Measuring SpO_2 and Heart Rate Using the MAX32664C – A Quick Start Guide

UG6924; Rev 7; 04/15

Abstract

The MAX32664C is a variant of the MAX32664 sensor-hub family, which is specifically targeted for measurement of SpO_2 and heart rate. Combined with the MAX86141/40 /MAXM86161/ MAXM86146 optical sensor and a 3-axis accelerometer, it provides the sensor's raw data, as well as calculated SpO_2 and heart-rate data, to a host device through its I^2C slave interface. This document provides step-by-step instructions that enable a user to communicate with the MAX32664C and to calibrate, configure, and receive measurement and monitoring data.

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Introduction

The MAX32664C is a variant of the MAX32664 sensor-hub family that enables users to capture raw data, as well as calculated SpO_2 and heart-rate data. The firmware includes the drivers and algorithm that are required to interface with a sensor device, such as the MAX86141, through the SPI port, or the MAXM86161 through first I^2C port as master. The second I^2C interface is slave and dedicated to establishing communication with a host microcontroller.

To properly capture and calculate the data, this solution requires an accelerometer. The MAX32664C firmware includes the required drivers for either the Kionix® KX122 or the ST LIS2DS12 accelerometer. Alternatively, a host-side accelerometer can be used. In this case, the sampled accelerometer data must be periodically reported to the MAX32664C by the host microcontroller using commands described in this application note.

NOTE: The instructions in this document are compatible with the MAX32664C firmware version 30.13.x (MAX86141), 32.13.0 (MAXM86161), or 33.13.x (MAXM86146) and later. If you are using older firmware, make sure to upgrade the firmware.

1 Architecture

An accelerometer is mandatory for MAX32664C heart-rate monitoring. A KX122/LIS2DS12 accelerometer may be connected directly to the MAX32664C. The interrupt line of the accelerometer is should be connected to the MAX32664C to support motion detection power saving. Alternatively, an external 3-axis host-side accelerometer can be used. In this case, the host needs to periodically provide accelerometer readings to the sensor hub using the commands provided in this document. For more information, see the **MAX32664 User Guide**.

The optical sensor utilizes green and/or red and infrared (IR) LEDs to transmit pulses and one or more photodiodes (PD) to collect reflected or residual light. By default, the heart-rate monitoring algorithm uses a green LED (LED1) and two PDs (PD1 and PD2). The SpO_2 employs one IR LED (LED2) and one red LED (LED3) with one PD (PD1).

Note: If a configuration other than default is used, the user should change the LED and PD configuration for heart-rate and SpO_2 algorithms using the provided commands (see **Table 12**) prior to enabling the algorithm.

The MFIO pin (normally set to high) is used in Application mode to wake up the MAX32664C from its Deep Sleep mode prior to any I^2C communication. The MAX32664C interfaces to the optical sensor through either the SPI bus (such as the MAX86141), or I^2C bus (such as the MAXM86161), subject to firmware support of the sensor.

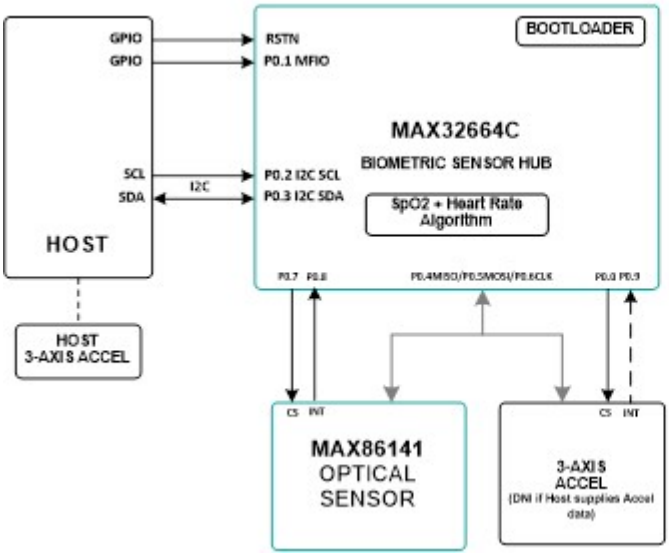

Figure 1. Architecture diagram for health-sensing applications using an SPI interface to communicate with the sensor (such as the MAX86141). Accel support for Kionix KX122 and ST LIS2DS12

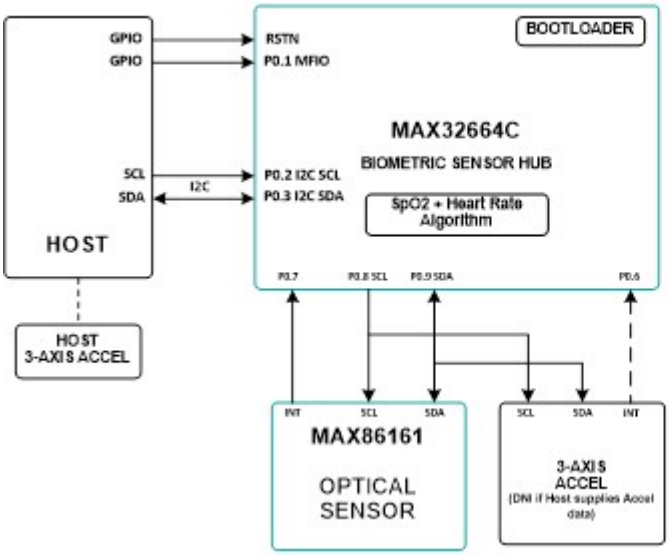

Figure 2. Architecture diagram for health-sensing applications using an I²C interface to communicate with the sensor (such as the MAXM86161). Accel support for Kionix KX122 and ST LIS2DS12

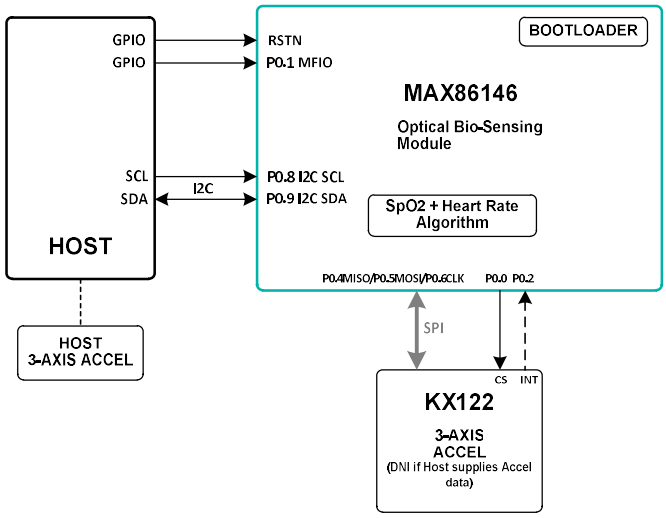

Figure 3. Architecture diagram for health-sensing applications using an I²C interface to communicate with MAXM86146 Module.

1.1 Reset to Bootloader or Application Mode

A typical health-sensing design includes a host microcontroller that communicates with the MAX32664C through the I2C bus. Two GPIO pins are needed to control the reset and the startup in Application or Bootloader mode through the RSTN and multifunction input/output (MFIO) pins.

To enter Bootloader mode:

- Set the RSTN pin to low for 10ms.
- While RSTN is low, set the MFIO pin to low. (The MFIO pin should be set to low at least 1ms before the RSTN pin is set to high.)
- After the 10ms has elapsed, set the RSTN pin to high.
- After an additional 50ms has elapsed, the MAX32664 is in Bootloader mode.

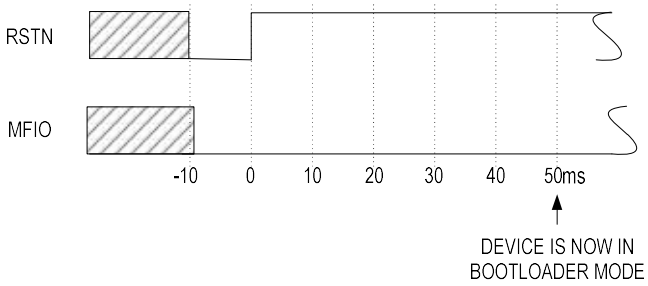

Figure 4 Entering bootloader mode using the RSTN pin and the MFIO GPIO pin.

To enter Application mode:

- Set the RSTN pin to low for 10ms.
- While RSTN is low, set the MFIO pin to high.
- After the 10ms has elapsed, set the RSTN pin to high. (The MFIO pin should be set to high at least 1ms before the RSTN pin is set to high.)
- After an additional 50ms has elapsed, the MAX32664 is in Application mode and the application performs its initialization of the application software.
- After approximately 1.5 second from when the RSTN pin was set to high, the application completes the initialization, and the device is ready to accept I2C commands.

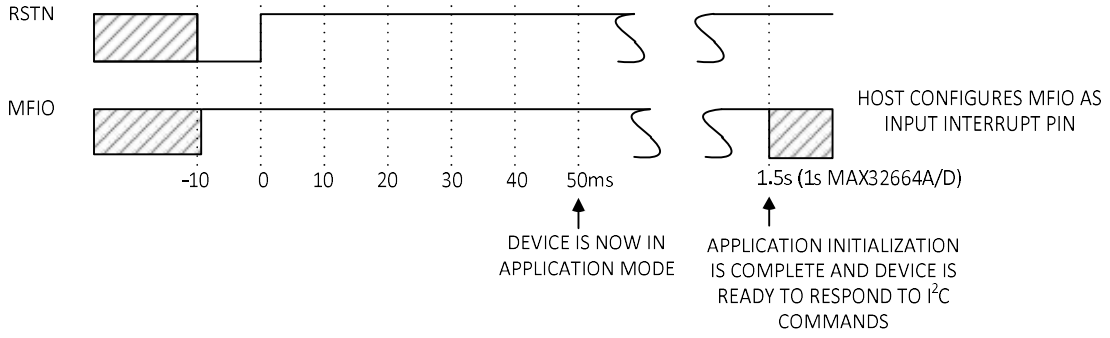

Figure 5 Entering application mode using the RSTN pin and MFIO pin.

To enter Application mode by timing out from Bootloader mode:

- Set the RSTN pin to low for 10ms.
- While RSTN is low, set the MFIO pin to low. (The MFIO pin should be set to low at least 1ms before the RSTN pin is set to high.)
- After the 10ms has elapsed, set the RSTN pin to high.
- After an additional 50ms has elapsed, the MAX32664 is in Bootloader mode.
- If no I2C commands are sent to the sensor hub within the next 1s, then the sensor hub will automatically switch to application mode.

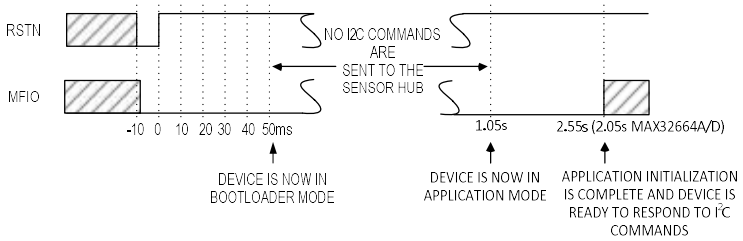

Figure 6 Entering application mode by timing out from Bootloader mode.

1.2 MAX32664C Handshaking

1.2.1 Normal MFIO Mode (default, host periodically empties the FIFO)

Normally, when MAX32664C is idle, it switches to Deep Sleep mode to save power. An external interrupt-like sensor, host MFIO, or RTC alarm forces the MAX32664C to wake up. Do not keep the MFIO pin at a constant low – when the MFIO pin is high, the MAX32664 wakes up to service the AFE.

In particular, the host is required to wake up the MAX32664C prior to any I2C communication by:

- Setting the MFIO pin to low at least 250µs before the beginning of an I2C transaction to make sure the MAX32664C is awake.
- Keeping the MFIO pin low during the I2C transaction to make sure the MAX32664C will not switch to Deep Sleep mode.
- Setting MFIO to high after the end of I2C communication to allow the MAX32664C to switch back to Deep Sleep mode.

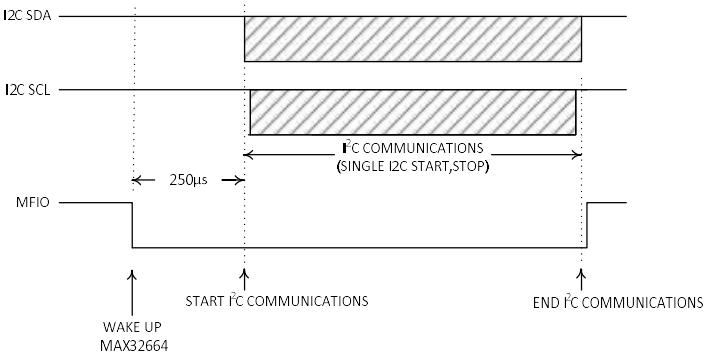

Figure 7. Normal MFIO Mode, host uses MFIO for enabling host communications.

1.2.2 MFIO Interrupt Mode (default, host periodically empties the FIFO)

MFIO interrupt mode is mode where FIFO pin is used by MAX32664C to interrupt Host when: measurement data is ready, report FIFO overflow events and skin contact detection event (when SCD state machine is enabled – see section SCD State Machine for MFIO Interrupt Mode).

- To set up for MFIO interrupt mode, the host sets the MFIO pin to input mode and assigns a GPIO interrupt handler to this pin to receive event reporting from the MAX32664C.
- The host initializes the MAX32664C to AEC or AEC mode.
- MAX32664C enters MFIO interrupt mode with command sequence 0xB8, 0x01.
- After the interrupt is received by the host, the host should wake the MAX32664C. When in MFIO interrupt mode, MAX32664C is woken up by:
  - Host sends byte 0x00 to I2C slave address 0x00 and wait for 200uc
  - Host sends bytes 0x00 to I2C slave address 0x00 and wait for 150us
- Host may sends commands to read samples in the output FIFO.

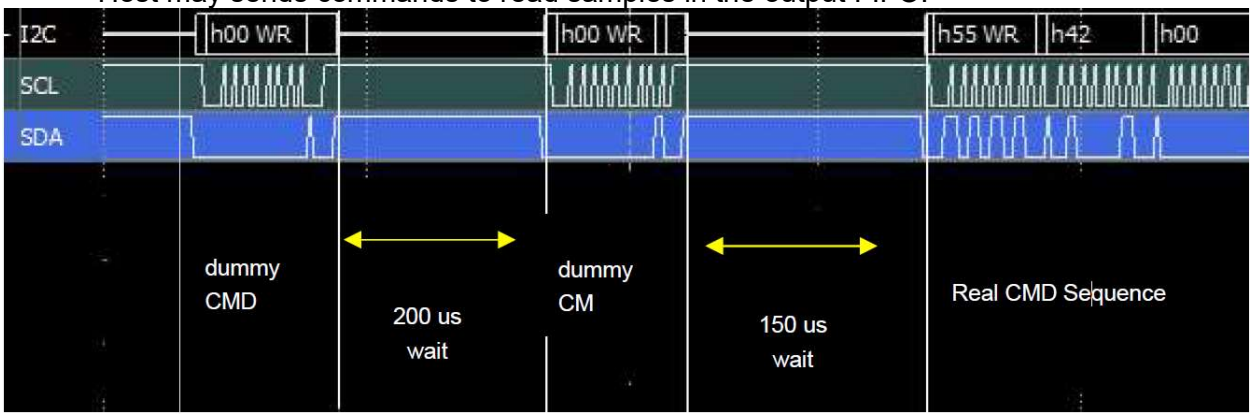

Figure 8. SDA wake-up sequence for MAX32664C

1.3 MAX32664C I2C Communications

A host uses the I²C bus to communicate with the MAX32664C (slave) using a series of commands. See the MAX32664 User Guide for details. The default CMD_DELAY is 2ms.

A generic write command includes the following fields:

```
Slave_WriteAddress(1 byte)|Command_Family(1 byte)|Command_Index(1 byte)|Value(multiple bytes)
```

A generic response includes the following fields:

```
Slave_ReadAddress(1 byte)|Status(1 byte)|Value (multiple bytes)
```

`Slave_WriteAddress` and `Slave_ReadAddress` are set to 0xAA and 0xAB, respectively.

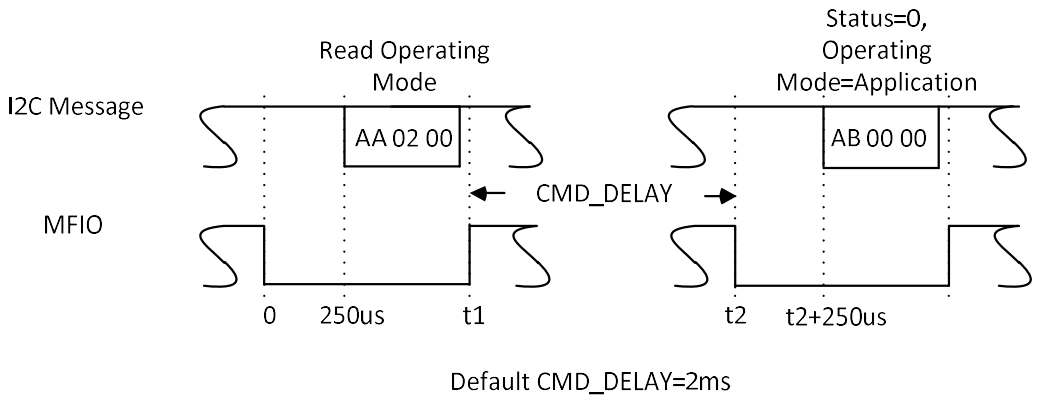

Figure 9. Example I²C, MFIO timing diagram.

The read status byte is an indicator of success (0x00) or failure, as shown in **Table 1**.

Table 1. Read Status Byte Value

STATUS BYTE VALUE	DESCRIPTION
0x00	The write transaction was successful.
0x01	Illegal Family Byte and/or Index Byte was used. Verify that the Family Byte, Index Byte are valid for the host command sent.
0x02	Illegal Index Byte and/or Write Byte was used. Verify that the Index Byte and Write Byte(s) are valid for the host command sent.
0x03	Incorrect number of bytes sent for the requested Family Byte. Verify that the correct number of bytes are sent for the host command.
0x04	Illegal configuration value was attempted to be set. Verify that the Index Byte is correct for Family Byte 0x44. Verify that the samples report period is not 0 for host command 0x10 0x02. Verify that the Write byte for host command 0x10 0x03 is in the valid range specified.
0x05	Not used in application mode. (In bootloader: Device is busy. Insert delay and resend the host command.)
0x80	Not used. General error while receiving/flashing a page during the bootloader sequence. Not used.
0x81	Bootloader checksum error while decrypting/checking page data. Verify that the keyed .msbl file is compatible with MAX32664A/B/C/D.
0x82	Bootloader authorization error. Verify that the keyed .msbl file is compatible with MAX32664A/B/C/D.
0x83	Bootloader detected that the application is not valid.
0xFE	Device is busy. Try again. Increase the delay before the command and increase the CMD_DELAY.
0xFF	Unknown error. Verify that the communications to the AFE/KX-122 are correct by reading the PART_ID/WHO_AM_I register. For MAX32664B/C, the MAX32664 is in deep sleep unless the host sets the MFIO pin low 250us before and during the I²C communications.
NAK	NAK received. Sensor hub was busy. Resend command after 1ms with a maximum of five retries. If this issue persists, then empty the FIFO by reading all the data or reduce the report rate.

This document provides examples of commands for establishing communication with the MAX32664C. For a complete list of commands and instructions for the I²C interface, see the **MAX32664 User Guide**.

1.2 Power-Saving Considerations

1.2.1 Samples Report Rate

The MAX32664C goes into deep sleep in Idle mode and wakes up on internal or external interrupts. To maximize the benefits of low power, the host may configure the samples report period of the algorithm to a longer time. In this case, the samples report is generated less frequently.

This samples report rate is configured through an I2C command, as shown in **Table 12**.

1.2.2 Host Reading Samples in Output FIFO Period and Samples Report Period

The host is required to regularly empty the measurement data in the MAX32664C FIFO at a periodic rate. The periodic rate depends on the rate that the MAX32664C samples report is generated. When the samples report period is reduced, the host will not need to empty the FIFO as often. If the FIFO becomes full, then the FIFO should be emptied.

The host may read samples in the output FIFO at a period (*host reading FIFO period*) five times the length of the samples report period (*samples report period*) to avoid FIFO overflow. In this example, an average of five samples will be in the output FIFO.

By default, the samples report period (read samples report period, 0x11 0x02) is set to 40ms. In this case, it is recommended that the host read samples from the output FIFO every 200ms (*host reading period*). At these rates, on average there will be five samples in the output FIFO for the host to read.

Steps 2.1 to 2.3 in the Host Commands Tables details the host commands necessary to read the measurement samples report.

1.2.3 Samples Report Content

If the sensor data such as accelerometer and photoplethysmogram (PPG) signals are not required, the host may choose to request only algorithm data in the samples report. This reduces the I^2C communication time and affects power consumption. This is performed by configuring the output mode to Algorithm Only.

This samples report output mode is configured through an I^2C command, as shown in **Table 12**.

1.3 Accelerometer

The MAX32664C requires accelerometer data to function properly. An accelerometer is mandatory for a heart-rate monitor to be able to compensate for the user's motion. Otherwise, the reported heart rate will not be correct during movement.

SpO_2 calculation requires a resting condition, and the algorithm uses accelerometer data to detect excessive motion. In such a condition, computation is paused, and the user is informed with a motion flag.

A sensor hub accelerometer can be integrated through the SPI port of the MAX32664C. In this case, the required driver for KX122/LIS2DS12 is already included. The user only needs to follow the reference schematics to connect the accelerometer and enable it before starting the algorithm, as described later in this document. Normally, the accelerometer is polled to collect samples. The interrupt line is only needed if the SCD-based power saving procedure is implemented in the host.

Alternatively, a host-side accelerometer can be used. However, this option requires strict timing synchronization between the sampled accelerometer data and PPG samples of ±40ms or less. In order to use the host-side accelerometer:

1. The host should start the accelerometer just before enabling the algorithm to maximize the initial synchronization between the PPG and accelerometer samples. However, accelerometer samples collected prior to receiving the confirmation of the algorithm enable I²C command should be discarded.
2. The host is required to use a 3-axis accelerometer at a 25Hz sampling rate. If a higher sampling rate is chosen, samples should be decimated to be synchronized with a 40ms PPG sampling time.
3. The host must queue five accelerometer samples and feed them at the same time to the MAX32664C using the commands shown in **Table 2**. The period of feeding samples should be 200ms. This is the longest delay that the MAX32664C can tolerate to receive accelerometer samples.

Because the sensor and the host accelerometer use different clock sources, exact synchronization between them is not possible. The MAX32664C internally decimates or interpolates accelerometer samples to compensate a drift.

Table 2. Host-Side Accelerometer—Sending Data to the MAX32664C

HOST COMMAND (HEX)	DESCRIPTION	MAX32664 RESPONSE (HEX)	DESCRIPTION
AA 44 04 01 01 (CMD_DELAY = 20ms)	Enable the host accelerometer.	AB 00	Success
AA 13 00 04	Read the sensor sample size for the accelerometer (optional).	AB 00 06	Success; 6 is the number of bytes per samples in FIFO
The following should be executed periodically at 200ms:			
AA 14 00 [Sample 1 values] … [Sample N values]	Write data to the input FIFO of the sensor hub. Each sample has three 2-byte integer values for X, Y, and Z in milli-g. N=5	AB 00	Success
AA 00 00	Read the sensor hub status.	AB 00 00	Success; sensor hub not busy

1.3.1 Converting Gs to Counts

The G's may be converted back to counts with the following psuedo code. The accelerometer resolution is set to 16 bits, 8G

```
float G_s
int plus_minus_counts
plus_minus_counts = (int)((float)(((G_s * 32768.0)+4.0)/8.0))
if (plus_minus_counts > 32767)
  plus_minus_counts =32767
```

```
else if (plus_minus_counts < -32768)
  plus_minus_counts = -32768
```

Eg., (int)((7.9997559*32768)+4)/8 =(int)(32767.5) =32767

2 Data Collection for SpO_2 Calibration Coefficients.

Due to variations in the physical design and optical shield of the final product, a calibration data collection procedure for SpO_2 is required to be performed once in a controlled environment. This procedure is important to ensure the quality of the SpO_2 calculation. This step is typically performed in a standard lab using the final form factor (with cover lens) with a reference SpO_2 device to determine three SpO_2 calibration coefficients: a, b, and c. The details of the SpO_2 calibration data collection and SpO2 coefficient derivation procedure are described in the **Guidelines for SpO_2 Measurement Using the Maxim MAX32664 Sensor Hub** application note.

Once three SpO_2 calibrations coefficients are obtained, they need to be loaded to the MAX32664C every time prior to starting the algorithm. But first, they are required to be converted to a 32-bit integer format using the following:

- A_{int32} = round (10^5 x a)
- B_{int32} = round (10^5 x b)
- C_{int32} = round (10^5 x c)

For example, the default measured SpO_2 calibration coefficients for MAXREFDES103# are:

- a = 0.0
- b = -26.224999
- c = 112.317421

These are sent to the MAX32664C using 32-bit signed integer format:

- A_{int32} = round (10^5 x a) = 0x00000000
- B_{int32} = round (10^5 x b) = 0xFFD7FBDD
- C_{int32} = round (10^5 x c) = 0x00AB61FE

The SpO_2 calibration coefficients may be stored in the host flash separately and loaded to the MAX32664C after every reset.

Table 3 shows the sequence of commands for the enabling the SpO2 data collection mode. **Table 4** shows the format of received samples report. R values are needed for the SpO_2 calibration process, as described in the **Guidelines for SpO_2 Measurement Using the Maxim MAX32664 Sensor Hub** application note.

Table 3. Host Commands—SpO_2 Calibration Data Collection Mode

	#	HOST COMMAND (HEX)	COMMAND DESCRIPTION	RESPONSE (HEX)
START ALGORITHM	Host initializes the MAX32664C to SpO2 calibration data collection mode and starts the algorithm using following commands:			
	1.1	AA 10 00 03	Set the output FIFO mode to sensor + algorithm data (streamed data will include PPG accelerometer and algorithm data).	AB 00
	1.2	AA 10 01 01	Set the sensor hub interrupt threshold.	AB 00
	1.3	AA 10 02 01	Set the samples report period to 40ms. Samples report rate to be one report per every sensor sample.*	AB 00
	1.4	AA 44 04 01 01 (if host accelerometer is used, CMD_DELAY = 20ms)	Enable the host-side accelerometer, if used. Otherwise, the sensor hub accelerometer is used by default, and there is no need to enable it.	AB 00
	1.5	AA 50 07 0A 06	Set the mode to SpO_2 Calibration Data Collection mode	AB 00
	1.6	Optional: Any command to change the algorithm settings and configurations (**Table 12**) from the default setting should appear here BEFORE enabling the algorithm.		
	1.7	AA 52 07 01 (CMD_DELAY = 465 ms)	Enable the algorithm; the analog front-end (AFE) and sensor hub accelerometer will be enabled automatically.	AB 00
READING SAMPLES REPORT IN OUTPUT FIFO	Host reads samples periodically (do not execute at a faster rate than the samples report period):			
	2.1	AA 00 00	Read the sensor hub status byte: Bit 0: Sensor comm error Bits 1 and 2: Reserved Bit 3: FIFO filled to threshold (DataRdyInt) Bit 4: Output FIFO overflow (FifoOutOvrInt) Bit 5: Input FIFO overflow (FifoInOverInt) Bit 6: Sensor hub busy (DevBusy) Bit 7: Reserved If DataRdyInt is set, proceed to the next step.	AB 00 08
	2.2	AA 12 00	Get the number of samples (nn) in the FIFO.	AB 00 nn
	2.3	AA 12 01	Read the data stored in the FIFO; nn samples will be included. The format of the samples report is shown in **Table 4.**	AB 00 data_for_ nn_samples
STOP	Host ends the procedure:			
	3.1	AA 52 07 00 (CMD_DELAY = 120ms)	Disable the algorithm.	AB 00

*The host is required to periodically check the MAX32664C for an available samples report. The default samples report period is 40ms which means sample rate is 25Hz. Depending on the output mode, the samples report may include algorithm and/or sensor data (see **section 1.2**)

Table 4. Samples Report from Output FIFO: SpO_2 Calibration Data Collection Mode Report

DATA SOURCE	DATA ITEM	# OF BYTES (MSB FIRST)	DESCRIPTION
MAX86141/40, MAXM86161 PPG Data (18 Bytes)* MAXM86146 PPG Data is 36 Bytes as described in Table 7	PPG1 (PD1)	3	N/A
	PPG2 (PD1)	3	IR LED counts
	PPG3 (PD1)	3	Red LED counts
	PPG4 (PD2)	3	N/A
	PPG5 (PD2)	3	N/A
	PPG6 (PD2)	3	N/A
Accelerometer (6 Bytes)*	accelX	2	Two's complement. LSB = 0.001g
	accelY	2	Two's complement. LSB = 0.001g
	accelZ	2	Two's complement. LSB = 0.001g
Wearable Suite Algorithm (24 Bytes)	Op mode	1	Current operation mode: 0: Continuous Heart-Rate Monitor (HRM) and Continuous SpO_2 1: Continuous HRM and One-Shot SpO_2 2: Continuous HRM 3: Sampled HRM (~15s) 4: Sampled HRM and One-Shot SpO_2 (~30s) 5: Activity Tracking 6: SpO_2 Calibration Data Collection
	HR	2	N/A
	HR confidence	1	N/A
	RR	2	N/A
	RR confidence	1	N/A
	Activity class	1	N/A
	R	2	1000x calculated R value
	SpO_2 confidence	1	Calculated confidence in %
	SpO_2	2	N/A
	SpO_2 % complete	1	N/A
	SpO_2 low signal quality flag	1	Shows the low quality of the PPG signal: 0: Good quality 1: Low quality
	SpO_2 motion flag	1	Shows excessive motion: 0: No motion 1: Excessive motion
	SpO_2 low PI flag	1	Shows the low perfusion index (PI) of the PPG signal: 0: Normal PI 1: Low PI
	SpO_2 unreliable R flag	1	Shows the reliability of R: 0: Reliable 1: Unreliable
	SpO_2 state	1	Reported status of the SpO_2 algorithm: 0: LED adjustment 1: Computation 2: Success 3: Timeout

	Skin contact detector (SCD) state	1	Skin contact state (SCD updates provided in Op mode 0 to 4) 0: Undetected 1: Off skin 2: On some subject 3: On skin
	IBI offset	1	Reported when IBI is calculated. Defines number of samples between current algo sample and previous algo sample where IBI is calculated
	Unreliable orientation flag	1	Flag reporting not appropriate orientation of wrist for reliable SpO2 measurement 0: correct orientation 1: wrong orientation
	RESERVED	2	Reserved for future use

*If the output mode includes the sensor. LED assignment example is for the default configuration.

3 Measuring SpO_2 and Heart Rate on Wrist—SpO_2 and WHRM

3.1 Raw Data Mode

For hardware testing purposes, the user may choose to start the MAX32664C to collect raw PPG samples. In this case, the host configures the MAX32664C to work in Raw Data mode (no algorithm) by enabling the accelerometer and the AFE. **Table 5** lists the set of commands that are needed to work in this mode. In Raw Data mode, only raw PPG samples and accelerometer data are included in the received samples. (The PPG raw data is stripped of the tags that are in the AFE FIFO and the sensor hub outputs the data in the order specified in the samples report tables).

Table 5. Host Commands—Raw Data Mode

	#	HOST COMMAND (HEX)	COMMAND DESCRIPTION	RESPONSE (HEX)
START	Host initializes the MAX32664C in Raw Data mode using following commands:			
	1.1	AA 10 00 01	Set the output FIFO mode to Sensor data only.	AB 00
	1.2	AA 10 01 01	Set the sensor hub interrupt threshold.	AB 00
	1.3	AA 44 04 01 00 (if sensor hub accelerometer is used, CMD_DELAY = 20ms) AA 44 04 01 01 (if host accelerometer is used, CMD_DELAY = 20ms)	Enable the accelerometer.	AB 00
	1.4	AA 44 00 01 00 (CMD_DELAY = 250ms)	Enable AFE (MAX86141/40, MAXM86146, or MAXM86161).*	AB 00
	Any command to change the sensor registers should appear AFTER enabling the sensor or they will be overwritten. By default, the algorithm sets the following AFE registers: Sample rate: 100Hz, 1-sample averaging (samples report period: 10 msec) ; Integration time: 117µs ; ADCs 1 and 2 range: 32µA LEDs 1, 2, and 3 full range: 124mA			
	1.5	AA 40 00 12 18 AA 40 00 12 20	Set the sample rate of the MAX86141 to 100Hz with 1-sample averaging. Set the sample rate of the MAX86141 to 200Hz with 1-sample averaging.	AB 00
	1.6	AA 40 00 23 7F	Set the MAX86141 LED1 current to half of full scale. Reduce [7F] if the signal is saturated.	AB 00
	1.7	AA 40 00 24 7F	Set the MAX86141 LED2 current to half of full scale. Reduce [7F] if the signal is saturated.	AB 00
	1.8	AA 40 00 25 7F	Set the MAX86141 LED3 current to half of full scale. Reduce [7F] if the signal is saturated.	AB 00
READING SAMPLES REPORT IN	Host reads samples periodically (do not execute at a faster rate than the samples report period):			
	2.1	AA 00 00	Read the sensor hub status byte: Bit 0: Sensor comm error Bits 1 and 2: Reserved Bit 3: FIFO filled to threshold (DataRdyInt) Bit 4: Output FIFO overflow (FifoOutOvrInt) Bit 5: Input FIFO overflow (FifoInOverInt) Bit 6: Sensor hub busy (DevBusy)	AB 00 08

			Bit 7: Reserved If DataRdyInt is set, proceed to the next step.	
	2.2	AA 12 00	Get the number of samples (nn) in the FIFO.	AB 00 nn
	2.3	AA 12 01	Read the data stored in the FIFO; nn samples. The format of samples report is shown in **Table 6**.	AB 00 data_for_ nn_samples
STOP	Host ends the procedure:			
	3.1	AA 44 00** 00 (CMD_DELAY = 250ms)	Disable the AFE (e.g., the MAX86141).**	AB 00
	3.2	AA 44 04 00, (CMD_DELAY = 20ms)	Disable the accelerometer.	AB 00

* The host is required to periodically check the MAX32664C for an available samples report. The default samples report period is 40ms which means sample rate is 25Hz

Table 6. Samples Report from Output FIFO: Raw Data Mode Report

DATA SOURCE	DATA ITEM	# OF BYTES (MSB FIRST)	DESCRIPTION
MAX86141 PPG Data (18 Bytes)* MAXM86146 PPG Data is 36 bytes as described in Table 7	PPG1 (PD1)	3	Green counts
	PPG2 (PD1)	3	IR counts
	PPG3 (PD1)	3	Red counts
	PPG4 (PD2)	3	Green2 counts (N/A if configured for MAX86140, MAXM86161, N/A means the data is not meaningful)
	PPG5 (PD2)	3	N/A
	PPG6 (PD2)	3	N/A
Accelerometer (6 Bytes)	accelX	2	Two's complement. LSB = 0.001g
	accelY	2	Two's complement. LSB = 0.001g
	accelZ	2	Two's complement. LSB = 0.001g

* LED assignment example is for the default configuration.

Table 7. PPG Samples Report from Output FIFO: MAXM86146

DATA SOURCE	DATA ITEM	# OF BYTES (MSB FIRST)	DESCRIPTION
MAXM86146 PPG Data (36 Bytes)*	PPG1 (PD1)	3	Green counts
	PPG2 (PD1)	3	N/A
	PPG3 (PD1)	3	N/A
	PPG4 (PD1)	3	N/A
	PPG5 (PD1)	3	N/A
	PPG6 (PD1)	3	N/A
	PPG7 (PD2)	3	N/A
	PPG8 (PD2)	3	Red counts
	PPG9 (PD2)	3	IR counts
	PPG10 (PD2)	3	N/A
	PPG11 (PD2)	3	N/A
	PPG12 (PD2)	3	N/A

* LED assignment example is for the default configuration.

3.2 AEC Mode

Automatic Exposure Control (AEC) is Maxim's gain control algorithm that is superior to AGC. The AEC algorithm maintains the optimally maintains the best SNR range and power optimization.

The targeted SNR range is maintained regardless of skin color or ambient temperature within the limits of the LED currents configurations.

In the example below, both the AEC and SCD are enabled. The algorithm mode of operation can be selected as described in previous section. The sequence of commands is shown in **Table 8**.

Table 8. Host Commands—AEC Mode

	#	HOST COMMAND (HEX)	COMMAND DESCRIPTION	RESPONSE (HEX)
START ALGORITHM	Host initializes the MAX32664C in AEC-SCD mode using the following commands:			
	1.1	AA 02 00 (optional)	Read the operating mode	AB 00 00 application mode
	1.2	AA 50 07 00 [00000000FFD7FBD D00AB61FE]	Set SpO2 coefficients. Bracketed SpO_2 coefficients are for example only. Values used in the final form factor may be different per section 2.	AB 00
	1.3	AA 10 00 03	Set the output FIFO mode to sensor + algorithm data (streamed data will include PPG, accelerometer, and algorithm data).	AB 00
	1.4	AA 10 01 01	Set the sensor hub interrupt threshold.	AB 00
	1.5	AA 10 02 01	Set the samples report period to 40ms. Samples report rate to be one report per every sensor sample.*	AB 00
	1.6	AA 44 04 01 01 (if host accelerometer is used, CMD_DELAY = 20ms)	Enable the host-side accelerometer, if used.	AB 00
	1.7	AA 50 07 0A 00	Set the algorithm operation mode to Continuous HRM and Continuous SpO_2 or as desired. See **Table 12**.	AB 00
	1.8	AA 50 07 0B 01	Enable AEC [enabled by default].	AB 00
	1.9	AA 50 07 12 01	Enable Auto PD Current Calculation [enabled by default].	AB 00
	1.10	AA 50 07 0C 01	Enable SCD [enabled by default].	AB 00
		Optional: Any command to change the algorithm settings and configurations (**Table 12**) from default should appear here BEFORE enabling the algorithm.		
	1.11	AA 41 00 FF (optional)	Read register FF (PART_ID) of [MAX86141/MAX86140//MAXM86161]	AB 00 [25/24/36]
	1.12	AA FF 03 (optional)	Read the sensor hub version for [MAX86141/MAX86140/MAXM86146/MAXM86161] (30.x.y/30.x.y/33.x.y/32.x.y)	AB 00 [1E/1E/21/20] XX YY
	1.13	AA 41 04 0F (accel data is required from either host or KX-122, optional)	Read register 0F (WHO_AM_I) of KX-122 if connected to sensor hub	AB 00 1B
	1.14	AA 52 07 01 (for normal algorithm report, CMD_DELAY = 465ms) AA 52 07 02 (for extended algorithm report, CMD_DELAY = 465ms)	Enable the WHRM and SpO_2 algorithm. The format of the samples report is shown in **Table 9** (normal algorithm report) or **Table 10** (extended algorithm report).	AB 00
READING SAMPLES REPORT IN-	Host reads samples periodically (do not execute at a faster rate than the samples report period):			
	2.1	AA 00 00	Read sensor hub status byte: Bit 0: Sensor comm error Bits 1 and 2: Reserved Bit 3: FIFO filled to threshold (DataRdyInt) Bit 4: Output FIFO overflow (FifoOutOvrInt)	AB 00 08

			Bit 5: Input FIFO overflow (FifoInOverInt) Bit 6: Sensor hub busy (DevBusy) Bit 7: Reserved If DataRdyInt is set, proceed to next step.	
	2.2	AA 12 00	Get the number of samples (nn) in the FIFO.	AB 00 nn
	2.3	AA 12 01	Read the data stored in the FIFO; nn samples will be read. The format of the samples report is shown in **Table 9** (normal algorithm report) or **Table 10** (extended algorithm report).	AB 00 data_for_ nn_samples
STOP	Host ends the procedure:			
	3.1	AA 52 07 00 (CMD_DELAY = 120ms)	Disable the algorithm.	AB 00

* The host is required to periodically check the MAX32664C for an available samples report. The default samples report period is 40ms which means sample rate is 25Hz. Depending on the output mode, the samples report may include algorithm and/or sensor data (see **section 1.2**)

Table 9. Samples Report from Output FIFO: Normal Algorithm Report

DATA SOURCE	DATA ITEM	# OF BYTES (MSB FIRST)	DESCRIPTION
MAX86141/40, MAXM86161 PPG Data (18 Bytes)* MAXM86146 PPG Data is 36 Bytes as described in Table 7	PPG1 (PD1)	3	Green counts
	PPG2 (PD1)	3	IR LED counts
	PPG3 (PD1)	3	Red LED counts
	PPG4 (PD2)	3	Green2 counts (N/A if configured for MAX86140, MAXM86161, N/A means the data is not meaningful)
	PPG5 (PD2)	3	N/A
	PPG6 (PD2)	3	N/A
Accelerometer (6 Bytes)*	accelX	2	Two's complement. LSB = 0.001g
	accelY	2	Two's complement. LSB = 0.001g
	accelZ	2	Two's complement. LSB = 0.001g
Wearable Suite Algorithm (24 Bytes)	Op mode	1	Current operation mode: 0: Continuous HRM and Continuous SpO_2 1: Continuous HRM and One-Shot SpO_2 2: Continuous HRM 3: Sampled HRM 4: Sampled HRM and One-Shot SpO_2 5: Activity tracking 6: SpO_2 Calibration Data Collection
	HR	2	10x last calculated heart rate
	HR confidence	1	Last calculated confidence level in %
	RR	2	10x RR – inter-beat interval in ms Only shows a nonzero value when a new value is calculated.
	RR confidence	1	Calculated confidence level of RR in % Only shows a nonzero value when a new value is calculated.
	Activity class	1	Activity class: 0: Rest 1: Other 2: Walk 3: Run 4: Bike
	R	2	1000x last calculated SpO_2 R value

	SpO_2 confidence	1	Last calculated SpO_2 confidence level in %
	SpO_2	2	10x last calculated SpO_2 %
	SpO_2 % complete	1	Calculation progress in % in one-shot mode of algorithm. In continuous mode, it is reported as zero and only jumps to 100 when the SpO_2 value is updated.
	SpO_2 low signal quality flag	1	Shows the low quality of the PPG signal: 0: Good quality 1: Low quality
	SpO_2 motion flag	1	Shows excessive motion: 0: No motion 1: Excessive motion
	SpO_2 low PI flag	1	Shows the low perfusion index (PI) of the PPG signal: 0: Normal PI 1: Low PI
	SpO_2 unreliable R flag	1	Shows the reliability of R: 0: Reliable 1: Unreliable
	SpO_2 state	1	Reported status of the SpO_2 algorithm: 0: LED adjustment 1: Computation 2: Success 3: Timeout
	SCD state	1	Skin contact state: 0: Undetected 1: Off skin 2: On some subject 3: On skin
	IBI Offset	1	Reported when IBI is calculated. Defines number of samples between current algo sample and previous algo sample where IBI is calculated
	Unreliable orientation flag	1	Flag reporting not appropriate orientation of wrist for reliable SpO2 measurement
	RESERVED	2	Reserved for future use

*If the output mode includes the sensor. LED assignment example is for the default configuration.

Table 10. Samples Report from Output FIFO: Extended Algorithm Report

DATA SOURCE	DATA ITEM	# OF BYTES (MSB FIRST)	DESCRIPTION
MAX86141/40, MAXM86161 PPG Data (18 Bytes)* MAXM86146 PPG Data is 36 bytes as described in Table 7	PPG1 (PD1)	3	Green counts
	PPG2 (PD1)	3	IR LED counts
	PPG3 (PD1)	3	Red LED counts
	PPG4 (PD2)	3	Green2 counts (N/A if configured for MAX86140, MAXM86161, N/A means the data is not meaningful)
	PPG5 (PD2)	3	N/A
	PPG6 (PD2)	3	N/A
Accelerometer	accelX	2	Two's complement. LSB = 0.001g

(6 Bytes)*	accelY	2	Two's complement. LSB = 0.001g
	accelZ	2	Two's complement. LSB = 0.001g
Wearable Suite Algorithm (56 Bytes)	Op mode	1	Current operation mode: 0: Continuous HRM and Continuous SpO_2 1: Continuous HRM and One-Shot SpO_2 2: Continuous HRM 3: Sampled HRM 4: Sampled HRM and One-Shot SpO_2 5: Activity Tracking 6: SpO_2 Calibration Data Collection
	HR	2	10x last calculated heart rate
	HR confidence	1	Last calculated confidence level in %
	RR	2	10x RR – inter-beat interval in ms Only shows a nonzero value when a new value is calculated.
	RR confidence	1	Calculated confidence level of RR in % Only shows a nonzero value when a new value is calculated.
	Activity class	1	Activity class: 0: Rest 1: Other 2: Walk 3: Run 4: Bike
	Total walk steps	4	Total number of walking steps since the last reset
	Total run steps	4	Total number of running steps since the last reset
	Total energy exp in kcal	4	10x total energy expenditure since the last reset in kcal
	Total AMR in kcal	4	10x total active energy expenditure since the last reset in kcal
	Is LED current adjustment requested in first time slot	1	Flag to notify if the LED current adjustment is requested or not in the first time slot
	Adjusted LED current in first time slot	2	10x value of the adjusted LED current (mA) in the first time slot, valid only if "Is LED current adjustment requested in first time slot" flag is true
	Is LED current adjustment requested in second time slot	1	Flag to notify if the LED current adjustment is requested or not in the second time slot
	Adjusted LED current in second time slot	2	10x value of the adjusted LED current (mA) in the second time slot, valid only if the "Is LED current adjustment requested in second time slot" flag is true
	Is LED current adjustment requested in third time slot	1	Flag to notify if the LED current adjustment is requested or not in the third time slot
	Adjusted LED current in third time slot	2	10x value of the adjusted LED current (mA) in third time slot, valid only if the "Is LED current adjustment requested in third time slot" flag is true

	Is integration time adjustment requested	1	Flag to notify if the integration time adjustment is requested or not
	Requested integration time	1	Value of the requested integration time option, valid only if the “Is integration time adjustment requested” flag is true
	Is sampling rate adjustment requested	1	Flag to notify if the sampling rate adjustment is requested or not
	Requested sampling rate	1	Value of the requested sampling rate option, valid only if the “Is sampling rate adjustment requested” flag is true
	Requested sampling average	1	Sampling average required for the requested sampling rate, valid only if the “Is sampling rate adjustment requested” flag is true
	WHRM AFE controller state for HRM channels	1	State of the AFE manager (for WHRM channels)
	Is high motion for HRM	1	Flag to notify if the motion is considered high for heart-rate measurement
	SCD state	1	Skin contact state: 0: Undetected 1: Off skin 2: On some subject 3: On skin
	R	2	1000x last calculated SpO_2 R value
	SpO_2 confidence	1	Last calculated confidence level in %
	SpO_2	2	10x last calculated SpO_2 %
	SpO_2 % complete	1	Calculation progress in % in one-shot mode of algorithm. In continuous mode, it is reported as zero and only jumps to 100 when the SpO_2 value is updated.
	SpO_2 status	1	**Bit7:** SpO_2 low signal quality flag Shows the low quality of the PPG signal: **0:** Good quality **1:** Low quality **Bit6**: SpO_2 motion flag. Shows excessive motion: **0:** No motion **1:** Excessive motion **Bit5:** SpO_2 low PI flag. Shows the low perfusion index (PI) of the PPG signal: **0:** Normal PI **1:** Low PI **Bit4:** SpO_2 unreliable R flag. Shows the reliability of R: **0:** Reliable **1:** Unreliable **Bit3:** SpO_2 orientation flag. Shows how good is wrist orientation for SpO2 measurement. **0:** correct **1:** not correct **Bits 2-0:** Reported status of the SpO_2 algorithm: 0: LED adjustment 1: Computation 2: Success 3: Timeout

	SpO2 IR PI	2	1000x IR channel PI value
	SpO2 RED PI	2	1000x RED channel PI value
	IBI Offset	1	reported when IBI is calculated. Defines offset to previous algo sample IBI is calculated
	RESERVED	3	Reserved for future use

*If the output mode includes the sensors. LED assignment example is for the default configuration.

3.3 AGC Mode

In this mode, the wearable algorithm suite (SpO_2 and WHRM) is enabled and the R value, SpO_2, SpO_2 confidence level, heart rate, heart-rate confidence level, RR value, and activity class are reported. Furthermore, automatic gain control (AGC) is enabled. Because AGC is a subset of AEC functionality, to enable AGC, AEC still needs to be enabled. However, automatic calculation of target PD should be turned off, and the desired level of AGC target PD current is set by the user. The user may change the algorithm to the desired configuration mode, as shown in **Table 11**. If signal quality is low, a LowSNR flag will be set. Excessive motion is also reported with a flag. The sequence of commands is shown in

Following operation mode of the algorithm can be selected as described in **Table 11**:

0. **Continuous HRM + Continuous SpO_2:** Both heart-rate and SpO2 values are continuously measured and updated.
1. **Continuous HRM + One-Shot SpO_2:** Heart rate is continuously monitored; SpO_2 is measured once.
2. **Continuous HRM:** Only the heart-rate algorithm in continuous mode is enabled.
3. **Sampled HRM:** It measures heart rate once using the sampled HRM algorithm and then switches to activity mode.
4. **Sampled HRM + One-Shot SpO_2:** It measures heart rate and SpO_2, and then switches to activity mode.
5. **Activity Tracking ONLY:** Only shows accelerometer data. LEDs are off.
6. **SpO_2 Calibration Data Collection:** Provides data used for SpO_2 calibration data collection. Only red and IR LEDs are activated.

Table 11. Host Commands—AGC Mode

	#	HOST COMMAND (HEX)	COMMAND DESCRIPTION	RESPONSE (HEX)
START	Host initializes the MAX32664C in AGC mode using the following commands:			
	1.1	AA 50 07 00 [00000000FFD7FBDD00AB61FE]	Bracketed SpO_2 coefficients are for example only. Values used in the final form factor may be different per section 2.	AB 00
	1.2	AA 10 00 03	Set the output FIFO mode to sensor + algorithm data (streamed data will include PPG, accelerometer, and algorithm data).	AB 00
	1.3	AA 10 01 01	Set the sensor hub interrupt threshold.	AB 00
	1.4	AA 10 02 01	Set the samples report period to 40ms. Samples report rate to be one report per every sensor sample.*	AB 00
	1.5	AA 44 04 01 01 (if host accelerometer is used, CMD_DELAY = 20ms)	Enable the host-side accelerometer, if used.	AB 00
	1.6	AA 50 07 0A 00	Set the algorithm operation mode to Continuous HRM and Continuous SpO_2. See **Table 12**.	AB 00
	1.7	AA 50 07 0B 01	Enable AEC [enabled by default].	AB 00
	1.8	AA 50 07 12 00	Disable Auto PD Current Calculation.**	AB 00
	1.9	AA 50 07 0C 00	Disable SCD.	AB 00
	1.10	AA 50 07 11 00 64	Set AGC Target PD Current to 10µA.	AB 00
	1.11	Optional: Any command to change the algorithm settings and configurations (**3**) from the default should appear here BEFORE enabling the algorithm.		
	1.12	AA 52 07 01 (normal algorithm report, CMD_DELAY = 465ms) AA 52 07 02 (extended algorithm report, CMD_DELAY = 465ms)	Enable WHRM and SpO_2 algorithm. The format of samples report is shown in **Table 9** (normal algorithm report) or **Table 10** (extended algorithm report).	AB 00
READING SAMPLES IN OUTPUT FIFO	Host reads samples periodically (do not execute at a faster rate than the samples report period):			
	2.1	AA 00 00	Read the sensor hub status byte: Bit 0: Sensor comm error Bits 1 and 2: Reserved Bit 3: FIFO filled to threshold (DataRdyInt) Bit 4: Output FIFO overflow (FifoOutOvrInt) Bit 5: Input FIFO overflow (FifoInOverInt) Bit 6: Sensor hub busy (DevBusy) Bit 7: Reserved If DataRdyInt is set, proceed to the next step.	AB 00 08
	2.2	AA 12 00	Get the number of samples (nn) in the FIFO.	AB 00 nn
	2.3	AA 12 01	Read the data stored in the FIFO; nn samples will be read. The format of the samples report is shown in **Table 9** (normal algorithm report) or **Table 10** (extended algorithm report).	AB 00 data_for_nn_samples
STOP	Host ends the procedure:			
	3.1	AA 52 07 00 (CMD_DELAY = 120ms)	Disable the algorithm.	AB 00

*The host is required to periodically check the MAX32664C for an available samples report. The default samples report period is 40ms which means sample rate is 25Hz. Depending on the output mode, the samples report may include algorithm and/or sensor data (see **section 1.2**)

**After disabling the Auto PD Current Calculation, the algorithm will use the value in step 1.10 to adjust AGC.

3.4 Power Saving Mode: Reduced Samples Rate, Sampled HRM

This mode is similar to the previously described mode where the algorithm, AEC and SCD are enabled (by default). The only differences are to change the following in :

- Change the output mode in step 1.2 T**able 11** to Algorithm Only (0x02) as shown in **Table 11.**
- Change the samples report period in step 1.4 T**able 11** to 25 (0x19) or more as shown in **Table 11**. For example, set the *samples report period* to 25 which is 1s (25*40ms).
- Host reads the samples in output FIFO at a period of five times the samples report period. For example, host reads output FIFO every 5 seconds (*host reading FIFO period*)
- Choose the desired algorithm operation mode in step 1.7 T**able 11**. The Sampled HRM mode saves more power as it automatically switches to Activity Tracking mode once the heart rate is measured (~15s). In this case, the host may choose to reconfigure the operation mode (e.g., in case of motion).
- Enable the WHRM and SpO_2 algorithm in step 1.14 in normal report mode.

This configuration helps the MAX32664C to wake up less often, and I^2C communication time is minimized. The report detailed in **Table 9** will only include algorithm data. For the MAXREFDES103, a fully charged battery will last about 8 hours in this mode. It is believed that the battery of the MAXREFDES103 may be updated to a 200 mAH of size 401530 and still have some clearance for expansion. Alternatively, the host may also run the algorithm in the sample one-shot mode say every 5 minutes to conserve power.

- **401530 200maH 3.7V Lithium Ion Polymer Battery, Alibaba**

Note: This mode is not appropriate for monitoring interbeat interval (RR) value. RR and RR Confidence are reported whenever a new value is calculated by the algorithm and shown as zero for the rest of the time. Therefore, the last reported value may be missed if the samples report rate is not set to 1.

3.4.1 IBI Mode

This is a sub mode for Power saving mode. Setting report period to 0XFF activates mode. In that mode when an IBI is calculated algorithm output sample it is reported with its offset as sample count (in time scale, 40ms * sample count) to previous algorithm output sample with IBI. When no IBI is calculated it reports first sample in 1 sec window with zero IBI value. This ensures min 1Hz data reporting where offsets can be used to generate 25hz data for analytical algorithms.

3.5 SCD Only Mode

In this mode, SCD is enabled and only SCD state is reported in the algorithm samples report. Before enabling SCD Only mode, the host should specify which LED is to be used by the SCD algorithm. The sequence of commands is shown in **Table 12**.

Table 12. Host Commands: SCD Mode

	#	HOST COMMAND (HEX)	COMMAND DESCRIPTION	RESPONSE (HEX)
START ALGORITHM	Host initializes the MAX32664C in SCD mode using the following commands:			
	1.1	AA E5 LED_IDX	Sets which LED index is to be used by the SCD algorithm. (Colors are for MAXREFDES103) LED_IDX = 0 for LED1 (Green) = 1 for LED2 (IR) = 2 for LED3 (Red)	AB 00
	1.2	AA 10 00 02	Set output mode to algorithm data (SCD Only when used with 1.7).	AB 00
	1.3	AA 10 01 01	Set sensor hub interrupt threshold.	AB 00
	1.4	AA 10 02 01	Set the samples report period to 40ms. Samples report rate to be one report per every sensor sample.	AB 00
	1.5	AA 44 00 01 00	Enable AFE (e.g., MAX86141) with sensor hub samples.	AB 00
	1.6	AA 44 04 01 00 (if sensor hub accelerometer is used, CMD_DELAY = 20ms) AA 44 04 01 01 (if host accelerometer is used, CMD_DELAY = 20ms)	Enable accelerometer with sensor hub or host-side accelerometer.	AB 00
	1.7	AA 52 07 03 (CMD_DELAY = 465ms)	Enable SCD Only algorithm The format of samples report is shown in **Table 13**	AB 00
READING SAMPLES REPORT IN OUTPUT FIFO	Host reads samples periodically (do not execute at a faster rate than the samples report period):			
	2.1	AA 00 00	Read sensor hub status byte: Bit 0: Sensor comm error Bits 1 and 2: Reserved Bit 3: FIFO filled to threshold (DataRdyInt) Bit 4: Output FIFO overflow (FifoOutOvrInt) Bit 5: Input FIFO overflow (FifoInOverInt) Bit 6: Sensor hub busy (DevBusy) Bit 7: SCDSM detected skin contact If DataRdyInt is set, proceed to next step.	AB 00 08
	2.2	AA 12 00	Get the number of samples (nn) in the FIFO.	AB 00 nn
	2.3	AA 12 01	Read the data stored in the FIFO; nn samples will be read. The format of samples report is shown in **Table 13.**	AB 00 data_for_ nn_samples
STOP	Host ends the procedure:			
	3.1	AA 44 00 00 (CMD_DELAY = 250ms)	Disable AFE (e.g., MAX86141).	AB 00
	3.2	AA 44 04 00 (CMD_DELAY = 20ms)	Disable accelerometer.	AB 00
	3.3	AA 52 07 00 (CMD_DELAY = 120ms)	Disable algorithm.	AB 00

Table 13. Samples Report from Output FIFO: SCD Only Mode

DATA SOURCE	BYTE INDEX	DATA ITEM	NUMBER OF BYTES (MSB FIRST)	DESCRIPTION
SCD Algorithm	0	SCD Classifier output	1	0 = Unidentified 1 = Off Skin

				2 = On Object 3 = On Skin

4 Configurations and Settings

The settings shown in **Table 14** are available for the wearable suite (SpO_2 and WHRM) algorithm. To update the algorithm settings, make sure to send the appropriate commands BEFORE enabling the algorithm.

Table 15 lists frequently used sensor hub settings and commands. For the full list, refer to the **MAX32664 User Guide**.

4.1 LEDs and PDs Configuration

The firmware is shipped with the default LEDs and PDs configuration suited for the reference design. Alternatively, the user may change the configuration if other combinations of LEDs and PDs provide superior performance according to the hardware and optomechanical design. The following 3 steps (commands elaborated in **Table 14)** are required to change LEDs and PDs configuration:

A. *Select the LEDs and firing order (Configuration index = 0x19):* The user needs to select which LED (or LEDs) are fired in each slot. The firing starts from LEDs selected in slot 1 and continues to slot 6. For example, if LED 1 is Green, LED 2 is IR and LED 3 is red, the firing sequence 0x123000 configures the firmware to fire them in that order. PPGs are also reported in the same order.

B. *Select WHRM two input channels (Configuration index = 0x17):* The user should configure which PD in which firing slot (as defined in A) is used as each of the two inputs of the algorithm. For example, 0x0001 means PD1 and PD2 of the LED fired in slot 1 (Green as configured in A) are selected for WHRM algorithm inputs.

C. *Select SpO_2 IR and Red input channels (Configuration index = 0x18):* The user should configure which PD in which firing slot (as defined in A) is used as two inputs of the algorithm. For example, 0x1020 means PD1 of the LEDs fired in slot 2 (IR as configured in A) and slot 3 (Red as configured in A) are selected for IR and Red inputs of SpO_2 algorithm.

Examples:

1) Configuration settings for two PDs, slot 1 green, slot 2 IR, slot 3 red (default for **MAXREFDES103(MAX86141)**)
   0x19: 0x123000 [slot 1 use LED1 (green); slot 2 use LED2 (IR); slot 3 use LED3 (red)]
   0x17: 0x0001 [HR input 1 uses slot 1, PD1; HR input 2 uses slot 1, PD2]
   0x18: 0x1020 [SpO_2 IR input uses slot 2 PD1; SpO_2 red input uses slot 3 PD1]
2) Configuration settings for two PDs, slot 1 green, slot 2 Red, slot 3 IR (Host configures sensor hub for **Maslak D6W space optimized schematic, MAX86141**)
   0x19: 0x123000 [slot 1 use LED1 (green);slot 2 use LED2 (Red); slot 3 use LED3 (IR)]
   0x17: 0x0001 [HR input 1 uses slot 1, PD1; HR input 2 uses slot 1, PD2]
   0x18: 0x2010 [SpO_2 IR input uses slot 3 PD1; SpO_2 red input uses slot 2 PD1]

3) Configuration settings for one PD, slot 1 green, slot 2 IR, slot 3 red (default for **MAX86140, MAXM86161EVSYS**).
   0x19: 0x123000 [slot 1 use LED1 (green); slot 2 use LED2 (IR); slot 3 use LED3 (red)]
   0x17: 0x0073 [HR Input 1 uses Slot 1 (green), PD1; HR Input 2 not used]
   0x18: 0x1020 [SpO_2 IR input uses slot 2 PD1; SpO_2 red input uses slot 3 PD1]
4) Configuration settings for LED1 green and LED2 green fired simultaneously using slot 1; LED4 and LED5 are IR and Red and are fired using slot 2 and 3; WHRM uses PD1 and PD2 when both LED1, LED2 are fired; $WSpO_2$ uses PD2 of LED4, LED5:
   0x19: 0x745000 [slot 1 uses LED1&2 (green) together; slot 2 uses LED4 (IR); slot 3 uses LED5 (red)]
   0x17: 0x0001 [HR input 1 uses IR slot 1, PD1; HR input 2 uses slot 1, PD2]
   0x18: 0x1121 [SpO_2 IR input uses slot 2 PD2; SpO_2 red input uses slot 3 PD2]
5) Configuration for one PD, no Green LED1; slot 2 IR, slot 3 red. (Host configures **MAXREFDES103** to the settings below)
   0x19: 0x230000 [slot 1 use LED2 (IR); slot 2 use LED3 (red)]
   0x17: 0x0073 [HR input 1 uses IR slot 1, PD1; HR Input 2 not used]
   0x18: 0x0010 [SpO_2 IR input uses slot 1 PD1; SpO_2 red input uses slot 2 PD1]
6) Configuration settings for two PDs, slot 1 green2, slot 2 IR, slot 3 red (Host configures **MAXREFDES103** to the settings below)
   0x19: 0x423000 [slot 2 use LED4 (green2); slot 2 use LED2 (IR); slot 3 use LED3 (red)]
   0x17: 0x0001 [HR input 1 uses slot 1, PD1; HR input 2 uses slot 1, PD2]
   0x18: 0x1020 [SpO_2 IR input uses slot 2 PD1; SpO_2 red input uses slot 3 PD1]

Modifying the LED, PD configurations will affect which LED counts will in the description column of the PPG raw data in samples report that is described in Tables 6, 7, 9, 10.

Table 12. Algorithm Configuration and Settings Command Definition

FAMILY BYTE	ALGORITHM INDEX	CONFIGURATION INDEX	DESCRIPTION	DEFAULT VALUE (MSB FIRST)
0x50 for write 0x51 for read	0x07	0x00	SpO_2 calibration coefficients x 100,000 (12 bytes comprised of three 32-bit signed values)	0x00000000 FFD7FBDD 00AB61FE
		0x01	SpO_2 motion-detection period (unsigned 16-bit int) [sec]. The algorithm will consider the state to be motionless if the motion is below the threshold for this duration of time.	0x0002
		0x02	SpO_2 motion-detection threshold (signed 32-bit int, equal to 10^5 x milli-G threshold value; value1: MSB in 4 bytes signed int, value4: LSB in 4 bytes signed int)	0x01C9C380 (.3 G)
		0x03	SpO_2 AGC Timeout [sec]	0x3C
		0x04	SpO_2 Algorithm Timeout [sec]	0x5A
		0x05	Initial HR value	0x3C
		0x06	Height [cm] (Height = 256 x <value_MSB> + <value_LSB> cm)	0x00AF
		0x07	Weight [kg] (Weight = 256 x <value_MSB> + <value_LSB> kg)	0x004E
		0x08	Age [years] (Age = <value> years)	0x1E
		0x09	Gender	0x00

			0x00: Male 0x01: Female	
		0x0A	Algorithm operation mode (can be switched in runtime): 0x00: Continuous HRM + Continuous SpO_2. 0x01: Continuous HRM + One-Shot SpO_2 0x02: Continuous HRM 0x03: Sampled HRM 0x04: Sampled HRM + One-Shot SpO_2 0x05: Activity Tracking ONLY 0x06: SpO_2 Calibration Data Collection	0x00
		0x0B	AEC enable 0x00: Disable 0x01: Enable	0x01
		0x0C	SCD enable 0x00: Disable 0x01: Enable	0x01
		0x0D	Adjusted target PD current period in seconds. (16-bit unsigned)	0x0708
		0x0E	Motion magnitude threshold in 0.001g. (16-bit unsigned)	0x0032 (0.050 G)
		0x0F	Minimum PD current in 0.1uA. (16-bit unsigned)	0x0032
		0x10	Initial PD current in 0.1uA. (16-bit unsigned) This sets the target PD current you would like AEC algorithm to maintain initially. It does not correspond to any register. Once you set what PD current you need, algorithm will calculate the appropriate LED current.	0x0064
		0x11	Target PD current in 0.1uA. (16-bit unsigned) Works only if Auto Target PD Current Calculation is enabled.	0x0064
		0x12	Automatic calculation of target PD current: 0x00: Disable 0x01: Enable	0x01
		0x13	Minimum integration time: 0x00: 14.8µs 0x01: 29.4µs 0x02: 58.7µs 0x03: 117.3µs	0x00
		0x14	Minimum sampling rate and averaging: 0x00: 25sps, avg = 1 0x01: 50sps, avg = 2 0x02: 100sps, avg = 4 0x03: 200sps, avg = 8 0x03: 400sps, avg = 16	0x00
		0x15	Maximum integration time: 0: 14.8µs 1: 29.4µs 2: 58.7µs	0x03

			3: 117.3µs	
		0x16	Maximum sampling rate and averaging: 0: 25sps, avg = 1 1: 50sps, avg = 2 2: 100sps, avg = 4 3: 200sps, avg = 8 4: 400sps, avg = 16	0x02
		0x1A	Initial integration time: 0: 14.8µs 1: 29.4µs 2: 58.7µs 3: 117.3µs	0x03
		0x1B	Initial sampling rate and averaging: 0: 25sps, avg = 1 1: 50sps, avg = 2 2: 100sps, avg = 4 3: 200sps, avg = 8 4: 400sps, avg = 16	0x02
		0x17	Slot and PD configuration for the two HR inputs to the WHRM algorithm 0xWX, 0xYZ WX is input 1 of the WHRM algorithm. W = 0 for Slot 1 W = 1 for Slot 2 W = 2 for Slot 3 W = 3 for Slot 4 W = 4 for Slot 5 W = 5 for Slot 6 W = 7 for Slot not used X = 0 for PD1 X = 1 for PD2 X = 3 for PD not used. YZ is input 2 of the WHRM algorithm. Y = 0 for Slot 1 Y = 1 for Slot 2 Y = 2 for Slot 3 Y = 3 for Slot 4 Y = 4 for Slot 5 Y = 5 for Slot 6 Y = 7 for Slot not used Z = 0 for PD1 Z = 1 for PD2 Z = 3 for PD not used. **The LED # that is fired in each slot is defined in 0x19 command.**	0x0001 is default for MAX86141 (0x0073 is default for MAX86140, MAXM86146 MAXM86161)
		0x18	Slot and PD configuration for the IR, red inputs to the WSpO2 algorithm 0xWX, 0xYZ WX is the LED/PD used for IR for the $WSpO_2$ algorithm. W = 0 for Slot 1 W = 1 for Slot 2	0x1020 (default) (used for MAX86141/40, MAXM86161)

			W = 2 for Slot 3 W = 3 for Slot 4 W = 4 for Slot 5 W = 5 for Slot 6 W = 7 for Slot not used X = 0 for PD1 X = 1 for PD2 X = 3 for PD not used. YZ is the LED/PD used for red for the $WSpO_2$ algorithm algorithm. Y = 0 for Slot 1 Y = 1 for Slot 2 Y = 2 for Slot 3 Y = 3 for Slot 4 Y = 4 for Slot 5 Y = 5 for Slot 6 Y = 7 for Slot not used Z = 0 for PD1 Z = 1 for PD2 Z = 3 for PD not used **The LED # that is fired in each slot is defined in 0x19 command.**	(0x2111 is default for MAXM86146)
		0x19 (3x.12.x+)	Slots used for LED firing sequence UV, WX, YZ U is Slot 1 V is Slot 2 W is Slot 3 X is Slot 4 Y is Slot 5 Z is Slot 6 U, V, W, X, Y, Z are defined as: 0: No LED firing 1: LED1 firing 2: LED2 firing 3: LED3 firing 4: LED4 firing 5: LED5 firing 6: LED6 firing 7: LED1 and LED2 firing 8: LED1 and LED3 firing 9: LED2 and LED3 firing LED firing sequence in firing slots 1-3 (slot 1-6 in case of MAXM86146) PPGs are reported in the same order. **The non-firing slots should appear to the end of sequence. If a slot is not fired, the ambient light will be reported as PPG for PD1 and 2. Each LED can only be fired once (e.g. if one slot is set to LED1_AND_LED2, LED1 or LED 2,**	0x123000 (slot 1:LED1, slot 2: LED2, slot 3: LED3, slot 4-6: Not used) (default) (used for MAX86141/40, MAXM86161) (0x123456 is default for MAXM86146)

			no other firing slot can be set to LED1 or LED2). If one or more LEDs appear in firing slots, but the corresponding slot numbers are not selected in slot and PD configuration for WHRM and SpO2 (i.e. configuration index 0x17 and 0x18), they will be fired with zero current.	

Table 13. Frequently Used Sensor Hub Settings and Commands

COMMAND FAMILY BYTE	COMMAND INDEX	VALUE	DESCRIPTION
0x01 for write	0x00	0x01	Shut down the MAX32664C. Restart is only possible by power cycle or toggling RSTN.
0x10 for write 0x11 for read	0x00	One byte in the 1–3 range	Output mode: 1: Sensor only 2: Algorithm only 3: Algorithm and sensor data
0x10 for write 0x11 for read	0x02	One byte	Configures the *samples report period*. LSB is 40ms. N, where a report is generated once every N samples. For example, if the value is 1 (default), the samples report is generated every sample (40ms). If the value is 25, the samples report is generated once every 25 samples (1s).
0x11 for read (v32.9.21/22 only)	0x05	One byte	Reads the number of PPG bytes that in the samples report. (18 bytes for MAXM86161)
0x10 for write	0x03	New one-byte I^2C address	Change the default I^2C address from 0xAA. The new address will be effective only AFTER sending the response of this command to the host.
0x46 for write	0x04	0x00 followed by a 3-byte value	Enable/disable wake up on motion detection (3-byte value): - MS byte: Enable wake up on motion: 0: Disabled 1: Enabled - Middle byte: WUFC*: the time in seconds in which motion should be present before a wake up interrupt. WUFC = desired time (s) x 25 Example: For a 0.2s time, set WUFC to 5. - LS byte: ATH*: the motion level threshold ATH = Desired threshold (g) x 16 Example: For 0.5g, set ATH to 8 **To disable wake up on motion, use 0x00FFFF.**

*As defined in the KX122/LIS2DS12 data sheet.

5 Using SCD State and Motion Detection for Power Saving

For the case of when the device is not on the skin, a motion-detection-enabled state machine can be implemented in the host to reduce power consumption. In this case, the MAX32664C stays in sleep mode until a motion event is reported by the accelerometer, or an I^2C command is received from the host. Below is an example of such a state machine.

- **Active State:** Normally, the MAX32664C runs in Active state in AEC mode (**section 3.2**) or Power Saving Mode (**section 3.4**). If the SCD state in the report shows off-skin for certain time, the state machine switches to Probing state.
- **Probing State:** In this state, the host periodically turns the algorithm on and off. If an On-Skin state is reported while the algorithm is running, it will switch back to Active state and continue running the algorithm. Otherwise, after several attempts of turning the algorithm on and off (the off period can be increased after each attempt), it will switch to Off-Skin state. In Active and Probing states, the procedure to start, read report, or stop are similar to the regular sequence described in for AEC mode**,** or as highlighted for Power Saving mode.
- **Off-Skin State**: In Off-Skin state, the goal is to save more power by allowing the MAX32664C to stay in sleep mode, so long as there is no motion. Depending on the use of a host or sensor hub accelerometer (**section 1.3**), the host is required to configure the MAX32664C differently, as shown in **Table 14.**
- If the KX122/LIS2DS12 is connected to the MAX32664C as the sensor hub accelerometer, the MAX32664C must be configured to wake up on motion. In this case, the accelerometer is enabled in the interrupt mode and the motion threshold and the duration of motion is configured using the wake up on motion configuration command, as shown in **Table 14.**

  To support this feature, the interrupt line of the accelerometer is required to be connected to the MAX32664C,. Once the MAX32664C is configured, the host should start only the accelerometer. As soon as a motion interrupt occurs, the MAX32664C will wake up and read accelerometer samples and store them in the sensor hub FIFO. The host should periodically read the MAX32664C FIFO to check if any accelerometer sample has been captured since the last polling period. If there is a sample, the host should switch to Active state by first disabling the wake up on motion configuration and then restarting the algorithm.

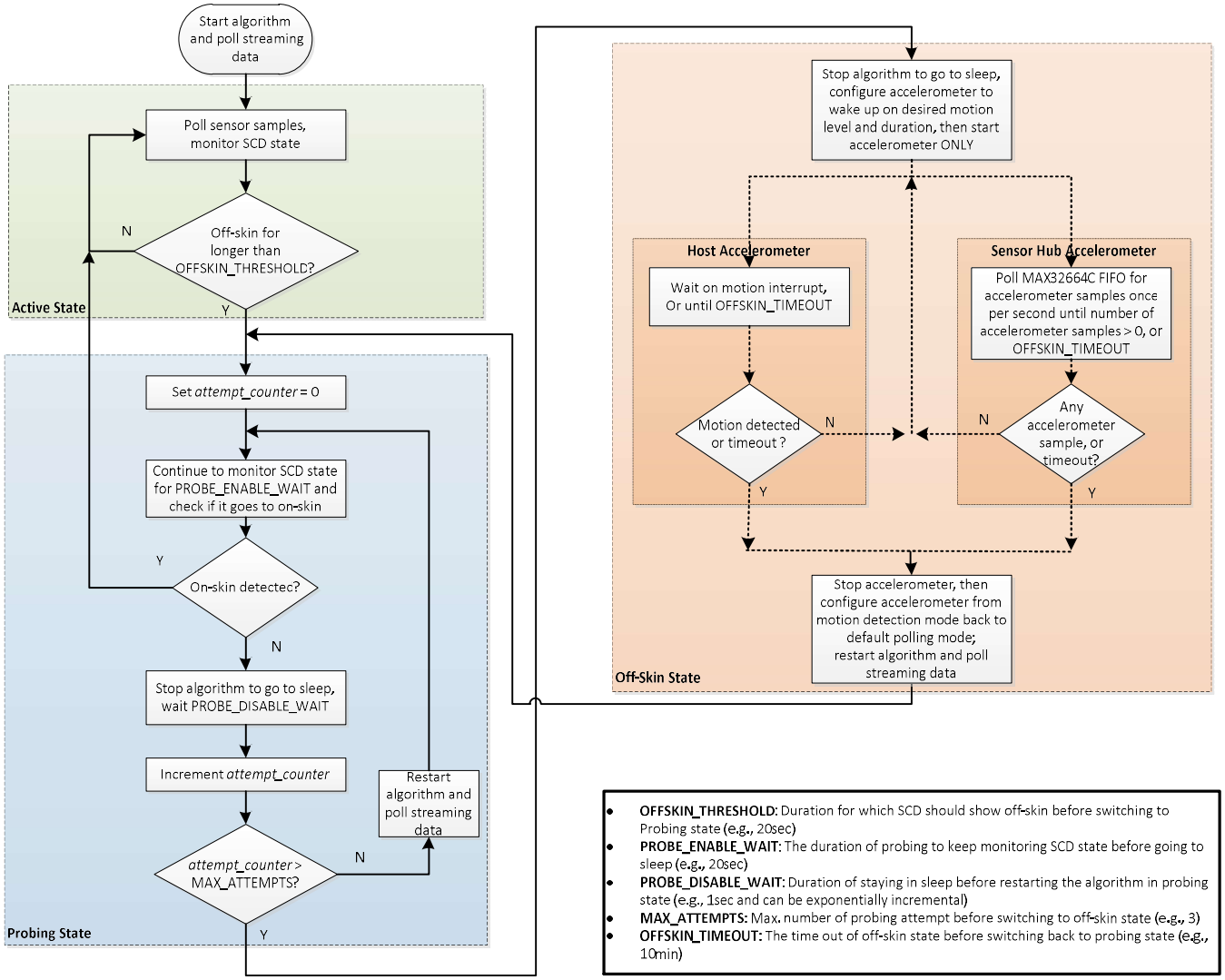

Figure 10. Example of an SCD-enabled, power saving state machine.

Table 14. Host Commands to Enable/Disable Wake Up on Motion Configuration of Sensor Hub Accelerometer for Off-Skin State

	#	HOST COMMAND (HEX)	COMMAND DESCRIPTION	RESPONSE (HEX)
START OFF-SKIN STATE	Host initializes the MAX32664C to wake up on accelerometer motion detection in order to go into off-skin state.			
	1.1	Stop the sensor, accelerometer, and algorithm if already enabled, as seen in step 3 in .		
	1.2	AA 46 04 00 01 [05] [08]	Set the sensor hub accelerator in wake up on motion mode if motion is greater than a threshold for a certain duration, for example: [05]: 0.2s motion duration, see **Table** 13. [08]: 0.5g motion threshold, see **Table** 13.	AB 00
	1.3	AA 10 00 01	Set the output FIFO mode to accelerometer data only.	AB 00
	1.4	AA 10 02 01	Set the samples report period to 40ms. Samples report rate to be one report per every sensor sample.*	AB 00
	1.5	AA 44 04 01 00 (CMD_DELAY = 20ms)	Enable the sensor-hub accelerometer. It will generate a report only if there is motion, according to step 1.4.	AB 00
READING SAMPLES REPORT IN OUTPUT FIFO	Host reads samples periodically repeatedly during off-skin state:			
	2.1	AA 00 00	Read sensor hub status byte: Bit 0: Sensor comm error Bits 1 and 2: Reserved Bit 3: FIFO filled to threshold (DataRdyInt) Bit 4: Output FIFO overflow (FifoOutOvrInt) Bit 5: Input FIFO overflow (FifoInOverInt) Bit 6: Sensor hub busy (DevBusy) Bit 7: Reserved If DataRdyInt is set, proceed to next step.	AB 00 08
	2.2	AA 12 00	Get the number of samples (nn) in the FIFO.	AB 00 nn
	2.3	AA 12 01	Read the data stored in the FIFO; nn samples will be read. The samples report will only include accelerometer data (6 bytes).	AB 00 data_for_ nn_samples
END OFF-SKIN	Host ends the wake up on motion configuration.			
	3.1	AA 44 04 00 (CMD_DELAY = 20ms)	Disable the accelerometer.	AB 00
	3.2	AA 46 04 00 00 FF FF	Disable wake up on motion. See **Table 13.**	AB 00
	3.3	Proceed to start algorithm in AEC or Power Saving mode as in **Table 8.**		

6 Host Implemented Power Savings Using Accelerometer Wake

If the host has spare GPIOs, the accel interrupt can also be connected to the host. In this case, when SCD detects "off skin", the sensor hub/AFE may be put to deep sleep/shutdown and the accel can be configured to wake on motion via register writes from the host. Alternatively MAX86141 interrupt and proximity detection may be used in a similar manner.

7 SCD State Machine for MFIO Interrupt Mode.

SCD state machine for MFIO interrupt mode (SCDSM) is MAX32664C application mode firmware algorithm which is only enabled in the MFIO interrupt mode. SCDSM is enabled via the command sequence AA BC 01 and it is disabled via the command sequence AA BB 00. SCDSM is also disabled when the algorithm is disabled or after a reset. Figure 11 is the flow chart for SCDSM.

- SCDSM is valid only when MAX32664C has direct connection to accelerometer
- SCDSM is only available in MFIO interrupt mode
- SCDSM is only available for continuous HRM modes.
- Enable SCDSM after the algorithm is enabled.

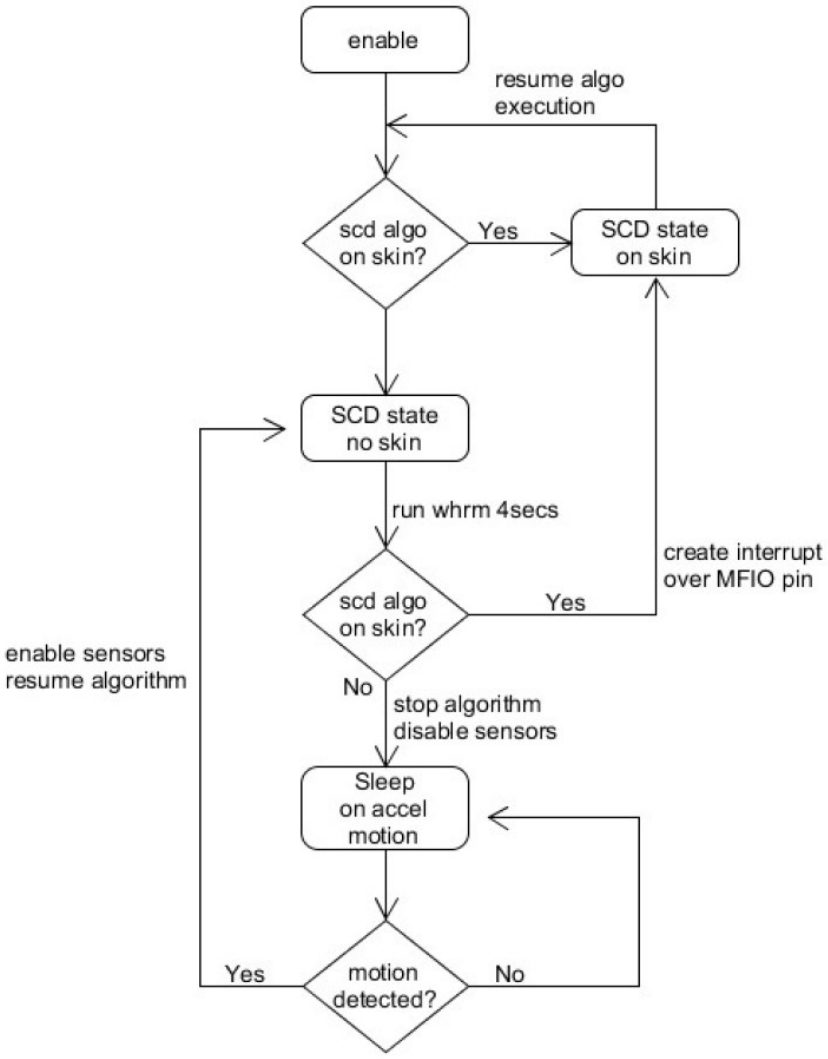

Figure 11. SCDSM operation within MAX32664C.

8 Authentication Process

Algorithms within in the Wellness Library Suite will not operate without proper authentication from the sensor hub. The authentication sequence with sensor hub is defined in **Table 17**.

Table 17. Authentication Commands

	#	HOST COMMAND (HEX)	COMMAND DESCRIPTION	RESPONSE (HEX)
AUTHENTICATE	Host executes the authentication steps below.			
	1.1	AA B3 00	Read authentication ARRAY0, 6 bytes, from sensor hub.	AB 00 <ARRAY0, six bytes>
	1.2		ARRAY0 is an input to `mxm_algosuite_manager_getauthinitials()*`, wellness library suite. `mxm_algosuite_manager_getauthinitials()*` outputs ARRAY1, 12 bytes	
	1.3	AA B5 00 <ARRAY1 twelve bytes>	Send ARRAY1, 12 bytes, to sensor hub.	AB 00
	1.4	AA B4 00	Read authentication ARRAY2, 12 bytes, from sensor hub.	AB 00 <ARRAY2, twelve bytes >
	1.5	AA B2 00	Read authentication ARRAY3, 32 bytes, from sensor hub.	AB 00 <ARRAY2, thirty-two bytes >
	1.6		To finalize authentication in wellness library suite call `mxm_algosuite_manager_authenticate()*` with the inputs ARRAY2 (12 bytes) and ARRAY3. (32 bytes)	

* Refer to Wellness Library Integration Guide distributed with MRD103 Documentation.

9 Power Consumption Estimate

The MAX32664 sensor hub family runs in two distinct operating modes. The Active mode is the mode in which the execution of the firmware occurs. The Deep Sleep mode is enabled by the sensor hub to save power when the processor is idle or there is no need for any processing. It makes all internal clocks of the MAX32664 gated off. In this mode, only RTC is enabled as a source of backup for wakeup. As soon as a sensor interrupt is received, the MAX32664 wakes up, completes the processing, and goes back to sleep. It also must wake up prior to I^2C communication by pulling MFIO low.

The tables below show the power consumption in each mode. To estimate the power consumption while running the algorithm, the percentage of time that the MAX32664 is in Active mode is measured. For this measurement, the report interval is set to 1 second and only algorithm data is reported. The estimated power consumption for a selected number of algorithm operation modes is summarized in **Table 16**.

Table 15. Comparison of Active and Deep Sleep Power—Single Supply (V_{DD} Only)

MAX32664 OPERATIONAL MODE	POWER CONSUMPTION
Active	15.5664mW
Deep Sleep	0.00756mW

Table 16. Estimated Power Consumption for the MAX32664C

WEARABLE SUITE ALGORITHM	MEASURED CPU ACTIVE TIME (AVERAGE) %	CALCULATED POWER CONSUMPTION (AVERAGE)*
		SINGLE-SUPPLY V_{DD} + INTERNAL LDO
Continuous HRM + Continuous SPO_2 mode	4.7%	0.74mW
Continuous HRM	4.3%	0.68mW
Sampled HRM	4.3%	0.68mW
Activity Tracking Only	4.2%	0.66mW

*V_{DD}: 1.8V and CPU clock: 96MHz.

10 References

MAX32664 website: MAX32664 user guides; C-keyed .msbl for MAX32664C; sample host code: MAX32664 Design Resources Website.

Application Note 7148, protocol definition between sample host (MAX32630) and PC UART/BLE: Interface Guide for MAX32664 Sensor Hub-Based Reference Design Platforms

Frequently Asked Questions: Maxim Support Center

MAXREFDES103# hardware, software files: MAXREFDES103#: Wrist-Based SpO_2, HR, and HRV Health Sensor Platform

MAXM86146EVSYS# hardware, software files: MAXM86146: Evaluation System for the MAXM86146

MAXM86161EVSYS# hardware, software files: MAXM86161: Evaluation System for the MAXM86161

Revision History

REVISION NUMBER	REVISION DATE	DESCRIPTION	PAGES CHANGED
0	06/19	Initial release	—
1	08/19	Updated for low power and host accelerometer.	All
2	08/19	Updated 1.2.2 Polling Period. Updated Table 12 for configuration index 0x15, 0x16, 0x17, and 0x18.	8, 23
3	10/19	Updated tables 4, 8, and 9 for definition of reported R value. Updated Table 11 for family bytes 0x46, 0x01, 0x03. New Table 12 to include additional commands in support of sensors like the MAXM86161 with an I^2C connection. New section 5 on SCD-enabled power saving.	All
4	1/20	Updated section 1, section 3.2, Table 7, Table 8, Table 9, Table 10, section 3.4, Table 11; added section 4.1	5, 14-18, 20-23
5	10/20	Figures 3,5,6,8,9, and 11 added. Figures 1, 2, and 7 updated. Updated all sections and Tables. Sections 3.2 and 3.3 swapped. Added section 3.5, 6, 7, 8, and 10. Table 8 and 11 swapped; Deleted Table 16. Added Tables 12, 13, and 17.	All
6	26/21	References section links updated. Table 5 updated .	18,41