AN2558

Phase Division Multiplexing of Sensors as Demonstrated in a Reflective Heart Rate Monitor

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INTRODUCTION

This application note introduces Microchip's proprietary method (hereafter "proprietary method") of measuring multiple signals in a body using pseudorandom binary sequence generation and phase division multiplexing (refer to Appendix D: US Patent Application). This proprietary method uses a special encoding/decoding scheme to allow multiple light-emitting diodes (LED) transmitting light simultaneously with a single photodiode to condition each light from the combined lights at the receiving side. Although this method is Microchip's proprietary property, it can be used freely by any of Microchip's customers that are designing their applications with Microchip's microcontrollers.

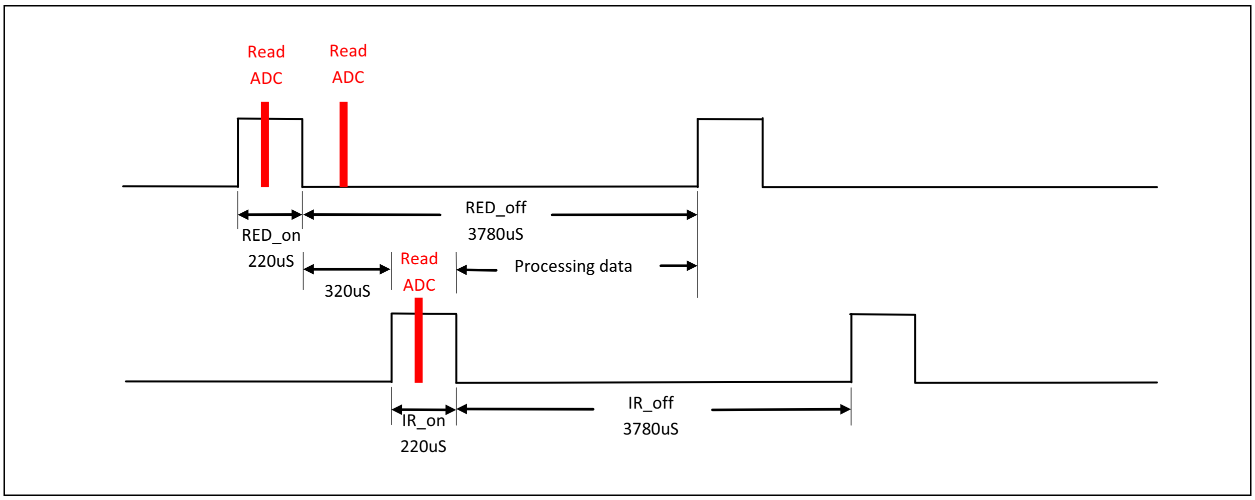
This proprietary method is implemented using the Configurable Logic Cells (CLC) module available in many of Microchip's microcontrollers. This application note shows how a fully functional reflective heart rate monitor application can be implemented using only a single Microchip 8-bit microcontroller and a reflective photosensor.

PHOTOSENSING

Many medical devices use an optical method to measure patients' biometric signals. These devices are often equipped with one, two, or more light sources with different wavelengths and a photodiode. A familiar example of such a device is a pulse oximeter which can monitor a user's blood oxygen saturation and heart rate by illuminating the skin and measuring changes in light absorption. A conventional pulse oximeter uses a red LED and an infrared (IR) LED with a single photodiode (refer to Microchip's application note AN1525, listed in **Appendix D: "References"**, for a detailed pulse oximeter reference design). More advanced monitors in operating rooms may use as many as eight wavelengths to measure heart rate, oxygen saturation, carbon monoxide levels and other factors relevant to a patient under general anesthesia.

The challenge in a multiple signal sources system (for example, the LEDs in the case of a pulse oximeter) is that each LED must share the same photodiode. A classic solution is to turn on each light source in sequence and then take each measurement in turn. Figure 1 shows a typical light timing diagram used in Microchip's pulse oximeter demo. In Figure 1, each light source gets its own slice of time in which the photodiode can get its measurement. This method is called Time-Division Multiplexing (TDM). The same principle is also applied to the TDMA-based cellular system.

FIGURE 1: TIMING DIAGRAM USED IN MICROCHIP'S PULSE OXIMETER DEMO



The drawback of the TDM approach is that adding more light sources, while keeping the data processing routine the same, results in more time to get a measurement from every source.

For example, if two more lights are added into the system, the red LED will have to wait to turn on again until the processing of the ADC data acquired from all four lights in the previous cycle is complete. So the more lights added, the more time each LED has to wait to turn on again, reducing the overall sample rate for each source.

Another classic solution adopted in many wireless applications is Code Division Multiple Access (CDMA). In this technique, systems use coded sequences (e.g. gold codes) that have a very low cross-correlation between each other. This allows multiple users of the spectrum to coexist simultaneously over a single communication channel where each transmitter is assigned a code.

PRINCIPLE OF THE PROPRIETARY METHOD

Microchip's proprietary method uses a known concept called Maximal Length (ML) sequence, a type of pseudorandom binary sequence, to generate a gold code or a reference sequence. This reference sequence is then phase shifted using Phase Division Multiplexing (PDM) to drive multiple LEDs. The light amplitudes from these LEDs, after passing through a part of a body, are detected by a phototransistor or photodiode and digitized with an Analog-to-Digital Converter (ADC). The digitized ADC light amplitude values are re-correlated with each LED's driving sequence. Spread spectrum techniques are known for their noise mitigation properties and ability to pass multiple signals through the same medium without interference. Thus, these measurements of each light absorption of the body can be performed substantially simultaneously with minimal interference from each other.

The ML sequence represents the maximum number of (non-zero) states that can be represented by a given number of bits. And the sequence has almost an equal number of 1s and 0s (exactly one fewer 0 than 1).

For example, given the size of 4 bits, the maximum length of the sequence will be $2^n–1$ where n=4, that is 15 states long, with eight 1s and seven 0s in it. Table 1 shows an example of ML sequence with n=4.

TABLE 1: EXAMPLE OF ML SEQUENCE FOR 2^4-1

1	1	1	1	0	0	0	1	0	0	1	1	0	1	0
0	1	1	1	1	0	0	0	1	0	0	1	1	0	1
1	0	1	1	1	1	0	0	0	1	0	0	1	1	0
0	1	0	1	1	1	1	0	0	0	1	0	0	1	1
1	0	1	0	1	1	1	1	0	0	0	1	0	0	1
1	1	0	1	0	1	1	1	1	0	0	0	1	0	0
0	1	1	0	1	0	1	1	1	1	0	0	0	1	0
0	0	1	1	0	1	0	1	1	1	1	0	0	0	1
1	0	0	1	1	0	1	0	1	1	1	1	0	0	0
0	1	0	0	1	1	0	1	0	1	1	1	1	0	0
0	0	1	0	0	1	1	0	1	0	1	1	1	1	0
0	0	0	1	0	0	1	1	0	1	0	1	1	1	1
1	0	0	0	1	0	0	1	1	0	1	0	1	1	1
1	1	0	0	0	1	0	0	1	1	0	1	0	1	1
1	1	1	0	0	0	1	0	0	1	1	0	1	0	1
1	1	1	1	0	0	0	1	0	0	1	1	0	1	0

The first row of Table 1 is the reference sequence. By shifting it to its right one bit at a time, 14 more output sequences can be generated before the reference sequence repeats itself. Therefore, a total of 15 unique sequences can drive up to 15 LEDs simultaneously; 1 to turn on the LED, and 0 to turn off the LED.

When the combined light is received by a single photodiode, the Analog-to-Digital Converter (ADC) of the microcontroller will measure the combined light signal. The ADC sample for each light source is separated from the combined light signal by applying a mathematical operation called autocorrelation to correlate the ADC result with each of the LED's driving sequences.

The autocorrelation resembles an impulse, a single spike with a peak value calculated using Equation 1. It is the sum of the ADC result times corresponding to the reference sequence.

EQUATION 1:

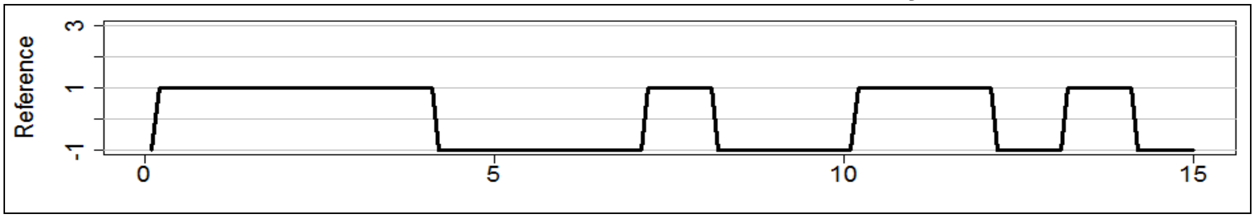
$$\sum_{n=0}^{2^n-1} CombinedADCSignal \bullet ReferenceSequence$$

The following examples use two LEDs, Red and IR, with a 15-bit (2^4–1) long driving sequences, to illustrate the proprietary method.

EXAMPLE OF THE PROPRIETARY METHOD

Figure 2 shows a 15-bit long ML reference sequence with an amplitude of 1 and -1.

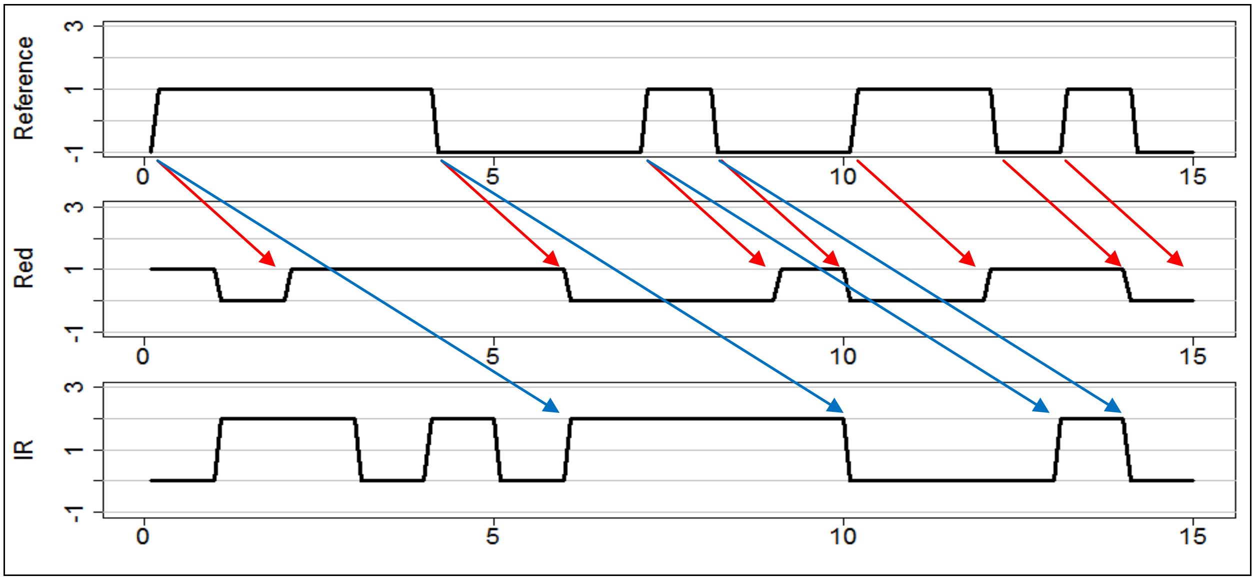
FIGURE 2: PROPRIETARY METHOD EXAMPLE - REFERENCE SEQUENCE



As indicated by the red arrows in Figure 3, the reference sequence is first phase shifted to its right by two to generate the second sequence which is used to drive the red LED. The output range of the red LED driving sequence is set from 0 to 1.

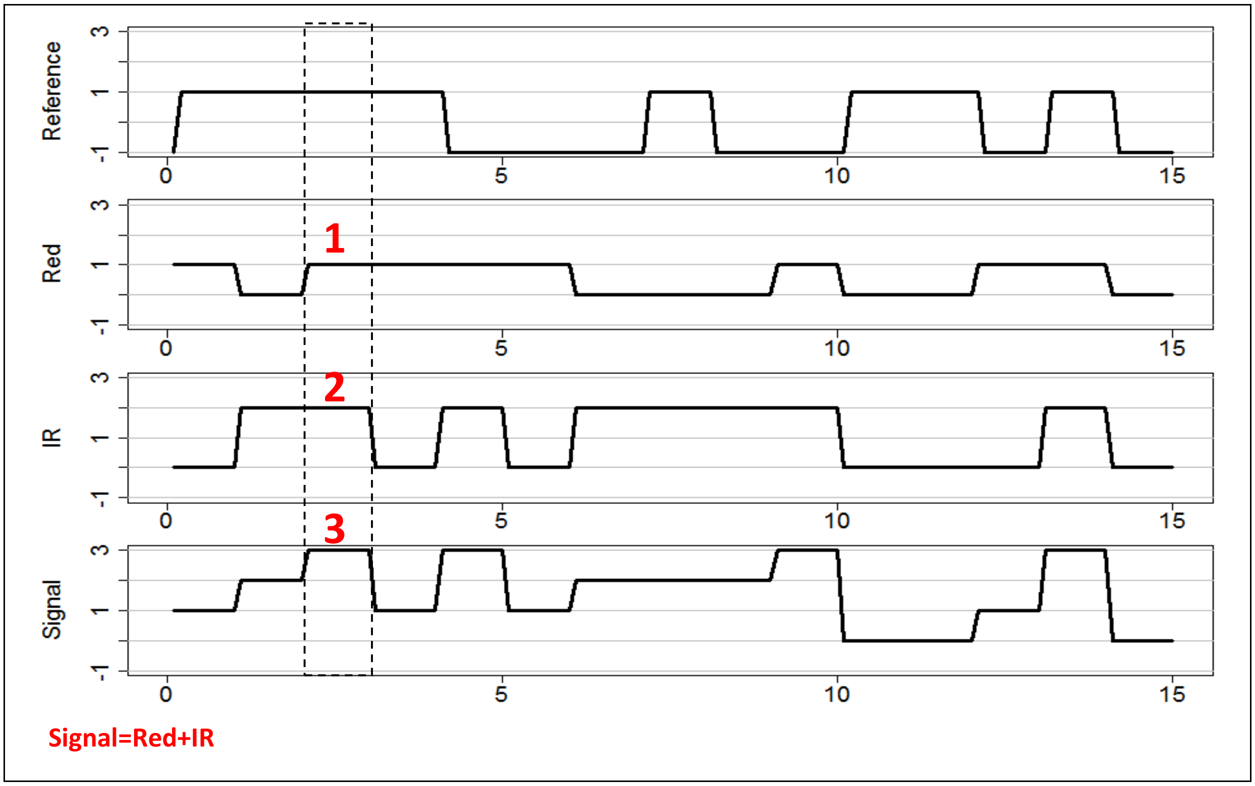
As indicated by the blue arrows in Figure 3, the reference sequence is next phase shifted to its right by six to generate the third sequence, which is used to drive the infrared (IR) LED. The output range of the IR LED driving sequence is set from 0 to 2 to make the IR light intensity a little stronger than the red light.

FIGURE 3: PROPRIETARY METHOD EXAMPLE - REFERENCE SEQUENCE RIGHT PHASE SHIFT BY 2 AND 6



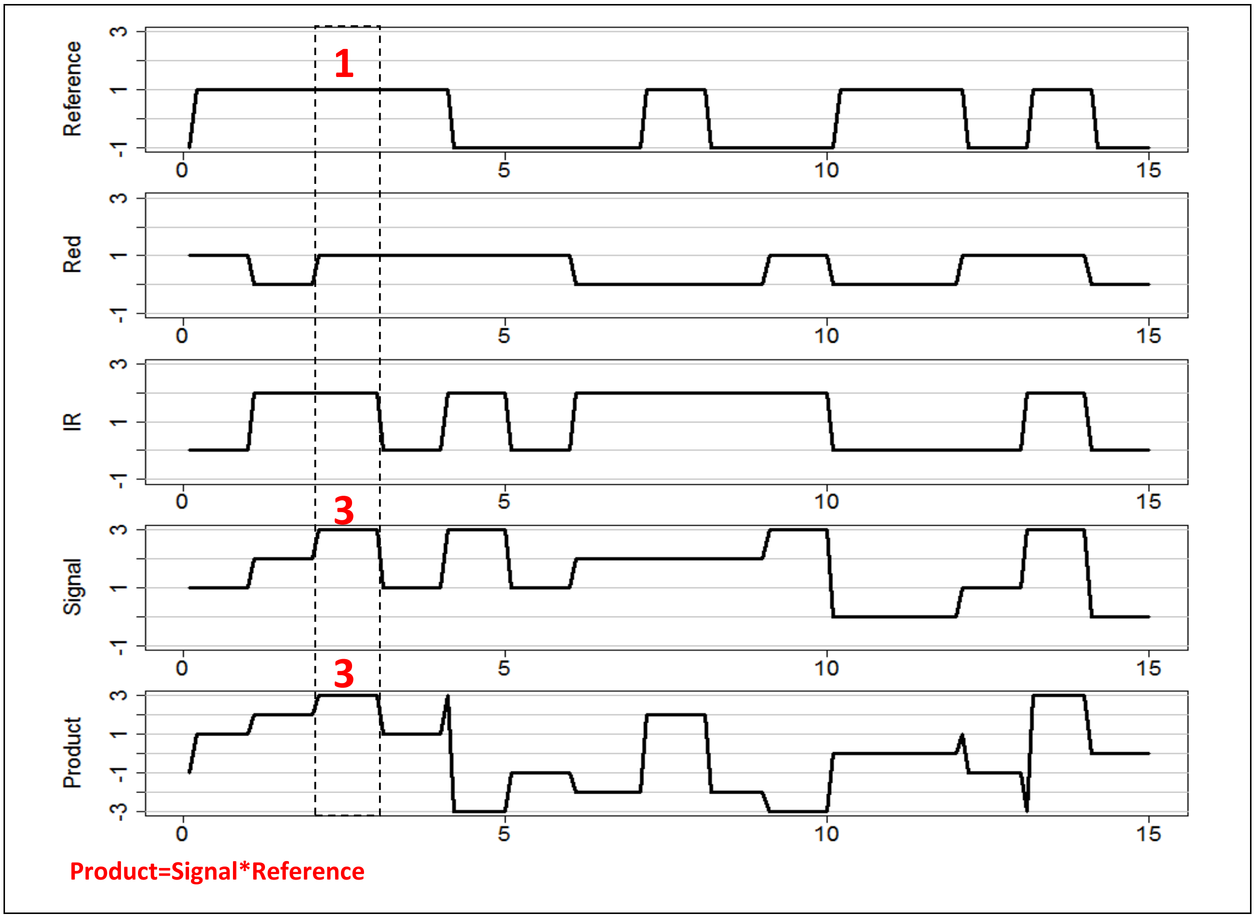
The fourth signal shown in Figure 4 is the combined light of the Red and IR that the ADC detected at the single photodiode. Take the third phase as an example. The amplitude for Red is 1, and for IR is 2. Hence the amplitude for the combined light signal at the third phase equals 1+2=3.

FIGURE 4: PROPRIETARY METHOD EXAMPLE - COMBINED SIGNAL



The fifth signal shown in Figure 5 is the product of the combined signal and the reference sequence. Again take the third phase as an example. The amplitude for the combined signal is 3, and its corresponding reference sequence's amplitude is 1. Hence the product at the third phase equals 3x1=3.

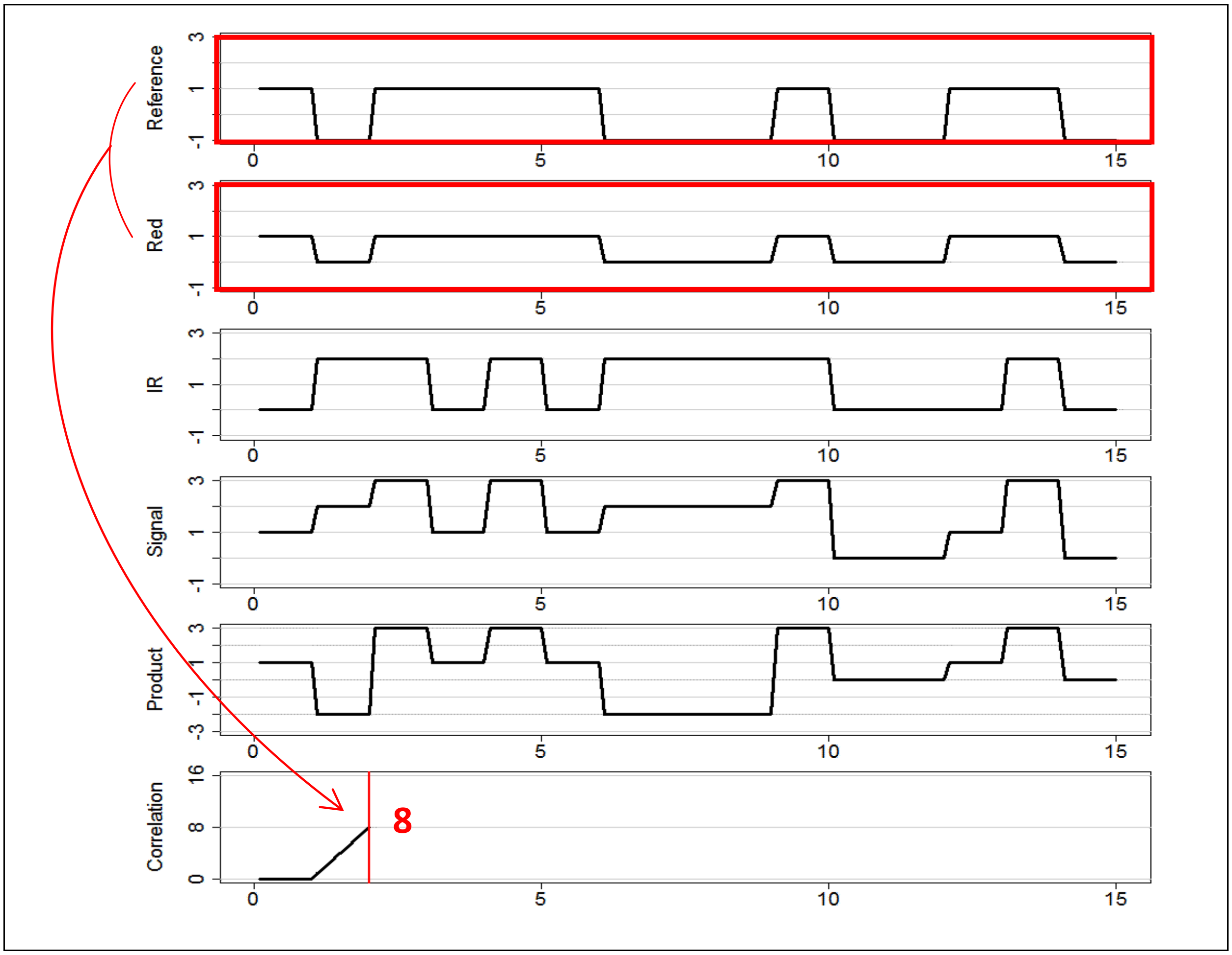
FIGURE 5: PROPRIETARY METHOD EXAMPLE - PRODUCT



The last step is to perform autocorrelation to separate each light from the combined signal. The autocorrelation of all 15 phases would generate two impulses in the correlation results. The two peaks should line up with the phase shifts for the red and IR signals. The correlation for all other phase offsets is zero.

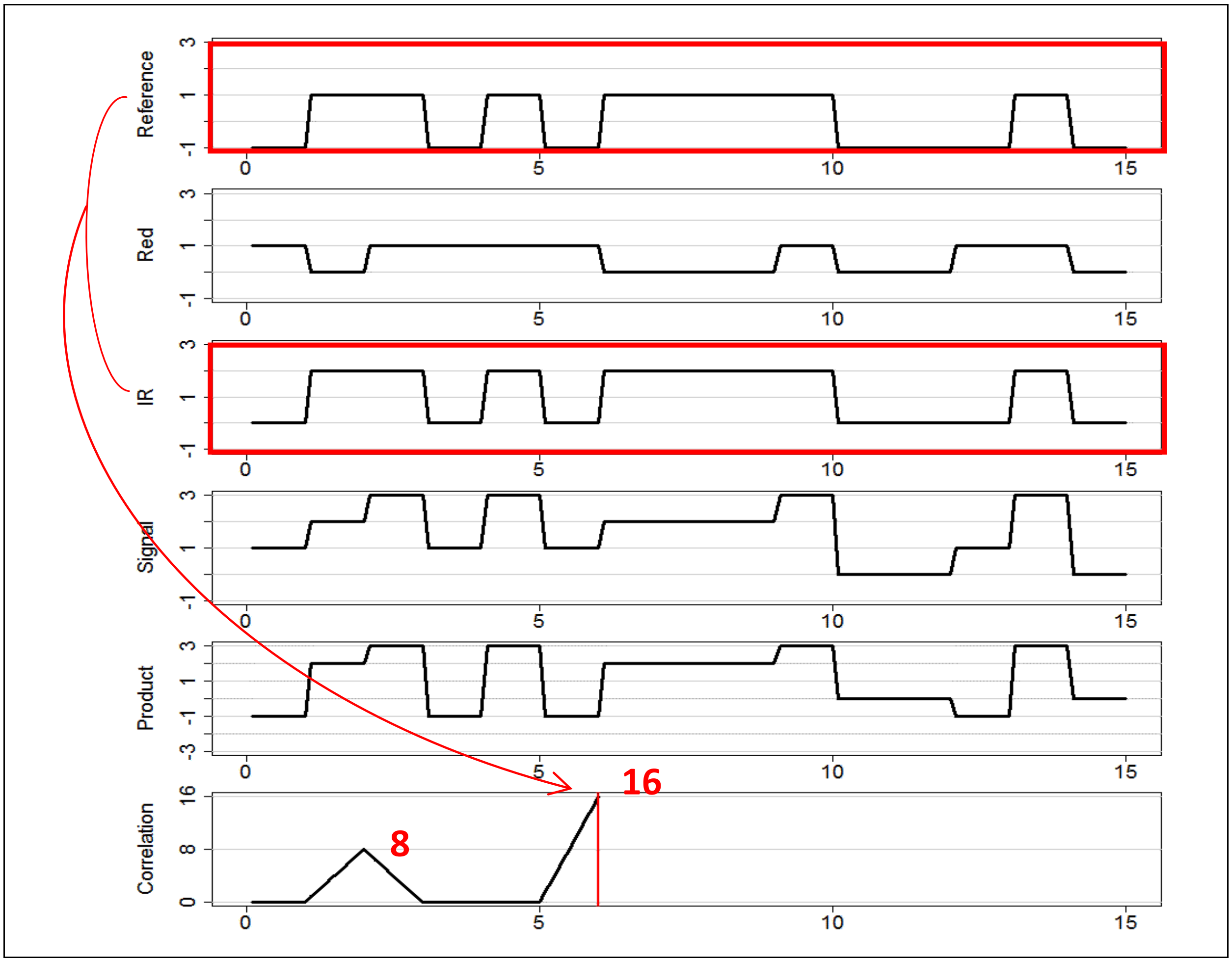
Figure 6 illustrates the autocorrelation execution in a microcontroller by sliding the reference sequence to its right side. As the reference sequence is sliding, the correlation signal is calculated using Equation 1. The correlation signal reaches its first peak when the reference sequence matches the red signal. The value of the first peak equals the sum of all 15 products, which is 1+(-2)+3+1+3+1+(-2)+(-2)+(-2)+3+0+0+1+3+0=8.

FIGURE 6: PROPRIETARY METHOD EXAMPLE - RED SIGNAL MATCHING REFERENCE SIGNAL DURING AUTOCORRELATION



As the reference sequence in Figure 7 keeps sliding to its right, the correlation signal reaches its second peak when the reference sequence matches the IR signal. The value of the second peak equals the sum of all 15 products, which is (-1)+2+3+(-1)+3+(-1)+2+2+2+3+0+0+(-1)+3+0=16.

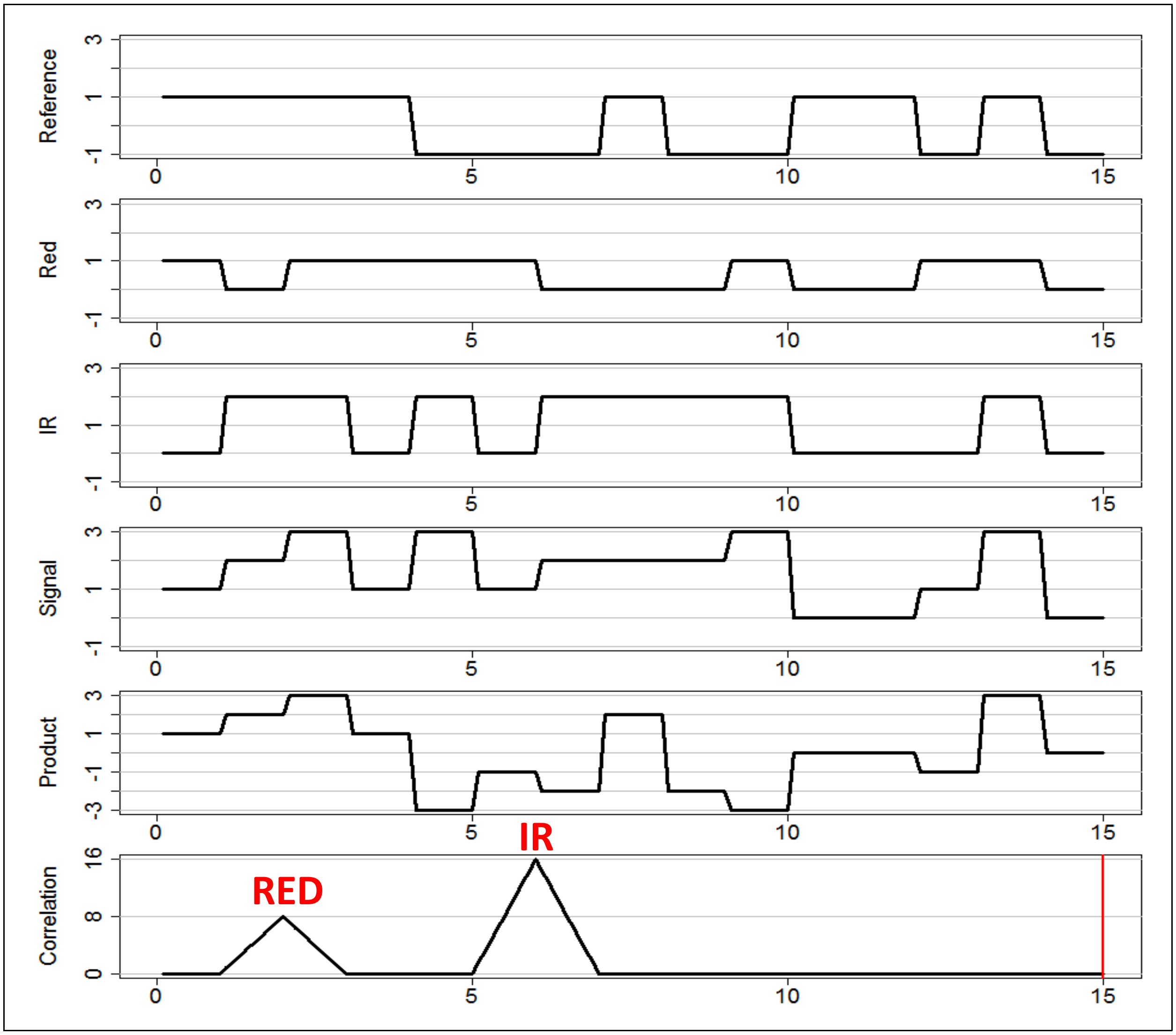
FIGURE 7: PROPRIETARY METHOD EXAMPLE - IR SIGNAL MATCHING REFERENCE SIGNAL DURING AUTOCORRELATION



After the reference sequence finishes sliding all 15 states from the initial state, Figure 8 shows two complete impulses which represent the red light and the IR light, respectively, in the combined light. The correlation results are all 0s when there is no light matching the reference sequence.

This means another 13 light sources could be slotted in without impacting the measurement period or the results of the other sources. That represents a massive gain over traditional TDM methods.

FIGURE 8: PROPRIETARY METHOD EXAMPLE - AUTOCORRELATION COMPLETE



PROPRIETARY METHOD VS TDM

Both the TDM method and proprietary method were evaluated using a reflective heart rate monitor demo board. The demo board uses a red LED, an IR LED, a green LED and a photodiode to measure user's heart rate in a reflective type of configuration. Detail of the demo board is introduced later in the application note. Figure 9 shows the TDM results, and Figure 10 shows the proprietary method results.

FIGURE 9: TDM EVALUATION RESULT

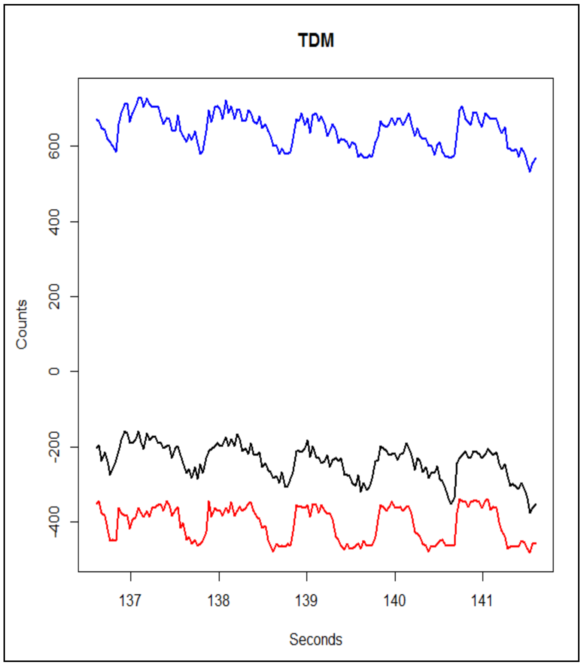
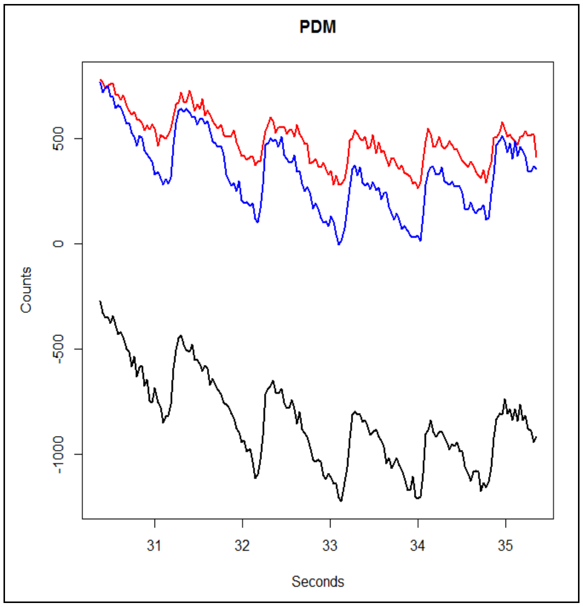


FIGURE 10: PROPRIETARY METHOD EVALUATION RESULT



Three pulsation waveforms in each plot were generated by three LEDs, respectively. The data of the TDM plot are the ADC samples taken on each light source in sequence similar to the timing diagram shown in Figure 1. The data of the proprietary method plot are the peak correlation values for each light source obtained from the combined light according to Figure 8.

The proprietary method results show about double the peak to peak amplitude in each pulsation waveform as the TDM results. Adding more light sources would not impact the measurement period or results of the other light sources using the proprietary method. Additionally, any noise jumping into the system would never be able to match the reference sequence so that the noise could be effectively removed from the system in the proprietary method.

On paper, our analysis noted that the advantages of the proprietary method become apparent with three or more sources (e.g., red, IR and green LEDs common in many wearables with heart rate monitoring or pulse oximetry applications). We put the equations we used for the analysis into a spreadsheet (see Figure 11) so users can estimate whether TDM or the proprietary method is better for their applications. The spreadsheet can be downloaded from Microchip's website (see **Appendix D: "References"**).

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FIGURE 11: SNAPSHOT OF THE SPREADSHEET FOR PROPRIETARY METHOD OF SENSORS

Input				
Raw Sample Rate	4.0E+3		Hz	
Background Measurement	50	+/-	5	(10%)
Sensor Measurement	500	+/-	5	(1%)
Sensor Count	3			
LFSR Size	4			
Sample Count Goal	30			
Samples / Chip	2			

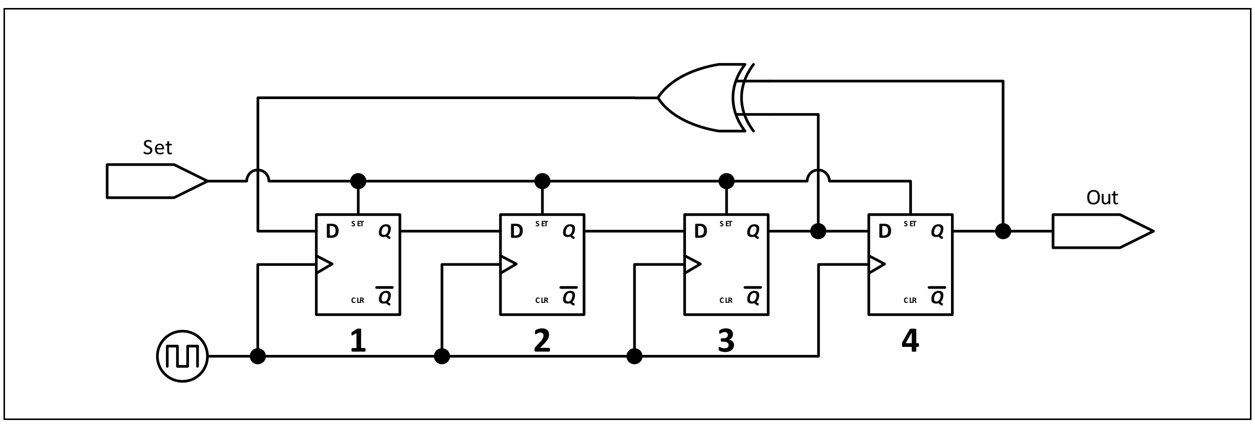
PDM				
Sequence Length	15			
Samples	30			
Decimated Sample Rate	133.3E+0		Hz	
Sensor On Time	16			
Total Bkg Samples	30			
Correlated Error	44.15880433			
Bkg Value	100	+/-	44.15880433	(44.1588043316392%)
Sensor Value	8100	+/-	44.15880433	(0.545170423847398%)
Relative Bkg Attenuation	-17.34184667	db		
Bkg Subtracted Reading	8000	+/-	62.44997998	(0.780624749799 8%)
Bkg %	1.25			

TDM				
Samples / Source	4			
Total Samples	28			
Decimated Sample Rate	142.9E+0		Hz	
Bkg Samples	7			
Sensor Samples	7			
Bkg Value	350	+/-	13.22875656	(3.77964473009227%)
Sample Value	3850	+/-	18.70828693	(0.485929530749863%)
Bkg Subtracted Reading	3500	+/-	22.91287847	(0.654653670707977%)
Bkg %	10			

PROPRIETARY METHOD IMPLEMENTATION

A computing function called Linear Feedback Shift Registers (LFSR) is used to generate the ML sequences. Figure 12 shows an implementation of the LFSR using 4 shift registers with XOR D flip-flop configurations. This LFSR can generate a 15-state long ML sequence.

FIGURE 12: LFSRS WITH SIZE 4



Adding more shift registers results in longer ML sequence. Table 2 provides a selection of valid parameters.

TABLE 2: LFSR PARAMETERS

Size (n)	Taps	Sequence Length
3	2	7
4	3	15
5	3	31
6	5	63
7	6	127
8	4, 5, 6	255
9	5	511
10	7	1023

LFSRs can be implemented in either hardware or software. This application note explains the hardware implementation utilizing the Configurable Logic Cell (CLC) featured in Microchip's 8-bit microcontroller.

CORE INDEPENDENT PERIPHERALS (CIP)

Many of Microchip's microcontrollers, such as the PIC16F1779, offer a high level of integration of intelligent analog and core independent digital peripherals. That includes four CLCs. CLCs support programmable logic that operates outside the speed limitations of software execution. Four CLCs are perfect for building the size 4 LFSRs to generate the sequence length of 15.

Once the CLCs are enabled, they run by themselves in hardware so that the core of the microcontroller is freed up to do other tasks. The CLCs can be easily configured in Microchip's graphical programming environment, MPLAB® Code Configurator (MCC), to implement the ML sequences. Figure 13 through Figure 16 show the MCC's CLC configurations in the mode of 2-input D flip-flop with R.

FIGURE 13: PIC16F1779'S CLC1 CONFIGURATION IN MCC

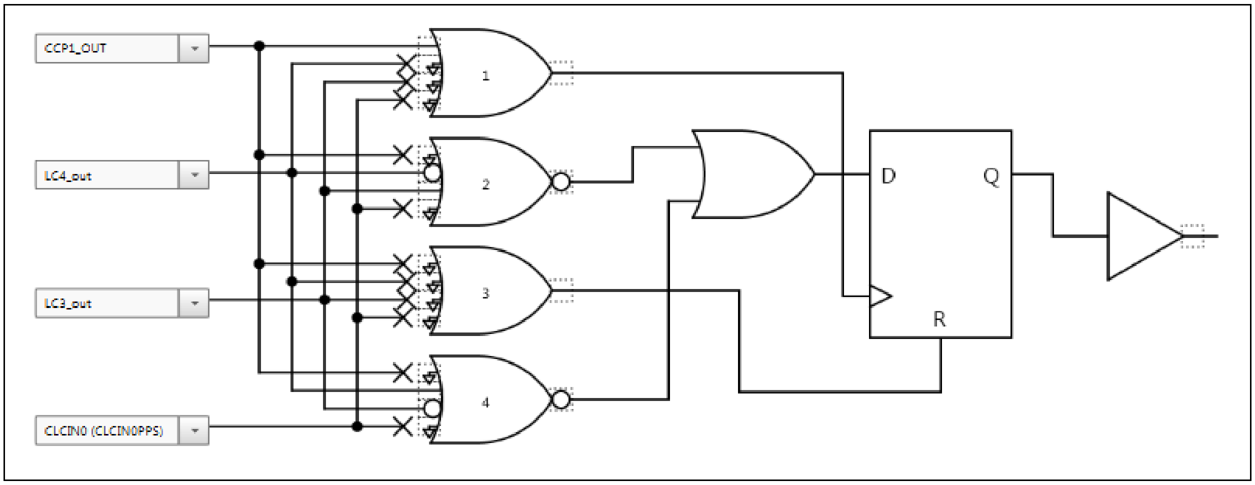


FIGURE 14: PIC16F1779'S CLC2 CONFIGURATION IN MCC

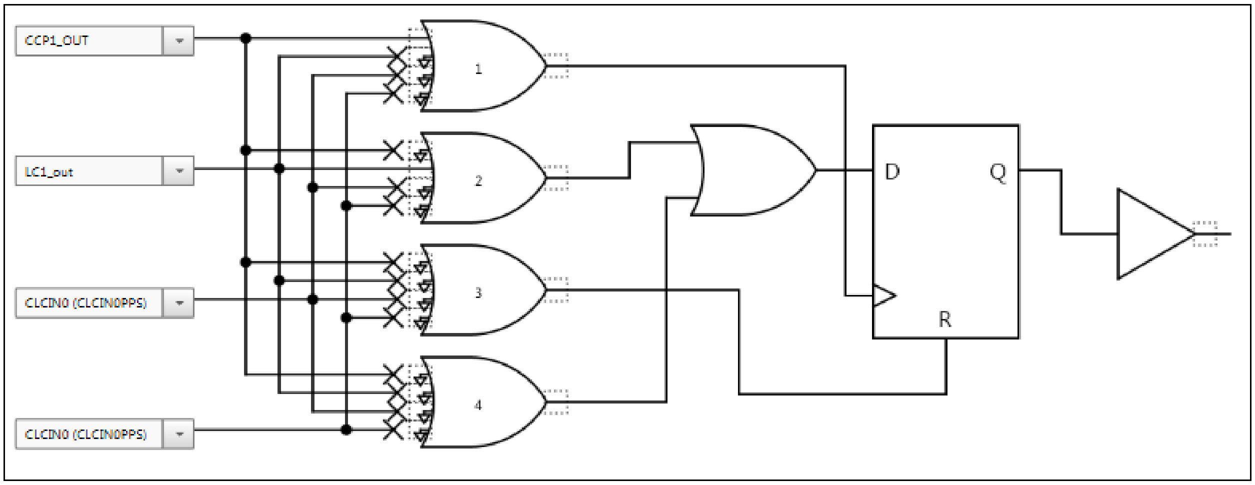


FIGURE 15: PIC16F1779'S CLC3 CONFIGURATION IN MCC

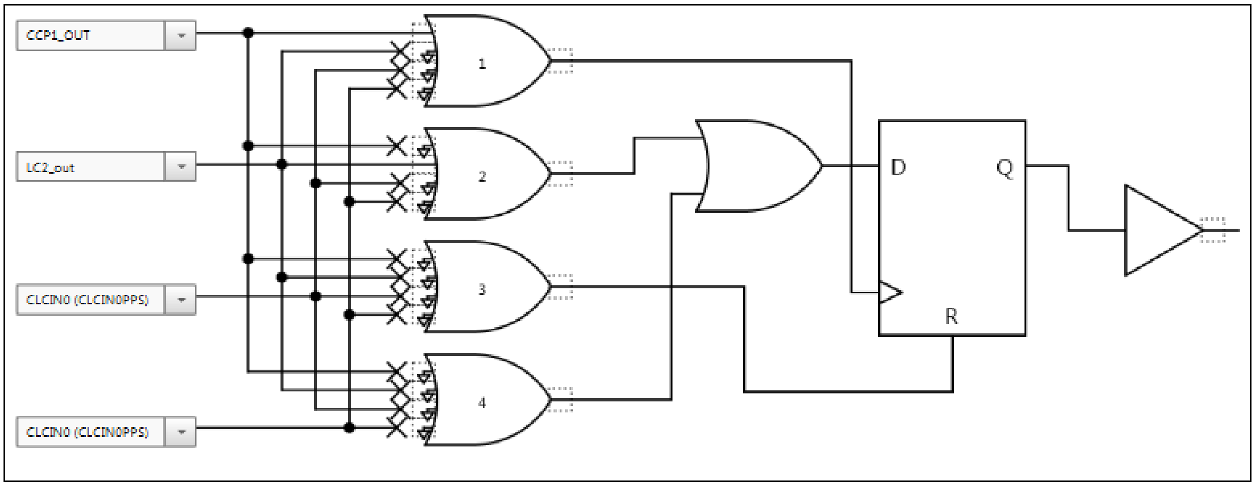
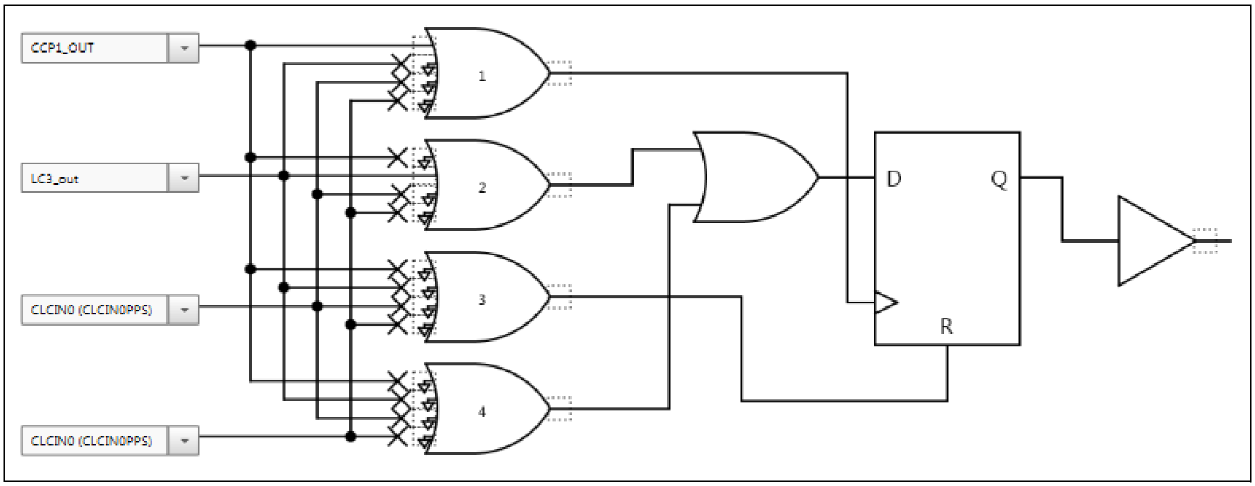


FIGURE 16: PIC16F1779'S CLC4 CONFIGURATION IN MCC



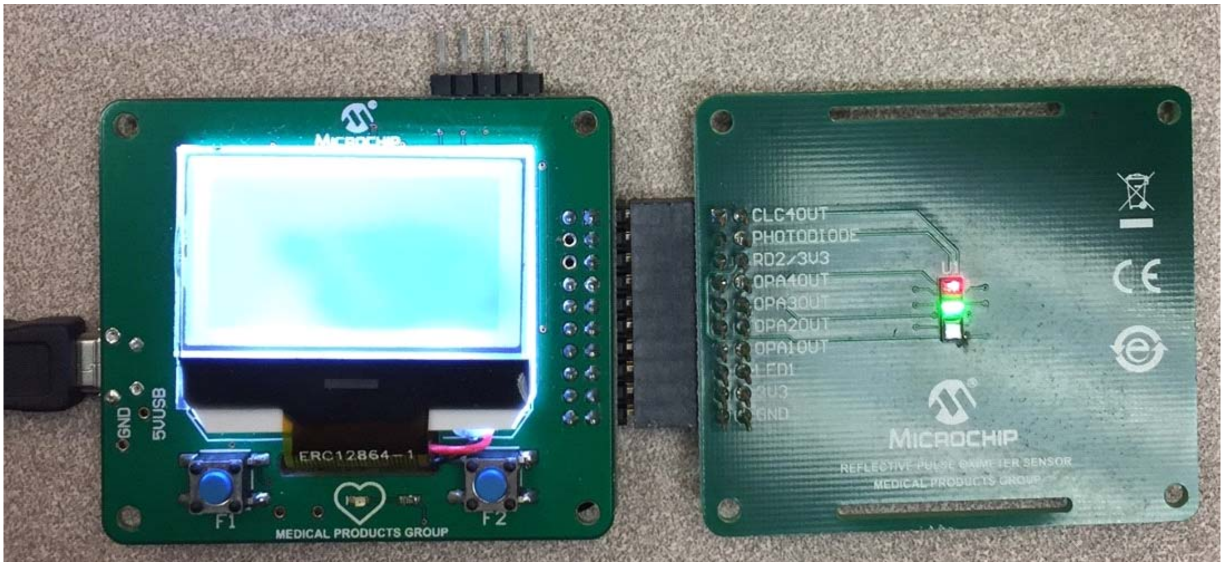
The PIC16F1779 also has four internal Operational Amplifiers (OPA), four 10-bit Digital-to-Analog Converters (DAC) and one 10-bit Analog-to-Digital Converter (ADC). All these internal analog peripherals and the CLCs, along with the proprietary method, make the PIC16F microcontroller family an excellent choice for low-power, low-cost, highly integrated photosensing applications.

REFLECTIVE HEART RATE MONITOR DEMO BOARD

A reflective heart rate monitor demo board was developed to demonstrate the proprietary method. The board design is fairly simple: a single PIC16F1779 microcontroller, plus one SFH7060 reflective photosensor. The SFH7060 made by OSRAM integrates three green, one red, one infrared emitter and one photodiode that are all placed in a reflective type of package. The reflective photosensing method has become increasingly popular in developing small, wearable biometric sensors, such as those green light sensors seen in the back of smart watches or activity tracker wristbands.

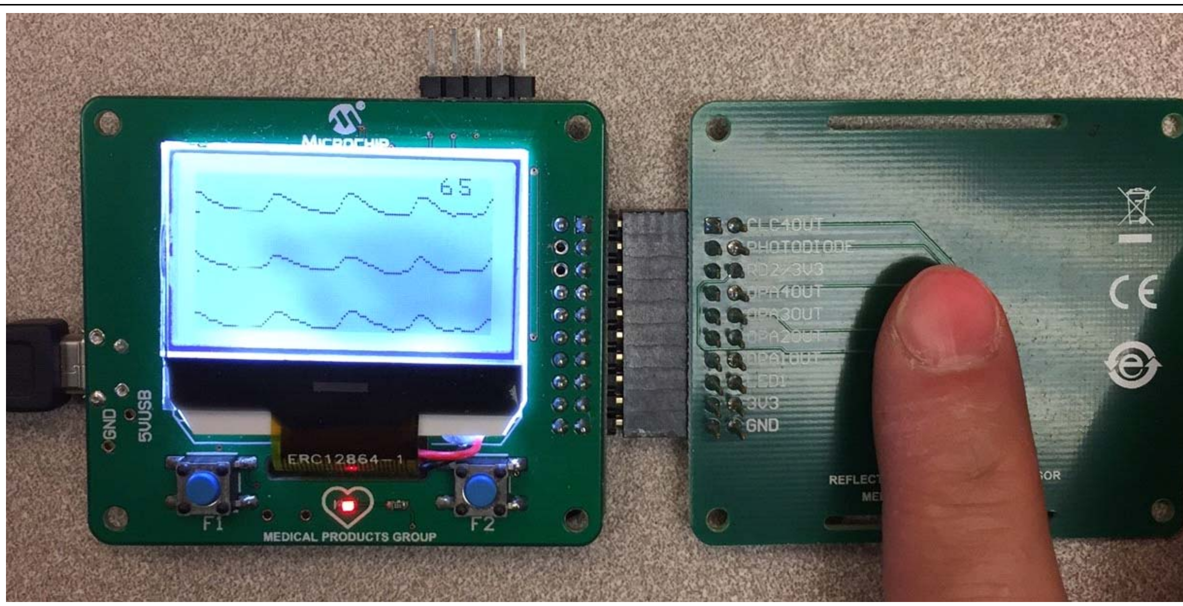
Upon powering on the demo board via USB, all the lights of SFH7060 are turned on as seen in Figure 17.

FIGURE 17: ALL LIGHTS OF SFH7060 ARE TURNED ON UPON POWER-ON



Press a finger on top of the SFH7060 photosensor and the heart rate measurement will automatically start. As seen in Figure 18, the demo board's LCD displays three pulsation waveforms generated by the green, infrared and red light, respectively (from the top down), and a user's heart rate of 65 beats per minute (bpm). All the data can be output to a computer from the microcontroller via the UART-to-USB interface MCP2221.

FIGURE 18: THE LCD ON THE DEMO BOARD DISPLAYING USER'S PULSATION WAVEFORMS AND HEART RATE

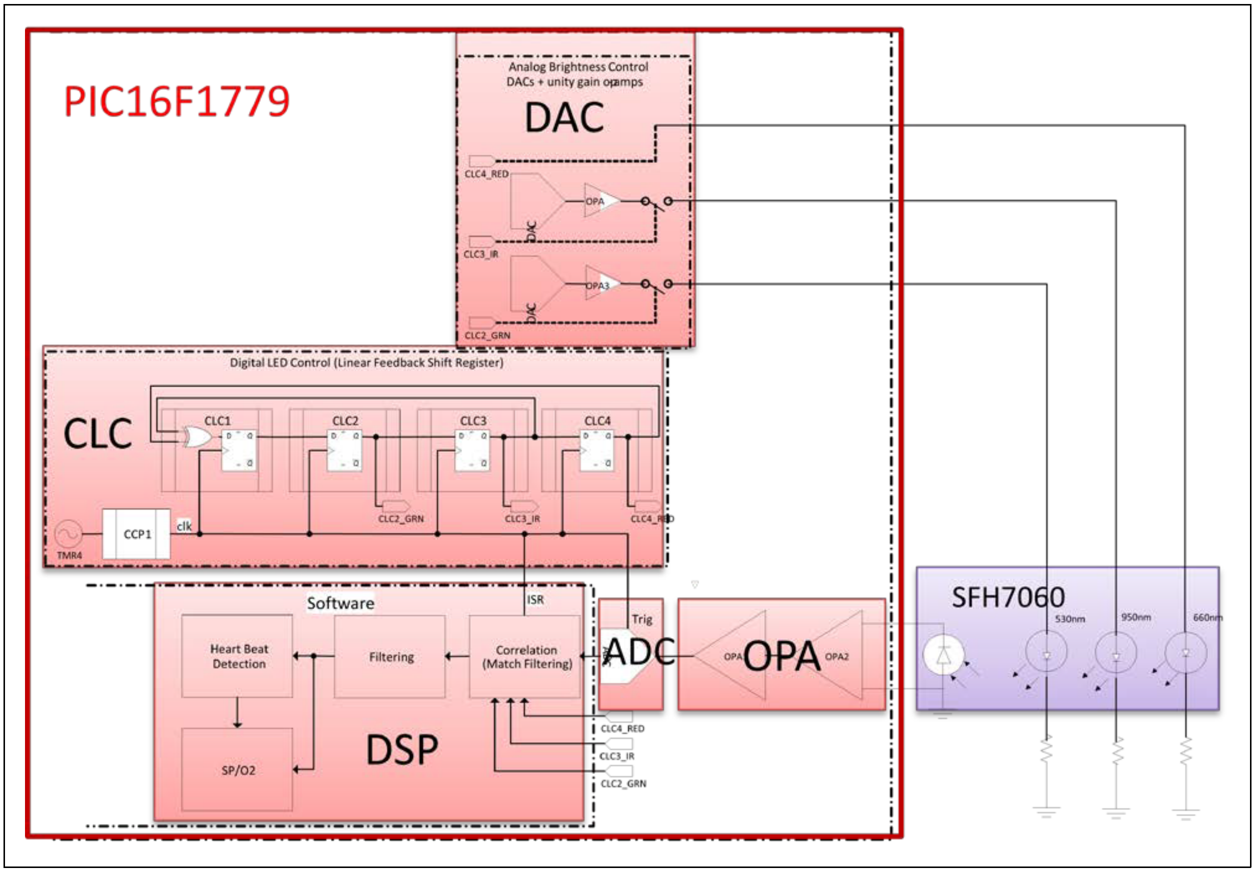


The schematics and the bill of materials of the reflective heart rate monitor demo board are listed in **Appendix A: "Schematics"** and **Appendix B: "Bill of Materials"**.

THEORY OF OPERATION

The PIC16F1779's internal analog and digital peripherals provide all the necessary functions to drive each light source in the SFH7060, as well as condition its photodiode. Figure 19 shows the reflective heart rate monitor demo block diagram.

FIGURE 19: REFLECTIVE HEART RATE MONITOR DEMO BLOCK DIAGRAM

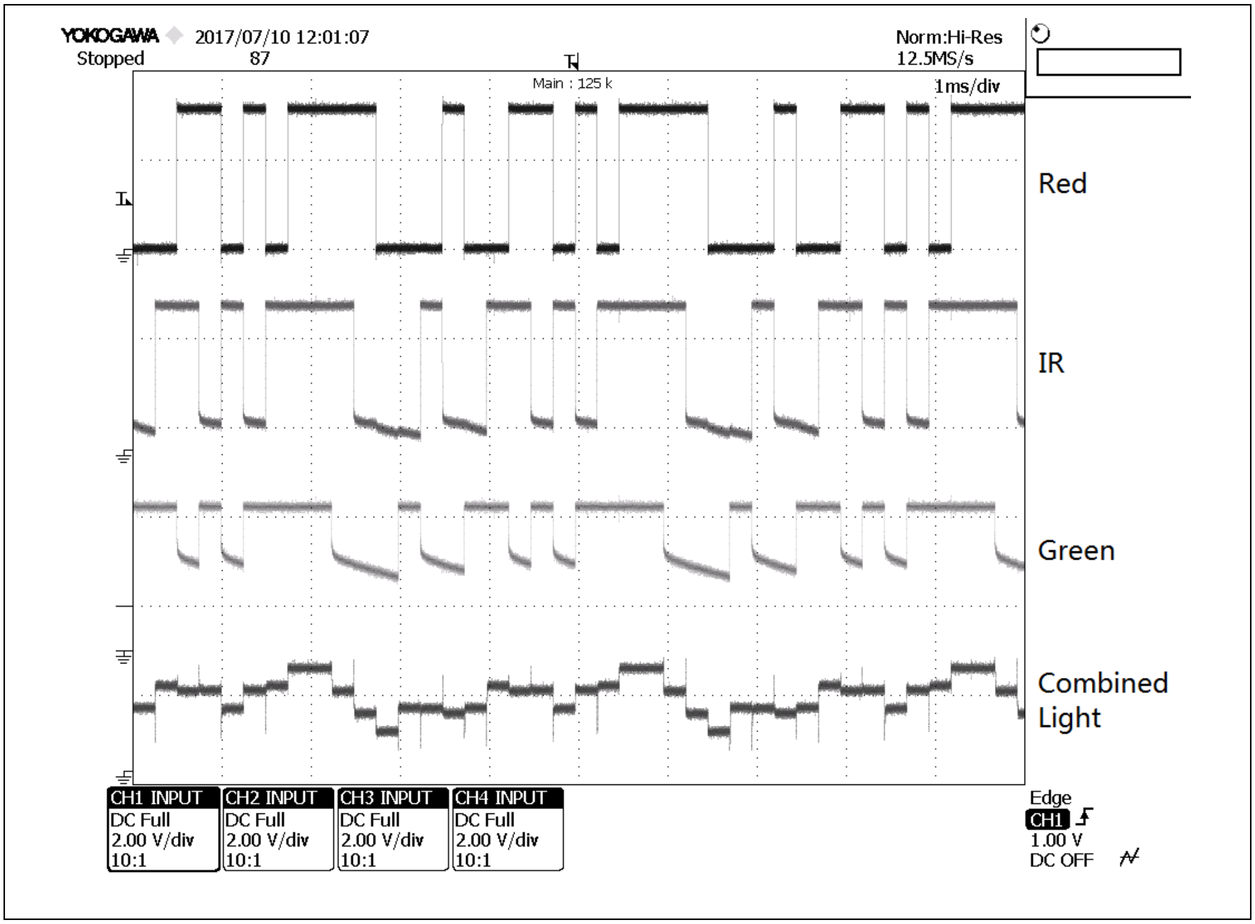


Three DACs (with two OPAs) deliver three driving signals with adjustable voltage to control the light intensity for each color of LED (green, red, IR). Four CLCs generate the LFSR clock, as well as the ML sequences to turn on/off the LEDs' driving signals based on the proprietary method.

The photodiode receives the combined light reflected from the user's skin (e.g., fingertip or wrist), and converts it to a small electric current. This current is next converted to voltage by a transimpedance amplifier, which is formed by an OPA. The voltage signal is then amplified by another OPA and sent to the ADC. The ADC module converts the analog signal to the digital signal with the combined light information.

Figure 20 shows real-time oscilloscope waveforms captured from the demo board. From the top down, waveform-1 is the CLC generated ML reference sequence used to drive the red light. Waveform-2 is the phase-shifted ML sequence used to drive the IR light. Waveform-3 is the phased-shifted ML sequence used to drive the green light. Waveform-4 is the combined light signal received by the photodiode.

FIGURE 20: OSCILLOSCOPE IMAGE DISPLAYING THREE LED DRIVING SIGNALS AND THE RECEIVED COMBINED LIGHT SIGNAL



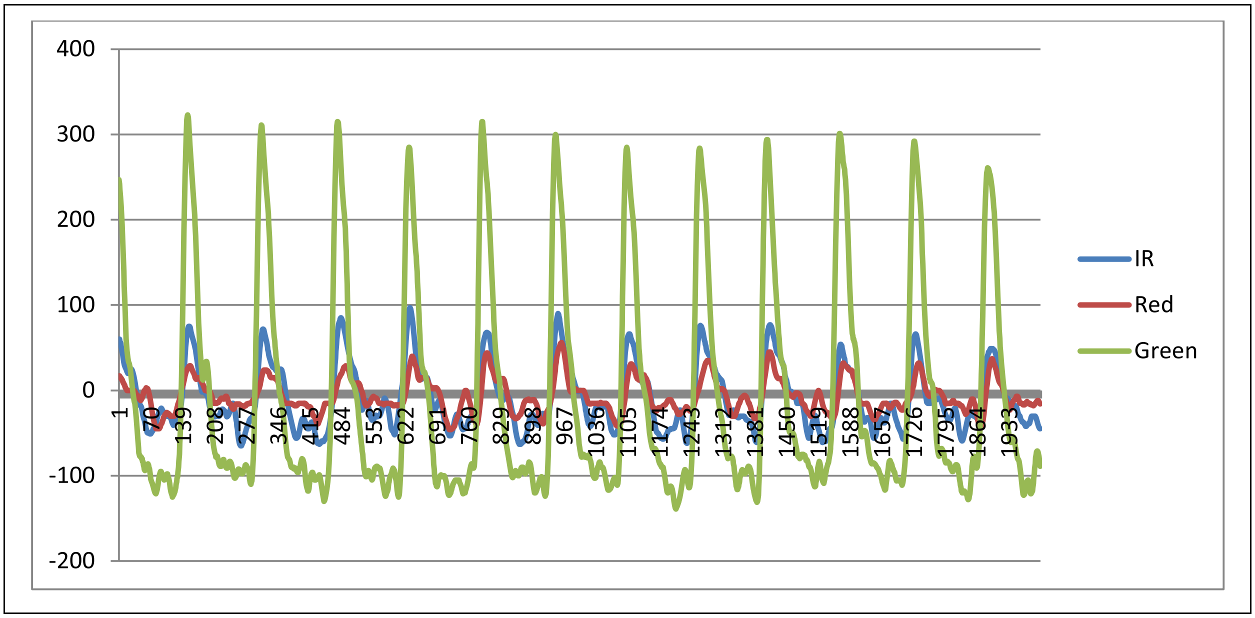
Several Digital Signal Processing (DSP) software routines are performed on the ADC results. The first operation is the correlation based on the proprietary method. It is done by adding the ADC results when the corresponding LED source is on, and subtracting when the corresponding LED source is off. The ADC conversion is triggered on the negative edge of the LFSR's clock source, and then each conversion result is correlated in an interrupt. Figure 21 shows the function called by every ADC interrupt. The function takes each ADC sample and correlates the sample with each of the three LEDs to separate them from the combined light.

FIGURE 21: CORRELATION CODE EXAMPLE

```
#define CS_Correlate(sample, reference)                                  \
  ((1 == (reference)) ? (sample) : -(sample))

// total samples accumulated
static uint16_t CS_sampleCount;
// samples to accumulate for each correlation
static uint16_t CS_sampleMax = 30;

// Called whenever an ADC conversion is completed
static void CS_AdcCallback(void) {
  if (CS_sampleMax > CS_sampleCount) {

    // Read ADC sample
    adc_result_t rawSample = ADC_GetConversionResult();

    // Shift for extra precision after filtering
    RPO_RAW_INT_T shiftedSample = rawSample <<= 2;

    // Correlate adc sample with LFSR taps
    CS_accumulatorRed += CS_Correlate(shiftedSample, redTap);
    CS_accumulatorIR1 += CS_Correlate(shiftedSample, ir1Tap);
    CS_accumulatorIR2 += CS_Correlate(shiftedSample, ir2Tap);
    CS_accumulatorBkg += CS_Correlate(shiftedSample, bkgTap);

    // Count number of samples correlated so far.
    CS_sampleCount++;
  } else {
    // Stop correlation when done
    bool err = CS_CorrelationStop();
    E_ASSERT(false == err);
  }
}
```

The second operation is filtering, which is to filter the correlated results for each light signal through a moving average filter. Figure 22 displays three filtered light signals.

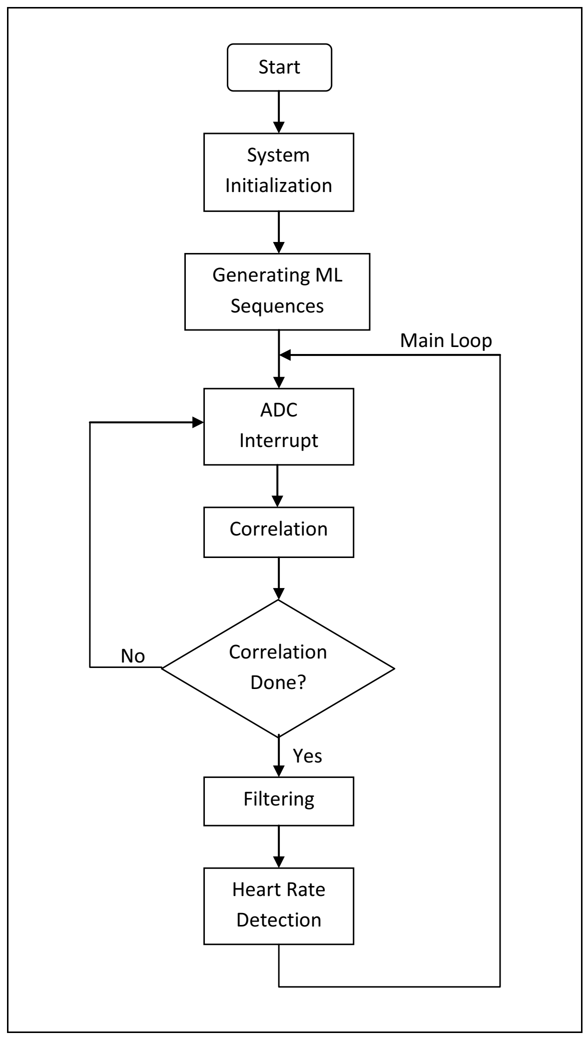
FIGURE 22: PULSATION WAVEFORMS FORMED BY FILTERED IR, RED, AND GREEN LIGHTS MEASURED AT FINGERTIP



The third operation is heart rate detection. The user's heart rate is calculated using the filtered green light signal. The red light signal and the infrared light signal may be further analyzed for measuring blood oxygen saturation (SPO2).

Figure 23 shows the microcontroller's firmware process flow.

FIGURE 23: FIRMWARE FLOWCHART



NOTES:

APPENDIX A: SCHEMATICS

Figure A-1 and Figure A-2 show the schematics for the reflective heart rate monitor demo.

FIGURE A-1: REFLECTIVE HEART RATE MONITOR DEMO CONTROL BOARD SCHEMATIC

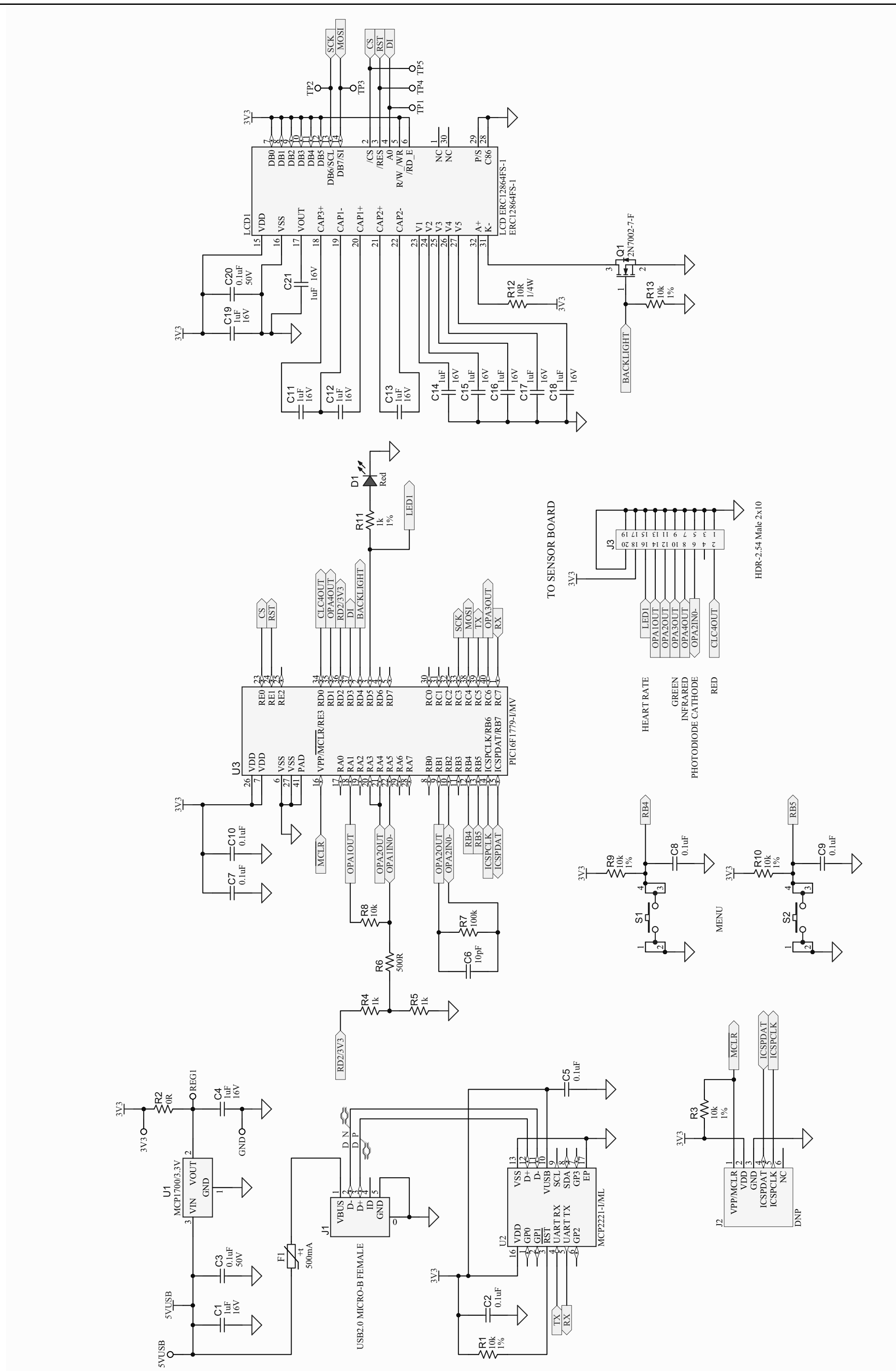
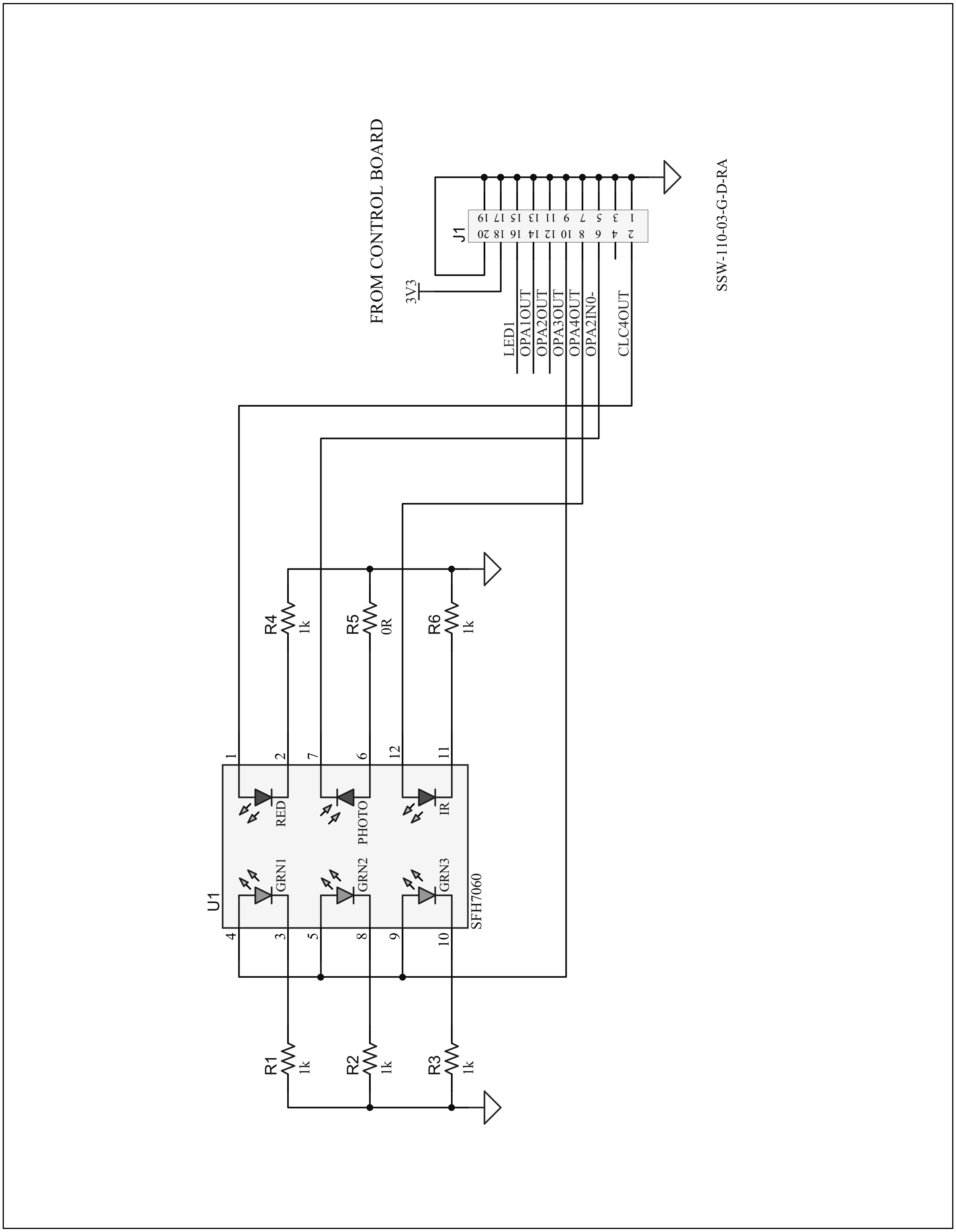


FIGURE A-2: REFLECTIVE HEART RATE MONITOR DEMO SENSOR BOARD SCHEMATIC



APPENDIX B: BILL OF MATERIALS

Table B-1 shows the Reflective Heart Rate Monitor Demo Control Board's Bill of Materials (BOM). The BOM for the Reflective Heart Rate Monitor Demo Sensor Board is in Table B-2.

TABLE B-1: BILL OF MATERIALS FOR THE REFLECTIVE HEART RATE MONITOR DEMO CONTROL BOARD

Designator	Description	Supplier	Supplier Part Number
C1, C4, C19	CAP CER 1uF 16V 10% X7R SMD 0603	Digi-Key	445-1604-1-ND
C2, C3, C5, C7, C8, C9, C10, C20	CAP CER 0.1uF 50V 20% X7R SMD 0603	Digi-Key	445-5098-1-ND
C6	CAP CER 10pF 50V 5% NP0 SMD 0603	Digi-Key	399-1049-2-ND
C11, C12, C13, C14, C15, C16, C17, C18, C21	CAP CER 1uF 16V 10% X7R SMD 0603	Farnell	1458900
D1	DIO LED RED 1.75V 20mA CLEAR SMD 0603	Digi-Key	511-1298-1-ND
F1	PTC RESTTBLE 0.50A 16V CHIP 1210	Digi-Key	507-1489-1-ND
J1	CON USB2.0 MICRO-B FEMALE TH/ SMD R/A	Digi-Key	609-4618-1-ND
J3	CON HDR-2.54 Male 2x10 Gold 5.84MH TH R/A	Digi-Key	SAM1045-10-ND
LCD1	DISPLAY LCD MODULE COG GRAPHIC 128x64 DISPLAY ST7565R ERC12864FS-1	BUYDISPLAY.COM	ERC12864FS-1
Q1	TRANS FET N-CH 2N7002-7-F 60V 170mA 370mW SOT-23-3	Digi-Key	2N7002-FDICT-ND
R1, R3, R8, R9, R10, R13	RES TKF 10k 1% 1/10W SMD 0603	Digi-Key	P10.0KHCT-ND
R2	RES TKF 0R 1/8W SMD 0805	Digi-Key	P0.0ATR-ND
R4, R5, R11	RES TKF 1k 1% 1/10W SMD 0603	Digi-Key	P1.00KHCT-ND
R6	RES TKF 500R 5% 1/10W SMD 0603	Digi-Key	RMC1/165005%R-ND
R7	RES TKF 100k 1% 1/10W SMD 0603	Digi-Key	P100KHTR-ND
R12	RES TKF 10R 1% 1/4W SMD 1206	Digi-Key	P10.0FCT-ND
S1, S2	SWITCH TACT SPST 12V 50mA PTS645SM43SMTR92 LFS SMD	Digi-Key	CKN9112CT-ND
U1	MCHP ANALOG LDO 3.3V MCP1700T-3302E/TT SOT-23-3	Microchip	MCP1700T-3302E/TT
U2	MCHP INTERFACE USB I2C UART MCP2221-I/ML QFN-16	Digi-Key	MCP2221-I/ML-ND
U3	MCHP MCU 8-BIT 32MHz 28kB 2kB PIC16F1779-I/MV UQFN-40	Microchip	PIC16F1779-I/MV

TABLE B-2: BILL OF MATERIALS FOR THE REFLECTIVE HEART RATE MONITOR DEMO SENSOR BOARD

Designator	Description	Supplier	Supplier Part Number
J1	CON HDR-2.54 FEMALE 2x10 TH RA 0.300 Gold Solder Tail	Samtec Inc	SSW-110-03-G-D-RA
R1, R2, R3, R4, R6	RES TKF 1k 1% 1/10W SMD 0603	Digi-Key	P1.00KHCT-ND
R5	RES TKF 0R 1/10W SMD 0603	Digi-Key	P0.0GTR-ND
U1	OSRAM SENSOR BioMon SFH7060 SMD COB	Digi-Key	475-3174-1-ND

APPENDIX C: WARNINGS, RESTRICTIONS, AND DISCLAIMER

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