED for displaying beats.

PulsOmeter Block Diagram

Figure 1 depicts the PulsOmeter flowchart. The device uses the modulation technique in the sensor signal processing to increase noise resistance. The carrier generator forms the modulation signal, which drives the infrared LED. The received light is converted into an electric signal by a photodiode FED, and amplified and filtered by a band-pass filter (BPF). The bias generator removes the low-frequency noise (any constant level or AC-powered lamp induced) from the photodiode signal. It also provides stable FED bias voltage, regardless of external light, together with high input impedance for modulation frequency photodiode current.

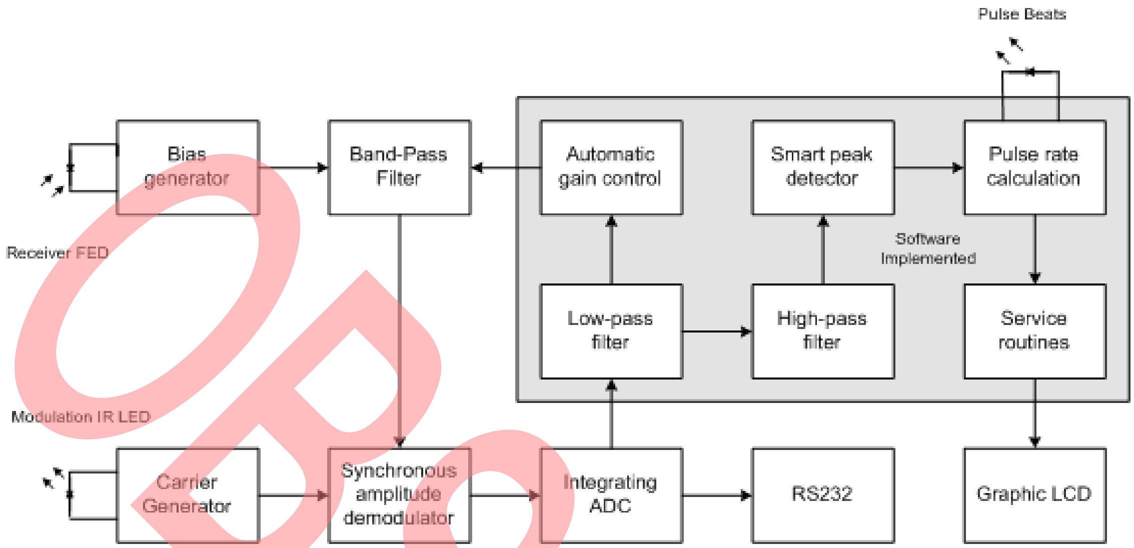
The BPF output signal is rectified by a synchronous amplitude demodulator. The demodulator reference signal is set to the modulation signal. The demodulator output is sampled directly by the integrating ADC. The ADCs with a sigma-delta modulator have a nice feature of conversion signals with a frequency much more than a sample frequency, performing the low-pass filtering in the internal hardware.

This feature allows elimination of additional hardware and connection of the ADC input directly to the rectifier output. Note that the conversion time is set equal to the carrier signal period integer number in order to place the ADC's gain-frequency characteristic zeros for carrier signal harmonics.

The processing of the ADC data stream is implemented in firmware. The low-pass filter (LPF) additionally removes the noise-on-output signal. To increase the dynamic range of input signals, the automatic gain control loop is implemented, which compresses the dynamic range of the input signal by properly adjusting the BPF gain level according to the LPF software output value. The high-pass filter (HPF) removes the DC component in the LPF output signal and separates the pulse signal. The pulse beats are detected by a smart peak detector with a threshold level that is automatically adjusted to increase the noise resistance. The software calculates the pulse rate in beats-per-minute, evaluates the minimum/maximum values during continuous measurement, and provides various PulsOmeter state information visualization, such as pulse beat signal level, error conditions, operational mode, gain level, etc.

For external pulse wave signal processing and debug purposes, the raw unfiltered ADC data can be sent via a RS232 port.

Figure 1. The PulsOmeter Flowchart



Device Schematic

The PulsOmeter schematic is represented in Figure 2. Q_1 is the voltage-to-current converter, which forms the DC bias level for photodiode D_1. The bias generator has low impedance for constant current or low frequency signals, and suppresses the noise signals caused by various external light sources. For the modulation frequency signals, the impedance is determined primarily by R_2. The Q_1 base signal is formed by a PSoC® programmable gain amplifier (PGA) module, which amplifies the photodiode signal. The PGA output voltage is determined by PGA reference, which is connected to AGND in this design. The bias generator allows reduction of the required photodiode signal gain level, reduction of the LED drive current, and in final, decreased noise level in the output waveform. Figure 3 shows the characteristics of the bias generator frequency.

Figure 2. External Hardware Schematic

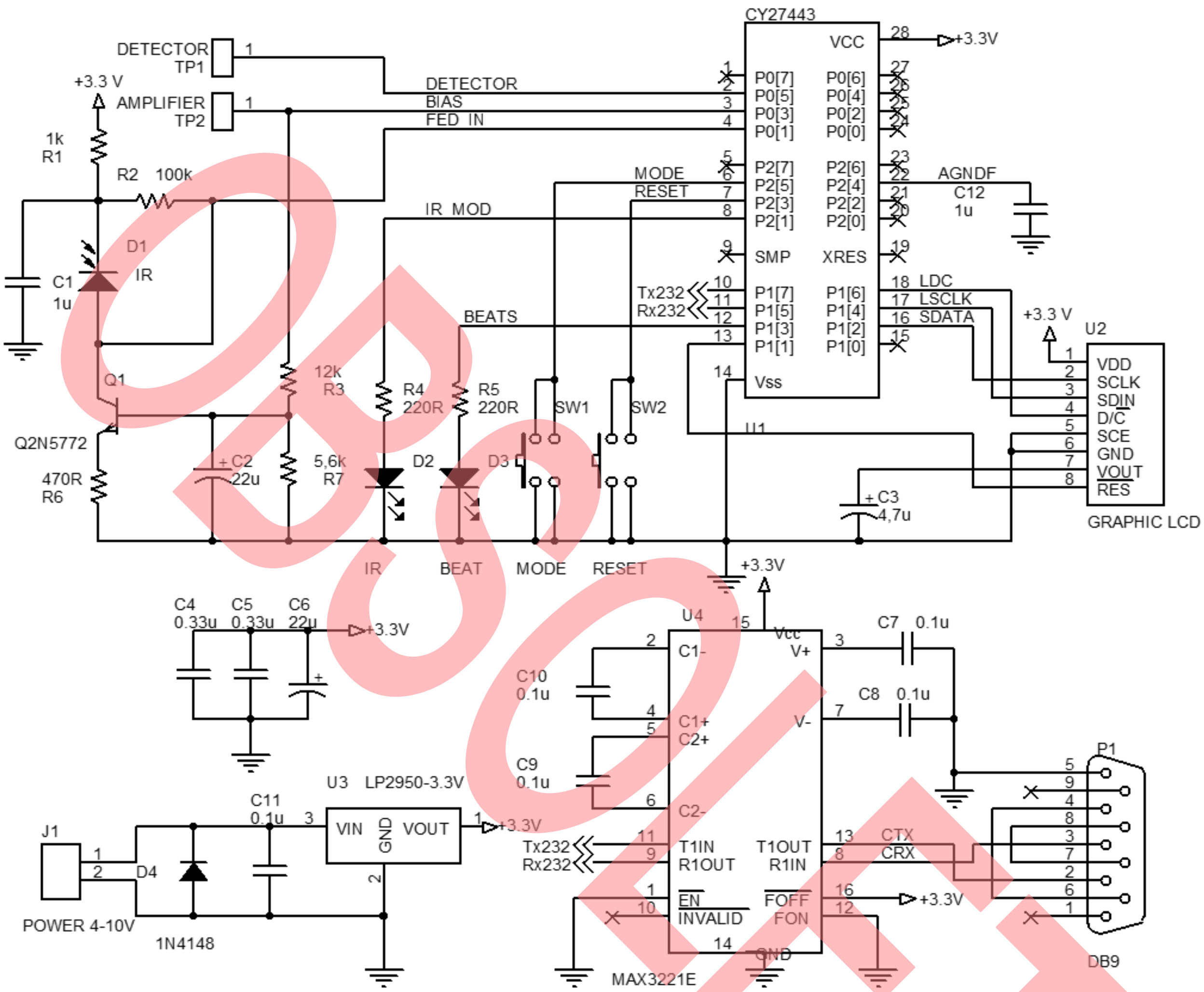
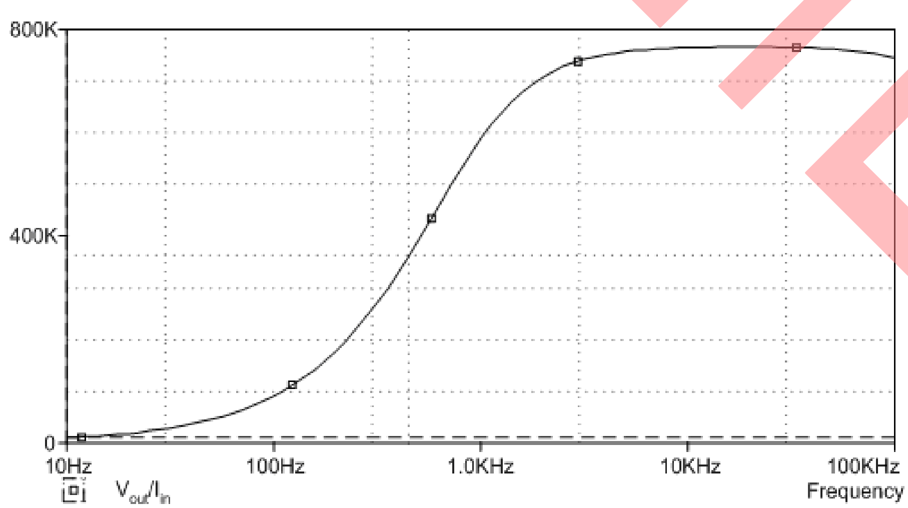


Figure 3. Bias Generator Characteristics



D_2 is the modulation infrared LED and D_3 is the beat LED for PulsOmeter work “visualization.” This LED flashes every time a beat is detected. The PulsOmeter uses a very low-cost graphic LCD, based on the PCD8544 LCD controller from Philips.

More details about this LCD are given in AN2152. Note that the PCD8544 requires the reset signal to be applied within a predefined interval after power-up. To satisfy this demand, the LCD reset pin is connected with P1[1], which is tied low after reset for a duration by PSoC internal hardware.

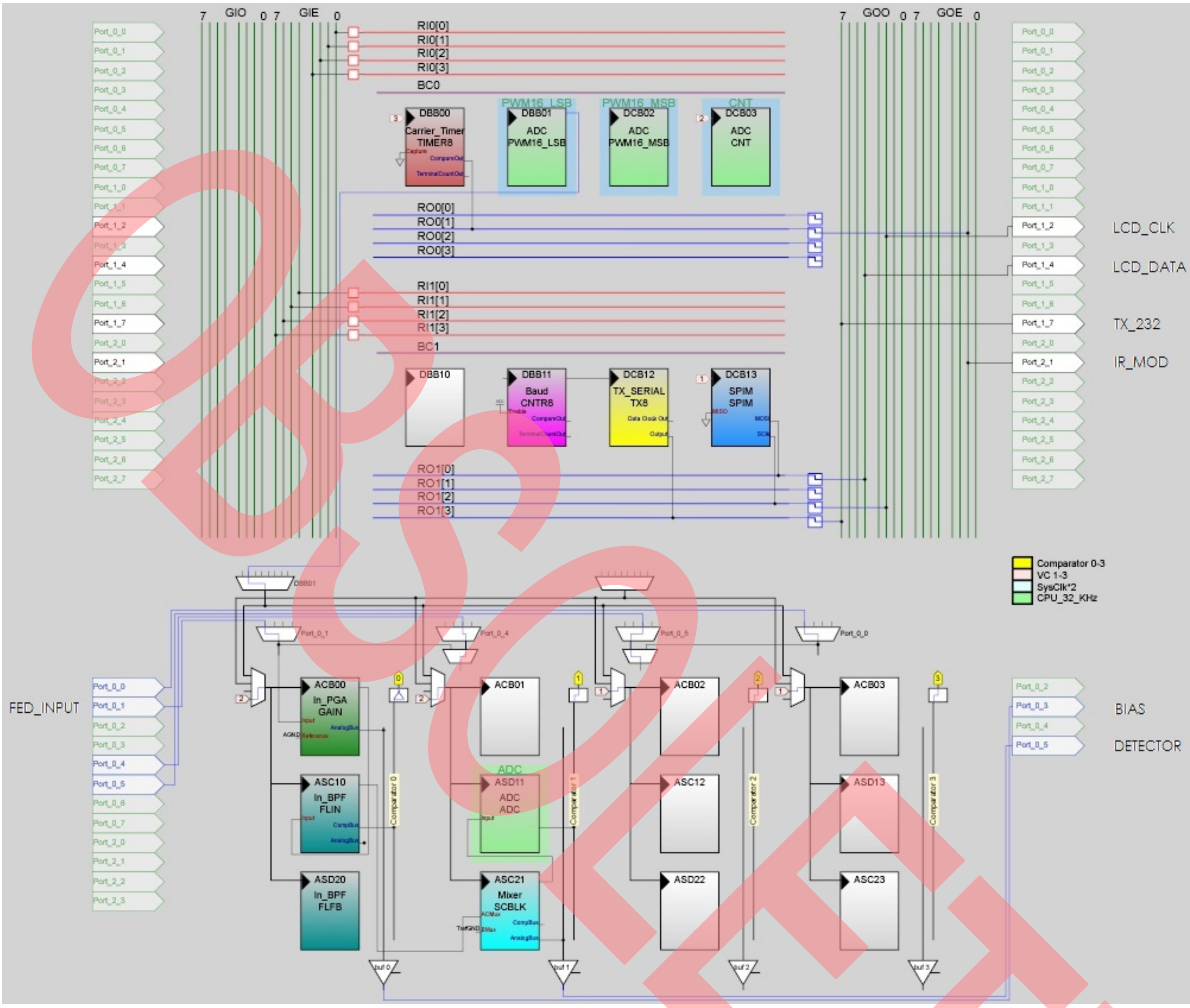
The two buttons are used to control the PulsOmeter: “Reset” and “Mode.” The user clears the last measured value and statistical information and reinitializes the measurement cycle by pressing the “Reset” button. “Mode” is used for changing the pulse rate calculation method. The optional RS232 level translator U_4 with auto-shutdown can be used for sensing the raw ADC data or measured pulse rate values from the external PC.

The low-drop linear regulator U_3 powers the device from a 4-10 V power supply or battery. Some commercial PulsOmeter applications can use a battery powered supply. The low-cost, low-noise switching regulated charge pumps from Texas Instruments, TPS60310, are ideal for battery voltage conversion via high-efficiently, ultra-low quiescent current and inductor-less operation. The PSoC can wake-up via a button-pressing event and go back to sleep when the sensor does not receive a signal during a predefined timeout. This yields increasing usefulness of the PulsOmeter.

PSoC Internals

The PSoC internal structure is shown in Figure 4. The bias generator PGA is placed in ACB00. The amplifier is connected to the BPF, which is placed in ASC10 and ASD20. The filter output signal is passed to the synchronous rectifier, which is built around the switched capacitor block. The rectifier reference comes from the BPF comparator bus, this requires using the vertical fitter topology. The rectifier module additionally amplifies the BPF output signal for better ADC dynamic range utilization. The rectifier output is sent via P0[5] to checkpoint TP_1 for test and debug purposes. Note that the column buffer BUF1 can be disabled to save power in the product release. In the 3.3 V powered PulsOmeter, the AGND level is Vdd/2 ± Vdd/2, but the 5 V version can use other AGND settings. The bias generator output is connected to the checkpoint TP_2 for debug purposes.

Figure 4. PSoC Internals



The rectifier output is connected to the ADC input. In this design, the sigma-delta ADC with counter-type filter (or incremental ADC in the terms of PSoC documentation) is used. The ADC resolution is set to 13 bits, and the integration time is adjusted to be an equal number of modulation signals in the firmware by directly writing to the ADC PWM16 period and compare registers. As a result, the effective resolution is 12.25 bits. The modulation frequency is set to 5 kHz and the fitter over-sample ratio is 100. ADC integration time is 10 mS, or 50 modulation signal periods, and the ADC sample frequency is very close to 100 Hz. All switched capacitor modules use the same column frequency for aliasing problem elimination.

The serial transmitter, placed in DCB12, together with the baud-rate timer, placed in DBB11, are used for transmitting debug ADC sample streams or other information to the PC. They can be omitted in the production release of the PulsOmeter. The timer, placed in DBB00, forms the modulation signal. The timer clock source is VC3. The SPIM User Module, placed in DCB13, is used for serial communication with the graphic LCD controller.

Note that the project can be ported to the low-cost CY8C24xxx PSoC device group without any problems. The serial transmitter and SPIM modules should be eliminated because debug functionality is not required in the production release. The LCD interface can easily be implemented in software because the data rate is so low. As an alternative, the low-cost graphic LCD with I2C communication interface, based on Phillips PCF8548 for example, can be used thanks to the I2C hardware support in both the CY8C24/27xxx device families.

The Software

The PulsOmeter software can be separated into two parts: real-time signal processing and service routines. Signal processing is run in the foreground. It performs the ADC data steam low-pass and high-pass filtering, pulse peak detection, and interval calculation between adjacent peaks. The pulse rate calculation routines are run in the background in the main program loop. The incremental ADC data-ready service routine triggers the signal-processing routine.

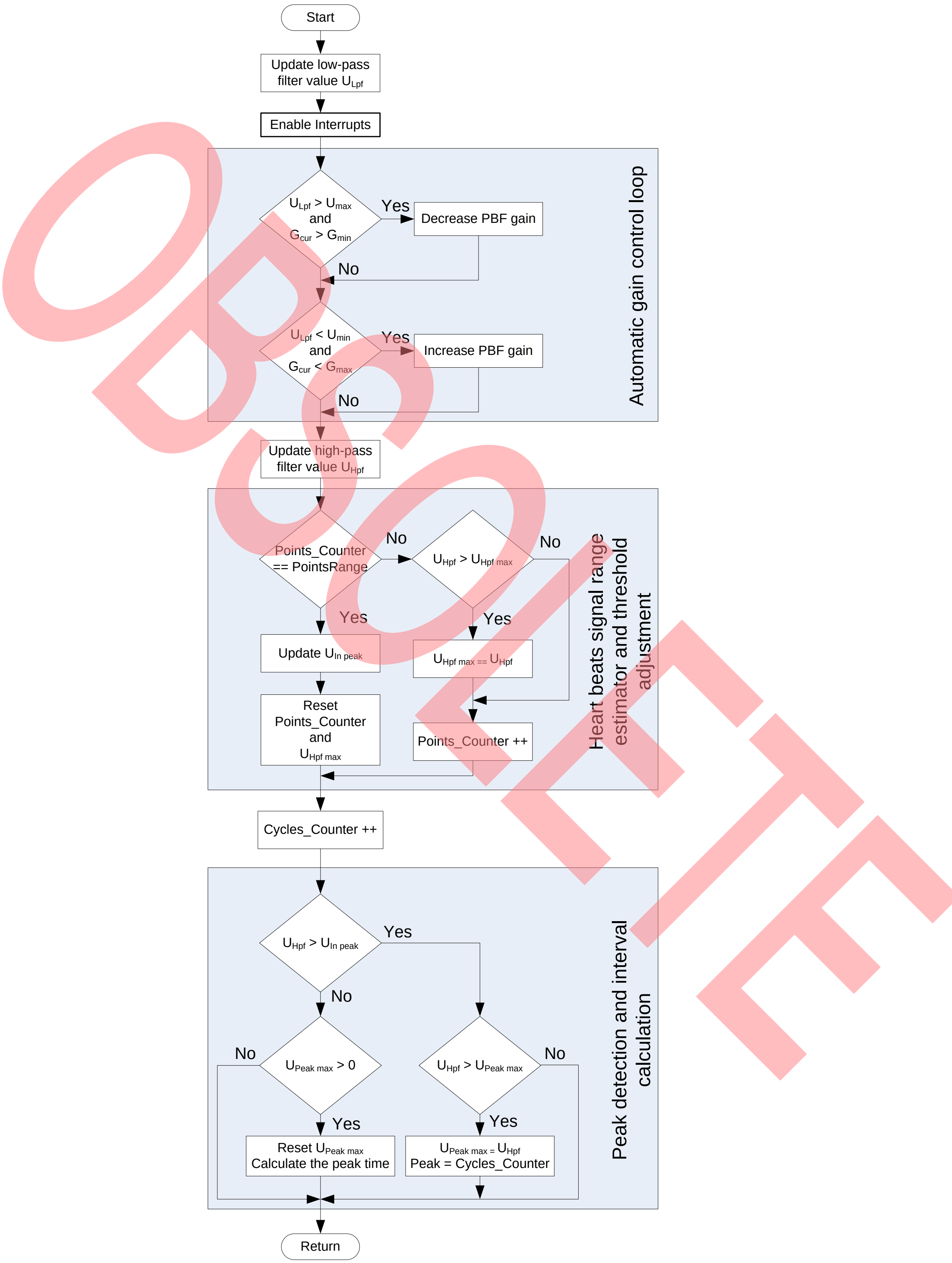
The existing user module library version is implemented in assembly, including ADC conversion service routines, which create additional work as modulator control, data pre-processing, etc. But I do not favor assembly programming and prefer to use 'C' when possible. To call a 'C' function from the ISR, all virtual registers should be saved. This is because the compiler does not automatically save these registers, and the `#pragma interrupt_handler` generates ISR code that ends with the RETI instruction instead of RET. ISR code ends with the RETI instruction because additional assembly code needs to be executed after the 'C' function ends. The elegant solution is to use software interrupts. When the ADC data is ready, the ADC conversion ISR triggers the software interrupt for an unused hardware module (I2C in this design) and the CPU jumps directly to the 'C' code of the ISR.

Figure 5 illustrates the real-time signal-processing algorithm. The ADC samples are filtered by a second order IIR LPF. The filter transfer characteristic is given in Equation 1, where a =0.25. The filter is implemented as a cascade connection of two first-order sections. The filter gain is a^{-1}.

$$H_{LPF}(z) = \frac{a}{1-2(1-a)z^{-1}+(1-a)^2 z^{-2}} \quad \text{Equation 1}$$

When the LPF value is updated, old ADC data is no longer required and the interrupts can be re-enabled. The heart activity causes the received signal amplitude modulation coefficient to range 0.015÷0.05, depending on the sensor position and individual human characteristics. This allows users to use the LPF output for automatic gain control (AGC) loop operation. When the filter signal is too low, the AGC increases the BPF gain, and when the input signal is too high, the AGC decreases the BPF gain to hold the LPF output signal within the predefined range.

Figure 5. PulsOmeter Signal Processing Algorithm



The HPF removes the DC component from the LPF output. The 7-order FIR HPF with differentiator characteristics is used. The filter transfer characteristic is given in Equation 2. The filter gain is 60.

$$H_{HPF}(z) = z^3 - 9z^2 + 45z^1 - 45z^{-1} + 9z^{-2} - z^{-3} \quad \text{Equation 2}$$

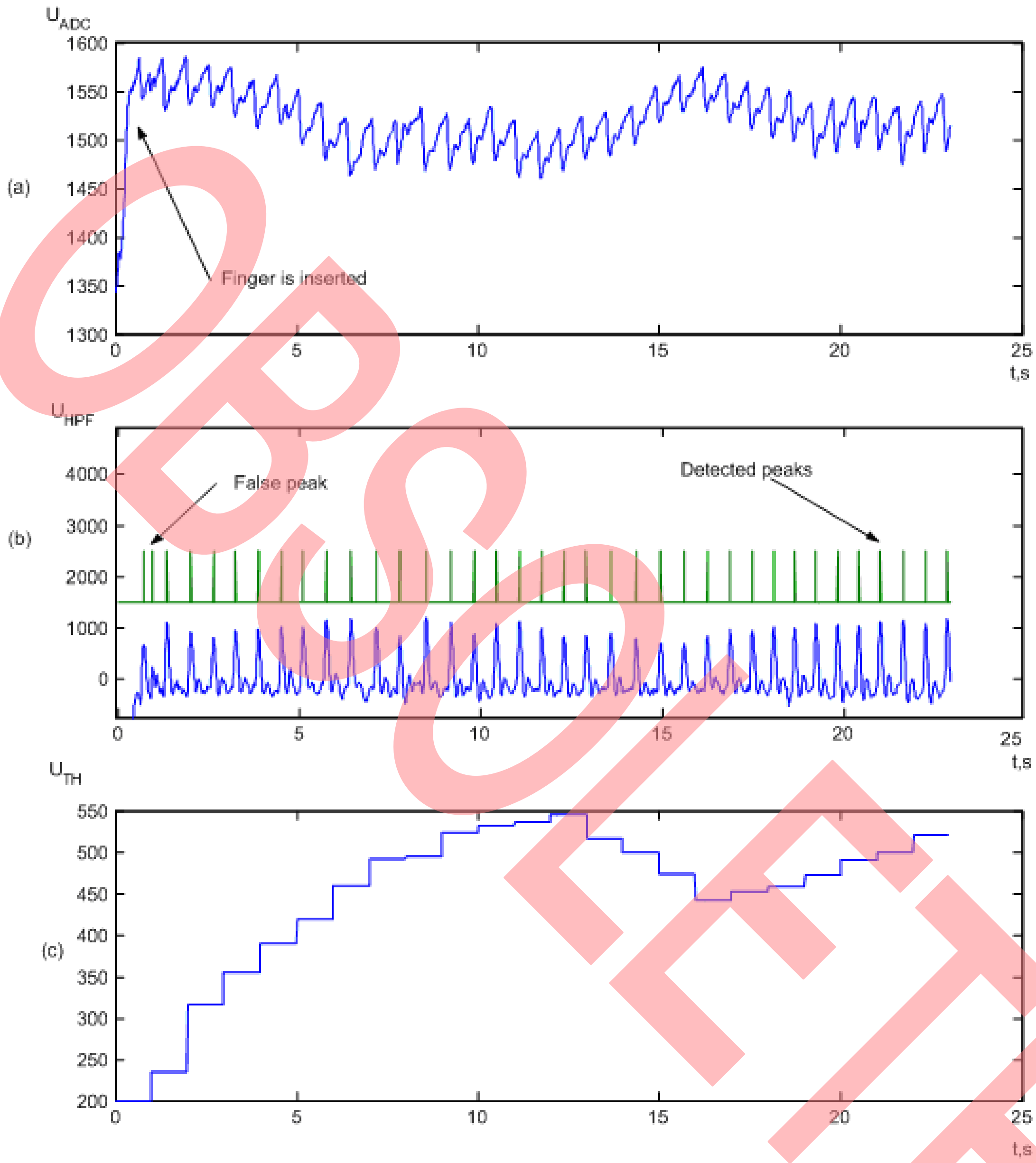
The HPF separates the moments when blood is put to vessels by the heart. The peak detector is used to detect the heartbeat. The detector searches for the maximum pulse signals when the HPF signal is greater than the threshold value. Note that the peak detector threshold is adjusted dynamically according to the pulse signal amplitude to increase noise resistance. The threshold is set to half of the maximum pulse amplitude during a predefined time interval, 1 or 2 s in this design, and is filtered by a non-linear first order IIR LPF, which is described in the following equation:

$$U_{th}^{i+1} = \max\left(U_{th}^{\min}, \min\left(U_{th}^{\max}, U_{th}^{i} + \Delta, \frac{1}{2}U_{th}^{i} + \frac{1}{4}U_{ADC}^{\max}\right)\right) \quad \text{Equation 3}$$

U_{th}^{i+1} and U_{th}^{i} are the peak detector threshold values for the current and previous time interval. $U_{ADC}^{\max}$ is the maximum ADC value for this interval and $U_{th}^{\min}, U_{th}^{\max}, \Delta$ are predefined constants. As can be seen in Equation 3, the filter checks the increasing speeds of the minimum, maximum and threshold values. Note that the experiment shows that the HPF signal amplitude varies over a range of 10 to 1, depending on sensor position and individual physiology. A peak detector with a fixed threshold is not satisfactory for this application.

Finally, the pulse signal-processing routine calculates the interval between the neighboring pulses using the sample clock as a time reference. Figure 6 demonstrates the algorithm operation using raw ADC data and Matlab simulation for signal processing.

Figure 6. ADC Data Signal Processing in PulsOmeter



(a) is unfiltered ADC data, (b) is the HPF output signal and detected pulse beats, and (c) is the peak detector threshold variation.

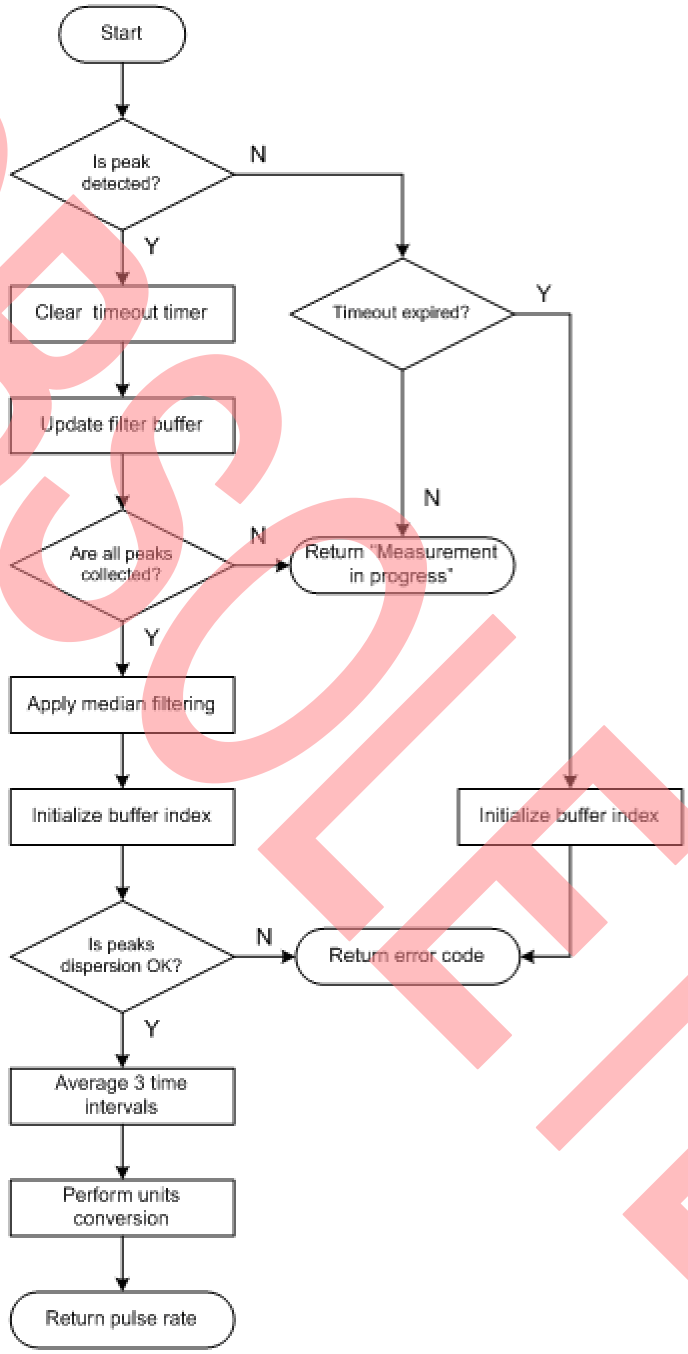
When the intervals between adjacent pulses are measured, the pulse rate in the standard form of beats-per-minute is calculated.

Small sensor displacement can generate false beat detection due to a very small modulation amplitude coefficient. Changing sensor position generates a noise signal with amplitude equal to or greater than a useful pulse signal. This is especially important when the PulsOmeter is embedded in the sport trainer, where pulse is measured in online mode during training. So, the additional filtering can be applied in the pulse intervals or amplitude domains to eliminate these false beats.

The proposed PulsOmeter uses two pulse calculation methods: faster, but less accurate pulse measuring, or a slower, but more accurate approach.

The user makes the selection by pressing the “Mode” button. The fast algorithm determines the pulse rate based on median filtering of intervals between several adjacent beats. Figure 7 illustrates the algorithm.

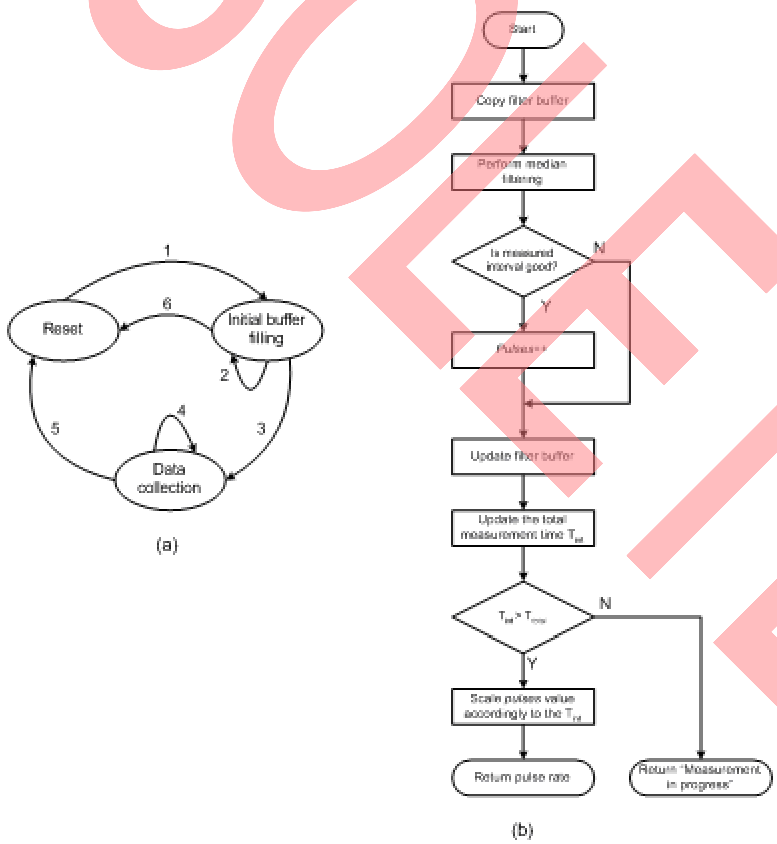
Figure 7. Fast Pulse Estimation Method



The routine collects into the internal buffer an odd number of pulse intervals (5, 7, or 9 for example), runs the median filter to exclude false pulse beats, and makes the peak dispersion check. If the median is greater than the multiplied difference between the adjacent-to-median-value pulse intervals, then the measurement is considered valid and a unit-conversion to beats-per-minute is made, otherwise an error is returned. The routine checks the interval between subsequent pulses. If no signal occurs during the predefined timeout, the internal buffer index is initialized (to correctly start the next cycle) and an error is returned. This feature automatically starts a new measurement cycle when the sensor is properly placed on the human body. To check timeouts, the sleep timer ISR is used. The ISR rate is 64 Hz. This routine flashes the beat's LED for a short time once a pulse beat is detected. Note that the fast pulse measuring method can be used to detect various arrhythmias, making human state diagnostics by applying a method that analyzes the short- and long-time pulse fluctuations.

The slow pulse estimation approach, based on counting the pulse beats within a fixed time interval, 30 or 60 s, is a well-known "classic" approach. But the measured pulse intervals are checked to ensure they are close to the previous measured samples. This eliminates noise from beats. The routine uses a dedicated state machine, which fills several samples into an intermediate buffer before pulse counting begins, checks pulse interval validity, and counts the beat number within a fixed time interval. A measured pulse interval is considered valid if it falls in between the following interval: $T_p \in [0.75T_m ... 1.25T_m]$, where T_p is the measured pulse interval and T_m is the median-filtered pulse interval, based on previously collected values. The state machine bubble diagram is represented in Figure 8 (a) and the pulse rate calculation algorithm is given in Figure 8 (b). After reset, the routine starts filling the initial buffer for the median filter (1,2), goes to pulse calculation (3,4), displays the calculated pulse rate, and jumps to reset (5) after cycle completion. If there is no pulse signal within the predefined timeout, the state machine goes to the reset state from any present state (5,6).

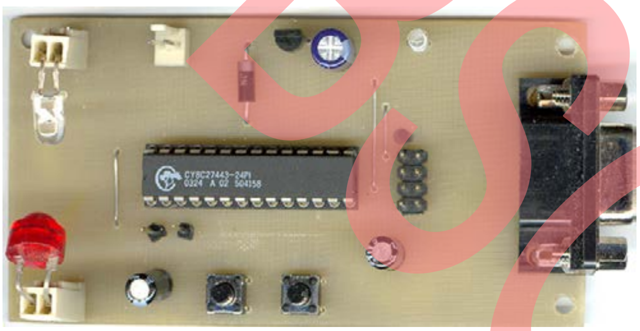
Figure 8. Slow Pulse Estimation Method



The service routines perform the estimation of minimum and maximum pulse values during continuous measurements, user interface functions, and graphic LCD library support. Users can switch the pulse calculation mode by pressing the “Mode” button, reset the Last/Min/Max measured pulse rate value, and start a new measurement cycle instantly by pressing the “Reset” button. To get reliable PulsOmeter operation, the sensor position should be set appropriately, where the pulse light modulation is enough. To simplify this task, the graphic LCD displays the special vertical bar-graph and users can adjust the sensor position to see the maximum bar-graph size. The bar-graph size is evaluated based on U_{ADC}^{max} value, which is periodically updated.

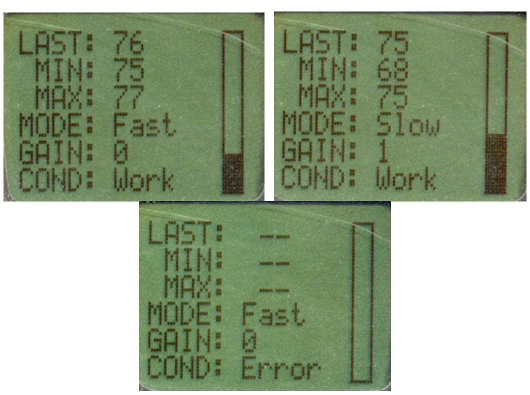
Photographs

Figure 9. Board Photograph



You can insert a finger between the LED and photodiode or bend the diodes up and place a hand on it.

Figure 10. LCD Image



Examples during pulse measurement and when sensor is located outside human body.

Suggested Improvements

The free LCD space allows users to place additional information. Users can place an hourglass to display the remaining time of a pulse measurement cycle. The AN2152 graphic library supports bitmap operations without any problems. As an alternative, the second vertical graph can be added for this purpose.

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Document History

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Revision	ECN	Orig. of Change	Submission Date	Description of Change
**	1505943	SSFTMP4	09/26/2007	Recataloged Spec.
*A	3182221	QVS	02/25/2011	Updated document and project to PSoC Designer 5.0. Updated title.
*B	3282488	ANBI_UKR	06/14/2011	Updated to latest PSoC Designer. Updated as per new template.
*C	4384693	GRAA	05/20/2014	Sunset Review. Updated template.
*D	4833433	DIMA	07/11/2015	Obsolete document. Completing Sunset Review.

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