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

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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/MAXM86161 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.

In order to properly capture and calculate the data, this solution requires an accelerometer. The MAX32664C firmware includes the required drivers for the Kionix® KX122 accelerometer, which is wired together with the sensor to the same SPI or I^2C port. 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.

This document provides the instructions necessary to create a solution with the MAX32664C based on the MAXREFDES102# reference design.

NOTE: The instructions in this document are compatible with the MAX32664C firmware version 30.9.x (MAX86141), or 32.9.x (MAXM86161) and later. If you are using older firmware, make sure to upgrade the firmware.

1 Architecture

A typical health-sensing design includes a host microcontroller that communicates with the MAX32664C through the I^2C 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.

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 second from when the RSTN pin was set to high, the application completes the initialization and the device is ready to accept I^2C commands.

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.

An accelerometer is mandatory for heart-rate monitoring. A KX122 accelerometer can be connected directly to the MAX32664C. The interrupt line of the accelerometer is recommended to 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 11**) prior to enabling the algorithm.

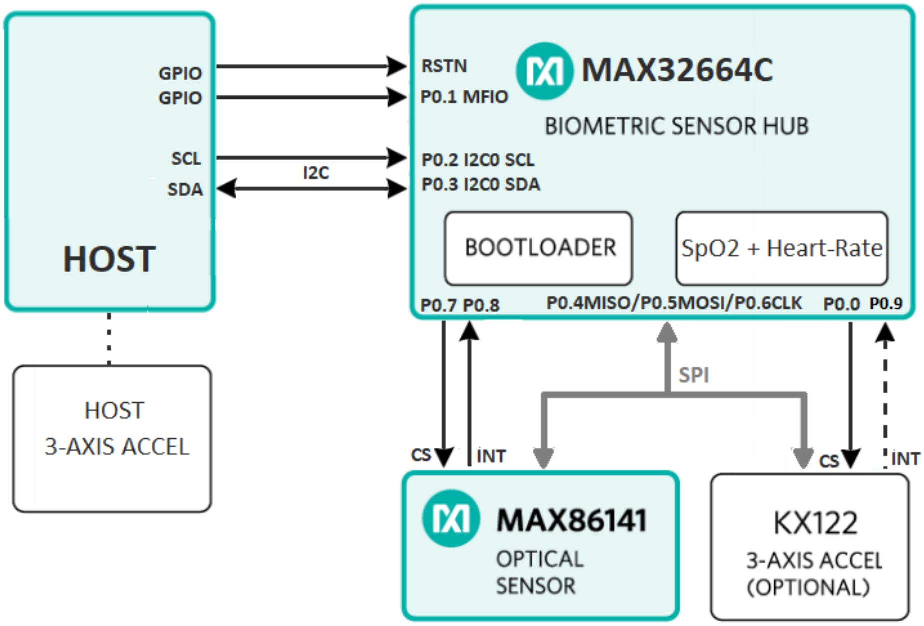

Figure 1. Architecture diagram for health-sensing applications using an SPI interface to communicate with the sensor (such as the MAX86141).

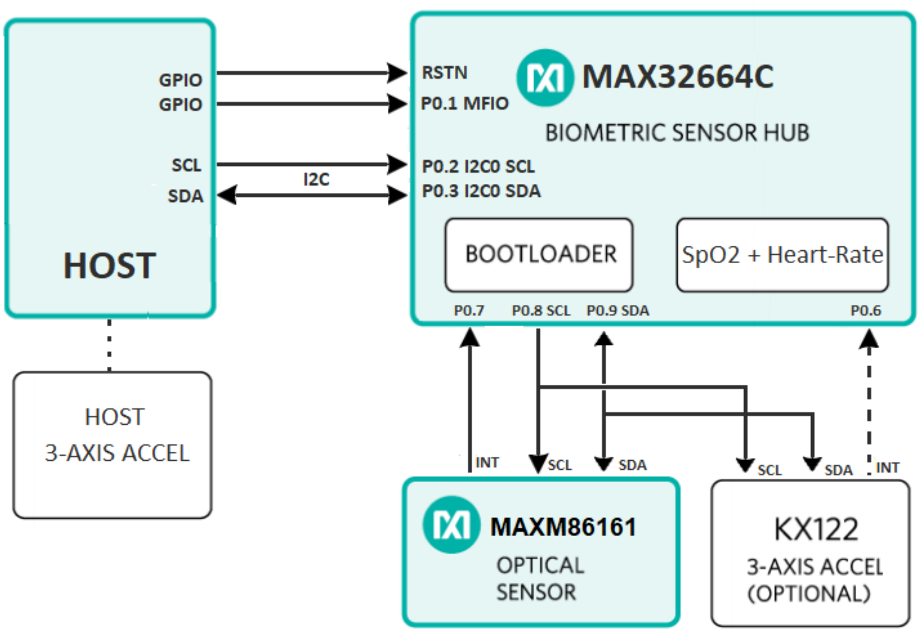

Figure 2. Architecture diagram for health-sensing applications using an I^2C interface to communicate with the sensor (such as the MAXM86161).

1.1 Communicating with the MAX32664C

A host uses the I2C bus to communicate with the MAX32664C (slave) using a series of commands. 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.

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 Command Byte was used.
0x02	This function is not implemented.
0x03	Incorrect number of bytes sent for the requested Family Byte.
0x04	Illegal configuration value was attempted to be set.
0x05	Incorrect mode specified. (In bootloader: Device is busy. Try again)
0x80	General error while receiving/flashing a page during the bootloader sequence.
0x81	Checksum error while decrypting/checking page data.
0x82	Authorization error.
0x83	Application not valid.
0xFE	Device is busy. Try again.
0xFF	Unknown error.

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.

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.

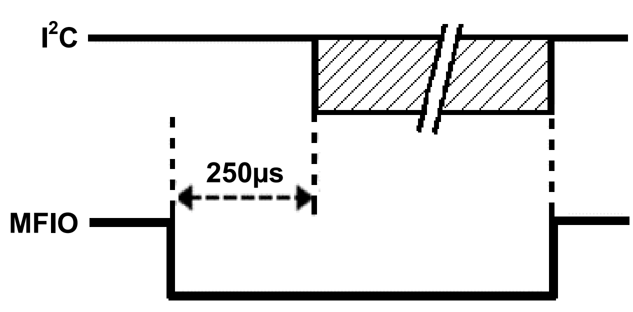

Figure 3. Host interface signaling.

This document provides examples of commands for establishing communication with the MAX32664C. For a complete list of commands and instructions for the I^2C interface, see the **MAX32664 User Guide**.

1.2 Power-Saving Considerations

1.2.1 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 report period of the algorithm to a longer time. In this case, the report is generated less frequently.

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

1.2.2 Polling Period

The host is required to regularly poll the MAX32664C to read available measurement data. The polling period depends on the rate that the MAX32664C report is generated. By reducing the report period, polling is needed less often and hence the number of wake-up events will be reduced significantly.

The polling period can be set four to five times the length of the report period to avoid FIFO overflow. In this case, several samples will be read in each polling.

By default, the report rate is set to one per sample, which translates to 40ms. In this case, a 200ms polling period is suggested.

1.2.3 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. This reduces the I^2C communication time and affects power consumption. This is performed by configuring the output mode to Algorithm Only.

This 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. In particular, 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 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 I^2C 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 as needed 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	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

2 SpO_2 Calibration

Due to variations in the physical design and optical shield of the final product, a calibration 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 with a reference SpO_2 device to determine three calibration coefficients: a, b, and c. The details of the calibration procedure are described in the **Guidelines for SpO2 Measurement Using the Maxim MAX32664 Sensor Hub** application note.

Once three 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 calibration coefficients are:

- a = -16.666666
- b = 8.333333
- c = 100

They are sent to the MAX32664C in integer format after conversion:

- A_{int32} = round (10^5 x a) = 0xFFE69196
- B_{int32} = round (10^5 x b) = 0x000CB735
- C_{int32} = round (10^5 x c) = 0x00989680

The 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 calibration process. **Table 4** shows the format of received samples. Typically, R values are needed for the calibration process, as described in the **Guidelines for SpO2 Measurement Using the Maxim MAX32664 Sensor Hub** application note.

Table 3. Host Commands—SpO_2 in Calibration Mode

	#	HOST COMMAND (HEX)	COMMAND DESCRIPTION	RESPONSE (HEX)
START ALGORITHM	Host initializes the MAX32664C in calibration mode and starts the algorithm using following commands:			
	1.1	AA 10 00 03*	Set the output 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 report rate to be one report per every sensor sample.*	AB 00
	1.4	AA 44 04 01 01 (if host accelerometer is used)	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.	AB 00
	1.6	Optional: Any command to change the algorithm settings and configurations (**Table 11**) from the default setting should appear here BEFORE enabling the algorithm.		
	1.7	AA 52 07 01	Enable the algorithm; the analog front-end (AFE) and sensor hub accelerometer will be enabled automatically.	AB 00
READING SAMPLES	Host reads samples periodically (repeated as needed):			
	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 is shown in **Table 4.**	AB 00 data_for_ nn_samples
STOP	Host ends the procedure:			
	3.1	AA 44 00** 00	Disable the AFE (e.g., the MAX86141).**	AB 00
	3.2	AA 44 04 00	Disable the accelerometer.	AB 00
	3.3	AA 52 07 00	Disable the algorithm.	AB 00

*The host is required to poll the MAX32664C for an available report. A report is available per every sensor sample. Since the effective sample rate is 25Hz, this means the report will be ready every 40ms. Depending on the output mode, the report may include algorithm and/or sensor data (see **section 1.2** and **Table 12**).
**Provided indexes are examples for sensors such as the MAX86141 or MAXM86161.

Table 4. Format of Received Samples—SpO_2 in Calibration Mode

DATA SOURCE	BYTE INDEX	DATA ITEM	# OF BYTES (MSB FIRST)	DESCRIPTION
MAX86141 PPG Data (18 Bytes)*	0	PPG1	3	N/A
	3	PPG2	3	N/A
	6	PPG3	3	N/A
	9	PPG4	3	N/A
	12	PPG5	3	IR LED counter
	15	PPG6	3	Red LED counter
Accelerometer (6 Bytes)*	18	accelX	2	Two's complement. LSB = 0.001g
	20	accelY	2	Two's complement. LSB = 0.001g
	22	accelZ	2	Two's complement. LSB = 0.001g
Wearable Suite Algorithm (20 Bytes)**	24	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 4: Sampled HRM and One-Shot SpO_2 5: Activity Tracking 6: SpO_2 Calibration
	25	HR	2	N/A
	27	HR confidence	1	N/A
	28	RR	2	N/A
	30	RR confidence	1	N/A
	31	Activity class	1	N/A
	32	R	2	1000x calculated R value
	34	SpO_2 confidence	1	Calculated confidence in %
	35	SpO_2	2	N/A
	37	SpO_2 % complete	1	N/A
	38	SpO_2 low signal quality flag	1	Shows the low quality of the PPG signal: 0: Good quality 1: Low quality
	39	SpO_2 motion flag	1	Shows excessive motion: 0: No motion 1: Excessive motion
	40	SpO_2 low PI flag	1	Shows the low perfusion index (PI) of the PPG signal: 0: Normal PI 1: Low PI
	41	SpO_2 unreliable R flag	1	Shows the reliability of R: 0: Reliable 1: Unreliable
	42	SpO_2 state	1	Reported status of the SpO_2 algorithm: 0: LED adjustment 1: Computation 2: Success 3: Timeout
	43	Skin contact detector (SCD) state	1	Skin contact state: 0: Undetected 1: Off skin 2: On some subject 3: On skin

*If the output mode includes the sensor.
**If the output mode includes the algorithm.

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

3.1 Raw Data Collection 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.

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 mode to Sensor 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) AA 44 04** 01 01 (if host accelerometer is used)	Enable the accelerometer.	AB 00
	1.4	AA 44 00** 01 00	Enable AFE (e.g., MAX86141).**	AB 00
	Wait for 100ms before sending the next command. 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 Integration time: 117µs ADCs 1 and 2 range: 32µA LEDs 1, 2, and 3 full range: 124mA			
	1.10	AA 40 00 12 18	Set the sample rate of the MAX86141 to 100Hz with 1-sample averaging.	AB 00
	1.11	AA 40 00 23 7F	Set the MAX86141 LED1 current to half of full scale. Reduce [7F] if the signal is saturated.	AB 00
	1.12	AA 40 00 24 7F	Set the MAX86141 LED2 current to half of full scale. Reduce [7F] if the signal is saturated.	AB 00
	1.13	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	Host reads samples periodically (repeated as needed):			
	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 (24 bytes each) will be included. The format of samples is shown in **Table 6**.	AB 00 data_for_ nn_samples
STOP	Host ends the procedure:			
	3.1	AA 44 00** 00	Disable the AFE (e.g., the MAX86141).**	AB 00
	3.2	AA 44 04 00	Disable the accelerometer.	AB 00

*The host is required to poll the MAX32664C for an available report. A report is available per every sensor sample.
**Provided indexes are examples for sensors such as the MAX86141 or MAXM86161.

Table 6. Format of Received Samples—Raw Data Mode

DATA SOURCE	BYTE INDEX	DATA ITEM	# OF BYTES (MSB FIRST)	DESCRIPTION
MAX86141 PPG Data (18 Bytes)	0	PPG1	3	Green counter
	3	PPG2	3	N/A
	6	PPG3	3	N/A
	9	PPG4	3	Green2 counter
	12	PPG5	3	IR counter
	15	PPG6	3	Red counter
Accelerometer (6 Bytes)	18	accelX	2	Two's complement. LSB = 0.001g
	20	accelY	2	Two's complement. LSB = 0.001g
	22	accelZ	2	Two's complement. LSB = 0.001g

3.2 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 **Table 7**.

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:** Used for SpO_2 calibration. Only red and IR LEDs are activated, and R value is being measured and updated to be used in the calibration procedure.

Table 7. 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 [FFE69196000CB735 00989680]*	This step is ONLY needed if non-default calibration coefficients are used to write the SpO_2 calibration coefficients as derived according to **section 2**. Provided coefficients are for example only.*	AB 00
	1.2	AA 10 00 03**	Set the output 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 report rate to be one report per every sensor sample.**	AB 00
	1.5	AA 44 04 01 01 (if host accelerometer is used)	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 or as needed. See **Table 11**.	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 or as needed.	AB 00
	1.11	Optional: Any command to change the algorithm settings and configurations (**Table 11**) from the default should appear here BEFORE enabling the algorithm.		
	1.12	AA 52 07 01 (normal algorithm report) AA 52 07 02 (extended algorithm report)	Enable WHRM and SpO_2 algorithm. The format of samples is shown in **Table 8** (normal algorithm report) or **Table 9** (extended algorithm report).	AB 00
READING SAMPLES		Host reads samples periodically (repeated as needed):		
	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 is shown in **Table 8** (normal algorithm report) or **Table 9** (extended algorithm report).	AB 00 data_for_ nn_samples
STOP		Host ends the procedure:		
	3.1	AA 52 07 00	Disable the algorithm.	AB 00

*Provided 12-byte calibration data is an example. Actual data should be derived as described in **section 2**.
The host is required to poll the MAX32664C for an available report. A report is available per every sensor sample. Since the effective sample rate is 25Hz, this means the report will be ready every 40ms. Depending on the output mode, the report may include algorithm and/or sensor data (see **section 1.2 and **Table 12**).
***Provided indexes are examples for sensors such as the MAX86141 or MAXM86161.
****After disabling the Auto PD Current Calculation, the algorithm will use the value in step 1.10 to adjust AGC.

Table 8. Format of Received Samples—Normal Algorithm Report

DATA SOURCE	BYTE INDEX	DATA ITEM	# OF BYTES (MSB FIRST)	DESCRIPTION
MAX86141 PPG Data (18 Bytes)*	0	PPG1	3	Green counter
	3	PPG2	3	N/A
	6	PPG3	3	N/A
	9	PPG4	3	Green2 counter
	12	PPG5	3	IR LED counter
	15	PPG6	3	Red LED counter
Accelerometer (6 Bytes)*	18	accelX	2	Two's complement. LSB = 0.001g
	20	accelY	2	Two's complement. LSB = 0.001g
	22	accelZ	2	Two's complement. LSB = 0.001g
Wearable Suite Algorithm (20 Bytes)**	24	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
	25	HR	2	10x last calculated heart rate
	27	HR confidence	1	Last calculated confidence level in %
	28	RR	2	10x RR – interbeat interval in ms Only shows a nonzero value when a new value is calculated.
	30	RR confidence	1	Calculated confidence level of RR in % Only shows a nonzero value when a new value is calculated.
	31	Activity class	1	Activity class: 0: Rest 1: Other 2: Walk 3: Run 4: Bike
	32	R	2	1000x last calculated SpO_2 R value
	34	SpO_2 confidence	1	Last calculated SpO_2 confidence level in %
	35	SpO_2	2	10x last calculated SpO_2 %
	37	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.
	38	SpO_2 low signal quality flag	1	Shows the low quality of the PPG signal: 0: Good quality 1: Low quality
	39	SpO_2 motion flag	1	Shows excessive motion: 0: No motion 1: Excessive motion
	40	SpO_2 low PI flag	1	Shows the low perfusion index (PI) of the PPG signal: 0: Normal PI 1: Low PI
	41	SpO_2 unreliable R flag	1	Shows the reliability of R: 0: Reliable 1: Unreliable
	42	SpO_2 state	1	Reported status of the SpO_2 algorithm: 0: LED adjustment

				1: Computation 2: Success 3: Timeout
	43	SCD state	1	Skin contact state: 0: Undetected 1: Off skin 2: On some subject 3: On skin

*If the output mode includes the sensor.
**If the output mode includes the algorithm.

Table 9. Format of Received Samples—Extended Algorithm Report

DATA SOURCE	BYTE INDEX	DATA ITEM	# OF BYTES (MSB FIRST)	DESCRIPTION
MAX86141 PPG Data (18 Bytes)*	0	PPG1	3	Green counter
	3	PPG2	3	N/A
	6	PPG3	3	N/A
	9	PPG4	3	Green2 counter
	12	PPG5	3	IR LED counter
	15	PPG6	3	Red LED counter
Accelerometer (6 Bytes)*	18	accelX	2	Two's complement. LSB = 0.001g
	20	accelY	2	Two's complement. LSB = 0.001g
	22	accelZ	2	Two's complement. LSB = 0.001g
Wearable Suite Algorithm (52 Bytes)**	24	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
	25	HR	2	10x last calculated heart rate
	27	HR confidence	1	Last calculated confidence level in %
	28	RR	2	10x RR – inter-beat interval in ms Only shows a nonzero value when a new value is calculated.
	30	RR confidence	1	Calculated confidence level of RR in % Only shows a nonzero value when a new value is calculated.
	31	Activity class	1	Activity class: 0: Rest 1: Other 2: Walk 3: Run 4: Bike
	32	Total walk steps	4	Total number of walking steps since the last reset
	36	Total run steps	4	Total number of running steps since the last reset
	40	Total energy exp in kcal	4	10x total energy expenditure since the last reset in kcal
	44	Total AMR in kcal	4	10x total active energy expenditure since the last reset in kcal
	48	Is LED current adjustment	1	Flag to notify if the LED current adjustment is requested or not in the first time slot

		requested in first time slot		
	49	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
	51	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
	52	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
	54	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
	55	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
	57	Is integration time adjustment requested	1	Flag to notify if the integration time adjustment is requested or not
	58	Requested integration time	1	Value of the requested integration time option, valid only if the "Is integration time adjustment requested" flag is true
	59	Is sampling rate adjustment requested	1	Flag to notify if the sampling rate adjustment is requested or not
	60	Requested sampling rate	1	Value of the requested sampling rate option, valid only if the "Is sampling rate adjustment requested" flag is true
	61	Requested sampling average	1	Sampling average required for the requested sampling rate, valid only if the "Is sampling rate adjustment requested" flag is true
	62	WHRM AFE controller state for HRM channels	1	State of the AFE manager (for WHRM channels)
	63	Is high motion for HRM	1	Flag to notify if the motion is considered high for heart-rate measurement
	64	SCD state	1	Skin contact state: 0: Undetected 1: Off skin 2: On some subject 3: On skin
	65	R	2	1000x last calculated SpO_2 R value
	67	SpO_2 confidence	1	Last calculated confidence level in %
	68	SpO_2	2	10x last calculated SpO_2 %
	70	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.

	71	SpO_2 low signal quality flag	1	Shows the low quality of the PPG signal: 0: Good quality 1: Low quality
	72	SpO_2 motion flag	1	Shows excessive motion: 0: No motion 1: Excessive motion
	73	SpO_2 low PI flag	1	Shows the low perfusion index (PI) of the PPG signal: 0: Normal PI 1: Low PI
	74	SpO_2 unreliable R flag	1	Shows the reliability of R: 0: Reliable 1: Unreliable
	75	Status	1	Reported status of the SpO_2 algorithm: 0: LED adjustment 1: Computation 2: Success 3: Timeout

*If the output mode includes the sensors.
**If the output mode includes the algorithm.

3.3 AEC Mode

In this mode, the algorithm and AEC and SCD are all enabled (by default). The algorithm mode of operation can be selected as described in previous section. The sequence of commands is shown in **Table 10**.

Table 10. 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 50 07 00 [FFE69196000CB73500989680]*	This step is ONLY needed if non-default calibration coefficients are used to write the SpO_2 calibration coefficients as derived according to **section 2**. Provided coefficients are for example only.*	AB 00
	1.2	AA 10 00 03**	Set the output 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 report rate to be one report per every sensor sample.**	AB 00
	1.5	AA 44 04 01 01 (if host accelerometer is used)	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 or as desired. See **Table 11**.	AB 00
	1.7	AA 50 07 0B 01	Enable AEC [enabled by default].	AB 00
	1.8	AA 50 07 12 01	Enable Auto PD Current Calculation [enabled by default].	AB 00
	1.9	AA 50 07 0C 01	Enable SCD [enabled by default].	AB 00
	1.10	Optional: Any command to change the algorithm settings and configurations (**Table 11**) from default should appear here BEFORE enabling the algorithm.		
	1.11	AA 52 07 01 (for normal algorithm report) AA 52 07 02 (for extended algorithm report)	Enable the WHRM and SpO_2 algorithm. The format of the samples is shown in **Table 8** (normal algorithm report) or **Table 9** (extended algorithm report).	AB 00
READING SAMPLES	Host reads samples periodically (repeated as needed):			
	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 format of the samples is shown in **Table 8** (normal algorithm report) or **Table 9** (extended algorithm report).	AB 00 data_for_nn_samples
STOP	Host ends the procedure:			
	3.1	AA 52 07 00	Disable the algorithm.	AB 00

*The provided 12-byte calibration data is an example. The actual data should be derived as described in **section 2**.
The host is required to poll the MAX32664C for an available report. A report is available per every sensor sample. Since the effective sample rate is 25Hz, this means the report will be ready every 40ms. Depending on the output mode, the report may include algorithm and/or sensor data (see **section 1.2 and **Table 12**).
***Provided indexes are examples for sensors such as the MAX86141 or MAXM86161.

3.4 Power-Saving Mode

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 **Table 10**:

- Change the output mode in step 1.2 to Algorithm Only (0x02) as shown in **Table 12**.
- Change the report rate in step 1.4 to 25 (0x19) or more as shown in **Table 12**.
- Adjust the host polling period according to the report rate.
- Choose the desired algorithm operation mode in step 1.7. The Sampled HRM mode saves more power as it automatically switches to Activity Tracking mode once the heart rate is measured. In this case, the host may choose to reconfigure the operation mode as needed (e.g., in case of motion).
- Enable the WHRM and SpO_2 algorithm in step 1.11 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 8** will only include algorithm data.

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 report rate is not set to 1.

4 Configurations and Settings

The settings shown in **Table 11** 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 12 lists a number of frequently used sensor hub settings and commands. For the full list, refer to the **MAX32664 User Guide**.

Table 11. Algorithm Configuration and Settings

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)	0xFFE69196 000CB735 00989680
		0x01	SpO_2 motion-detection period (unsigned 16-bit int) [sec]	0x0002
		0x02	SpO_2 motion-detection threshold (signed 32-bit int, equal to 10^5 x actual float threshold value; value1: MSB in 4 bytes signed int, value4: LSB in 4 bytes signed int)	0x01C9C380
		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: Male 0x01: Female	0x00
		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	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
		0x0F	Minimum PD current in 0.1mA. (16-bit unsigned)	0x0032
		0x10	Initial PD current in 0.1mA. (16-bit unsigned)	0x0064
		0x11	Target PD current in 0.1mA. (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 3: 117.3μs	0x03
		0x16	Maximum sampling rate and averaging: 0: 25sps, avg = 1 1: 50sps, avg = 2 2: 100sps, avg = 4	0x02

			3: 200sps, avg = 8 4: 400sps, avg = 16	
		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	LED PD configuration for 2 channels of WHRM (MS byte channel 1, and LS byte channel 2): For each channel, 4-bit MSB is LED # and 4-bit LSB is PD #: - LED #: 0–2 for LED1–LED3; 7: LED not used - PD #: 0–1 for PD1–PD2; 3: PD not used **For one channel case, use appropriate settings for channel 1 and set LED and PD for channel 2 as unused (0x73).**	0x0001
		0x18	LED PD configuration for SpO_2 (MS byte: IR channel; LS byte: red channel): For each red or IR channel, 4-bit MSB is LED # and 4-bit LSB is PD #: - LED #: 0–2 for LED1–LED3; 7: LED not used - PD #: 0–1 for PD1–PD2; 3: PD not used	0x1020

Table 12. 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 report period per number of samples. For example, if the value is 1 (default), the report is generated every sample (40ms). If the value is 25, the report is generated once every 25 samples (1s).
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 data sheet.

5 Using SCD State and Motion Detection for Power Saving

In order to further reduce power consumption when the device is not placed on the skin, a motion-detection-enabled state machine can be implemented in the host. 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. **Figure 4** demonstrates an example of such a state machine.

- **Active State:** Normally, the MAX32664C runs in Active state in AEC mode (**section 3.3**) 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 **Table 10** 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 **Figure 4.**

  If the KX122 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 13**. Note that the interrupt line of the accelerometer is required to be connected to the MAX32664C as shown in **Figure 1**, to support this feature. 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.

  In case of using a host-side accelerometer, the implementation exclusively relies on the host. In this case, the host accelerometer should be configured to interrupt on a certain level of motion for certain duration. Refer to the data sheet of the desired accelerometer for such a setting. The host can stop the MAX32664C when going to this mode and restart it as motion is detected using the same procedure shown in **Table 10.**

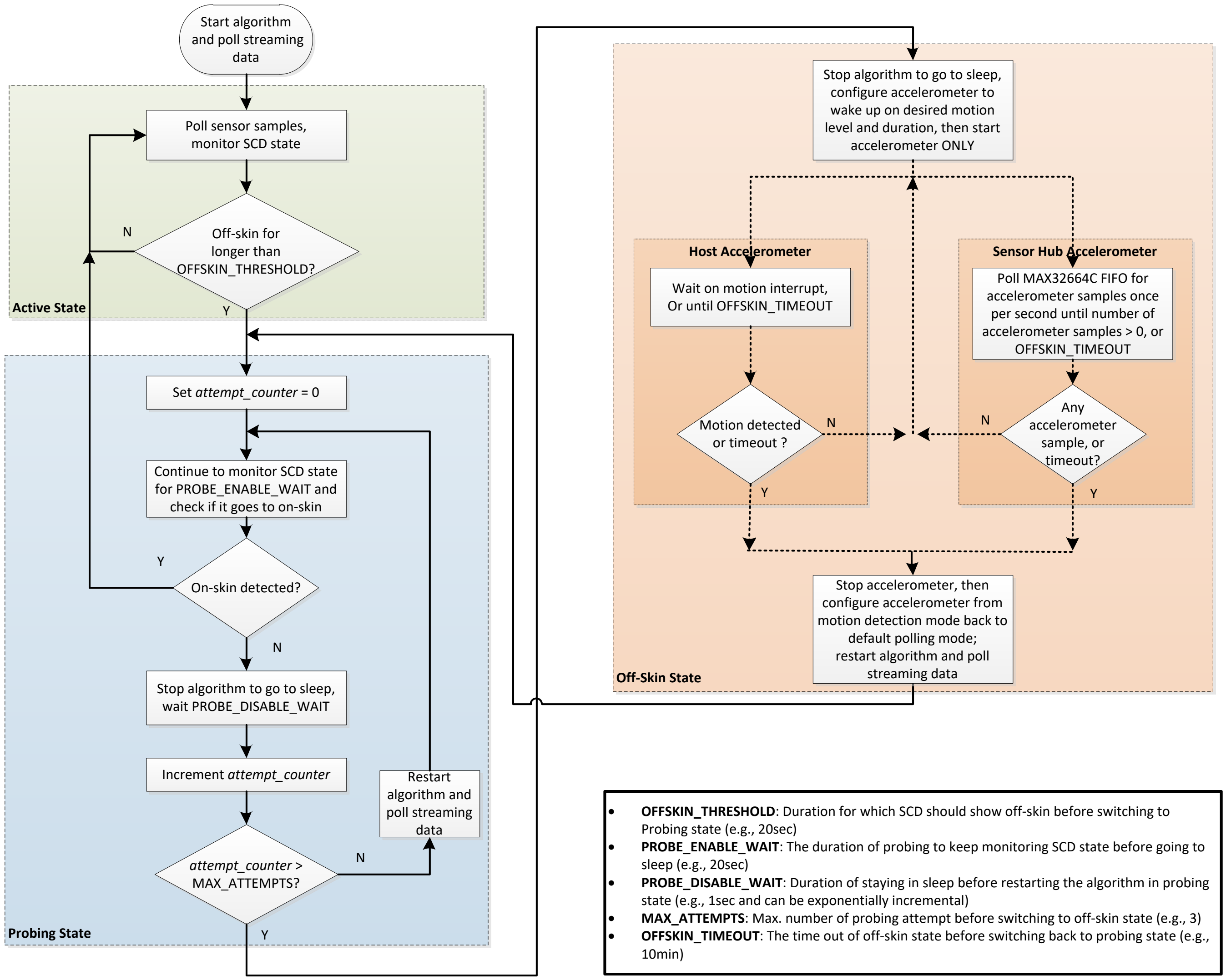

Figure 4. Example of an SCD-enabled, power-saving state machine.

Table 13. 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 MAX79356C to wake up on KX122 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 **Table 10**.		
	1.2	AA 46 04 00 01 [05][1] [08][2]	Set the sensor hub accelerator in wake up on motion mode if motion is greater than a threshold for a certain duration, for example: [1][05]: 0.2s motion duration, see **Table 12**. [2][08]: 0.5g motion threshold, see **Table 12**.	AB 00
	1.3	AA 10 00 01	Set the output mode to accelerometer only.	AB 00
	1.4	AA 10 02 01	Set the report rate to be one report per every sensor sample.	AB 00
	1.5	AA 44 04 01 00	Enable the sensor-hub accelerometer. It will generate a report only if there is motion, according to step 1.4.	AB 00
POLL	Host reads samples periodically (repeated as needed) during off-skin state:			
	2.1	Read samples as described in steps 2 in **Table 10.** Samples will only include accelerometer data (6 bytes) as shown in **Table 9**.		
END OFF-SKIN	Host ends the wake up on motion configuration.			
	3.1	AA 44 04 00	Disable the accelerometer.	AB 00
	3.2	AA 46 04 00 00 FF FF	Disable wake up on motion. See **Table 12.**	AB 00
	3.3	Proceed to start algorithm in AEC or Power Saving mode as in **Table 10.**		

6 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, as described in **section 1.1**.

Table 8 and **Table 15** 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, as described in **section 3.4**. The estimated power consumption for a selected number of algorithm operation modes is summarized in **Table 16**.

Table 14. 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 15. Comparison of Active and Deep Sleep Power—Dual Supply (V_{DD} and V_{CORE})

MAX32664 OPERATIONAL MODE	POWER CONSUMPTION
Active	9.64106mW
Deep Sleep	0.01383mW

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	DUAL-SUPPLY V_{DD} + V_{CORE}
Continuous HRM + Continuous SPO_2 mode	4.7%	0.74mW	0.47mW
Continuous HRM	4.3%	0.68mW	0.43mW
Sampled HRM	4.3%	0.68mW	0.43mW
Activity Tracking Only	4.2%	0.66mW	0.42mW

*V_{DD}: 1.8V, V_{CORE}: 1.1V, and CPU clock: 96MHz.

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