Optical Heart Rate Measurement at the Earbud

Christoph Kämmerer
Field Applications Engineer, Analog Devices, Inc.

Advancements in sensor technology have transformed how and where people diagnose their vitals and health. Portable, noninvasive measurement techniques permit fast and simple measurements that can be performed while we go about our daily lives. But although this diagnostic technology has become very popular in the fitness industry, there were limits to its accuracy that we have only recently overcome.

Fitness trackers enable the measurement of heart rate and other vitals that can help users set exercise routines. They often have built-in motion sensors that can detect movement patterns to help distinguish between walking, running, and swimming, which allows them to work as pedometers. For comfort and convenience in everyday life, the measurements are typically made on the wrist because the sensors can be housed in accessories such as watches, jewelry, and wrist straps. However, this position is not optimal for measurement quality. Heart rate detection is limited by motion artifacts and difficult because relatively high muscle mass limits access to arteries.

In contrast, the ear is much more suitable for optical heart rate measurements. The earlobe is already used by medical experts for the measurement of blood oxygen levels. However, up to now, this has not been fully exploited on a consumer level because ear-based measurement devices have limited space and require a large battery due to very high power consumption. But with the introduction of highly integrated, lower power consumption chips, Analog Devices has developed a solution that overcomes these problems. It is now possible to integrate a functioning vital sign measuring device into typical in-ear headphones. The improved responsivity opens up complete new fields of applications and possibilities. This system is described and evaluated in this article.

The underlying measurement method is of an optical nature. Short pulse signals from up to three LEDs are used for the measurement. The LED current can be up to 370 mA at a minimum pulse width of 1 µs. The optimum wavelength of the LED is selected according to the measuring position and the measurement method. Whereas only superficial arteries can be measured on the wrist and hence green light is selected here, infrared light and a greater penetration depth as well as a higher SNR can be used on the ear. A photodiode, whose detector area is directly related to its responsivity, measures the reflected light. It thus measures both the signal and the background noise. The downstream analog front end provides for a higher SNR. It functions as a signal filter and converts the detected current into a voltage and thus into a digital format. The algorithm includes, besides the reflection measurement, a correction for filtering out motion artifacts by means of an accelerometer.

The components of the measuring system are as follows. The ADPD144RI chip from Analog Devices is used as an analog front end, which additionally integrates the photodiode and the LEDs. The measurement is supported by a triple-axis accelerometer, which is used not only for the recognition of step patterns and motions but also for artifact removal. The ADXL362 model was used in the present example. The entire process is controlled by the ADuCM3029 microcontroller, which serves as an interface for the various sensors and contains the algorithm.

Figure 1. Test system with an integrated optical sensor and accelerometer with scale shown for comparison.

Figure 1 shows the test system, which houses both the optical sensor and the accelerometer in regular earbuds. Care was taken to limit the ADC sampling rate to 100 Hz and minimize the LED intensity to keep the power consumption as low as possible.

For system characterization, five different scenarios were considered for different movement patterns. Only the optical signal was used for evaluation. This allows for the evaluation of what scenarios pulse measurement inaccuracies appear in and when accelerometer data is required for increasing the accuracy of the pulse measurement. The scenarios cover the following movement sequences:

▶ Standing still
▶ Standing still and chewing
▶ Working at a desk
▶ Walking
▶ Running and jumping

Test Scenario 1

Standing Still

Figure 2 shows the spectrum of raw data with the amplitude plotted against the sampling rate. The pulse beats can be identified over time by the peak values. Without movement, the signal is very clear and the heart rate can be determined via the peak position and the known sampling rate.
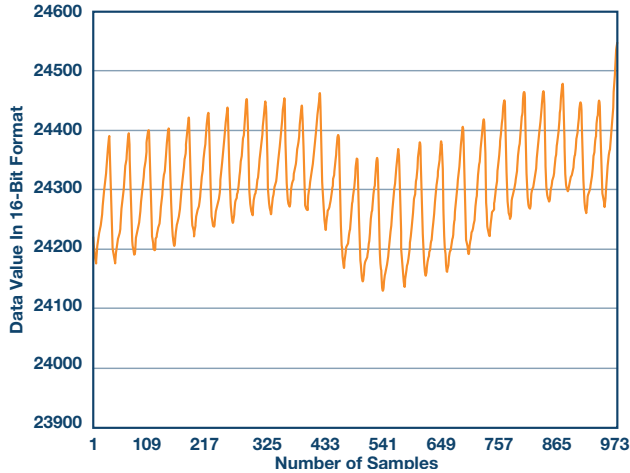

Figure 2. Measuring the amplitude oversampling rate provides information about the heart rate.

The optical sensor records heart rates in two LED colors—infrared and red—with four channels each. In this way, differentiation can be made between the measurements with the two different color channels and the more robust variant can be selected. The signals of the various channels are shown in Figure 3A. With six channels, a clearly defined signal can be identified, while two channels are saturated. To achieve a stronger and more robust signal, the algorithm adds the respective unsaturated channels and calculates the heart rate. Figure 3B shows the heart rate for the red channel (top) and the infrared channel (bottom) and simultaneously indicates the confidence level for the measurement by means of the color scale. Multiples of the heart rate are also given, whereby the original signal (dashed line) can be distinguished by the sampling rate and the confidence indication.

In summary, with no motion, the signal is strong and has no obstructing noise, so the algorithm can determine the rate with high confidence. The signal from the infrared channel is stronger than that from the red one.

Test Scenario 2

Standing Still and Chewing

In Scenario 2, additional chewing motions are introduced. The recorded spectra are shown in Figure 4. Unlike in Test Scenario 1, motion artifacts can be clearly seen, which are reflected in the signal as jumps. They also become clear in the sum of the channels, which no longer exhibit such clearly differentiated rates. Nevertheless, the algorithm is capable of correctly determining the heart rate with a high confidence without the additional help of motion sensors. Interestingly, the infrared signal strength is once again greater than that of the red channel.
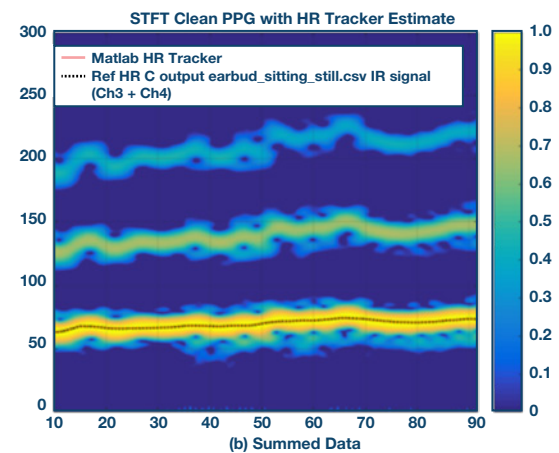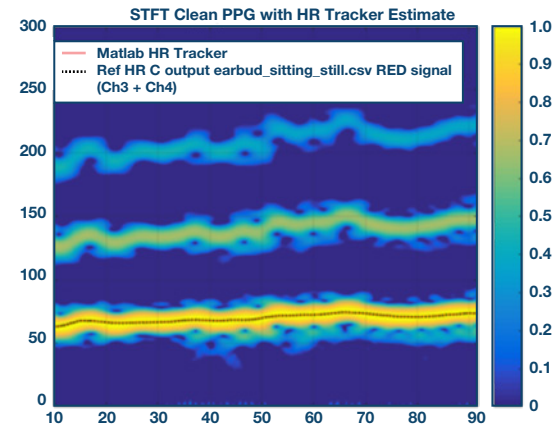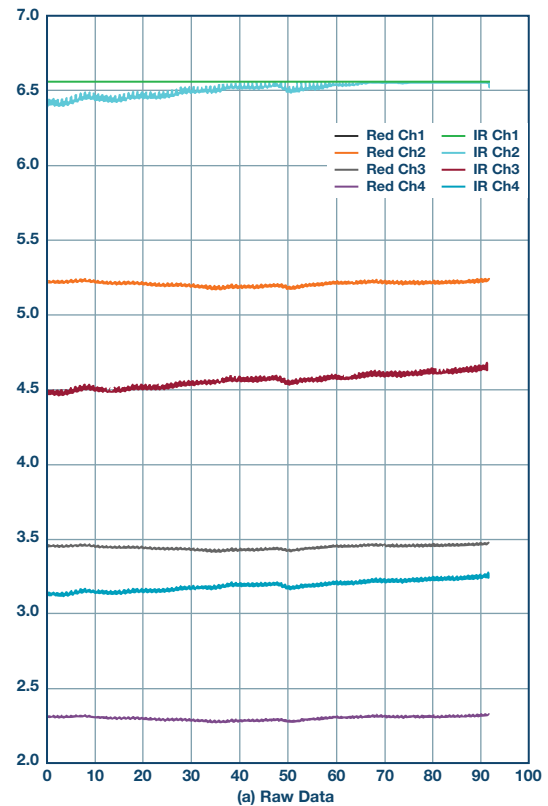

Figure 3. The red region (top) shows a four-channel measurement for standing still, while the infrared region (bottom) shows raw and summed data. The heart rate (black line) can be determined from the summed data by the algorithm, with the color scale indicating the confidence level.
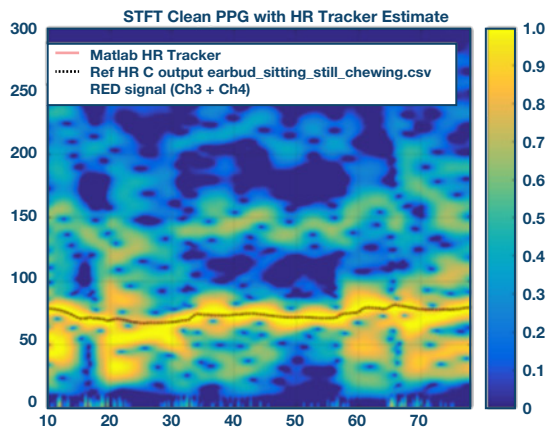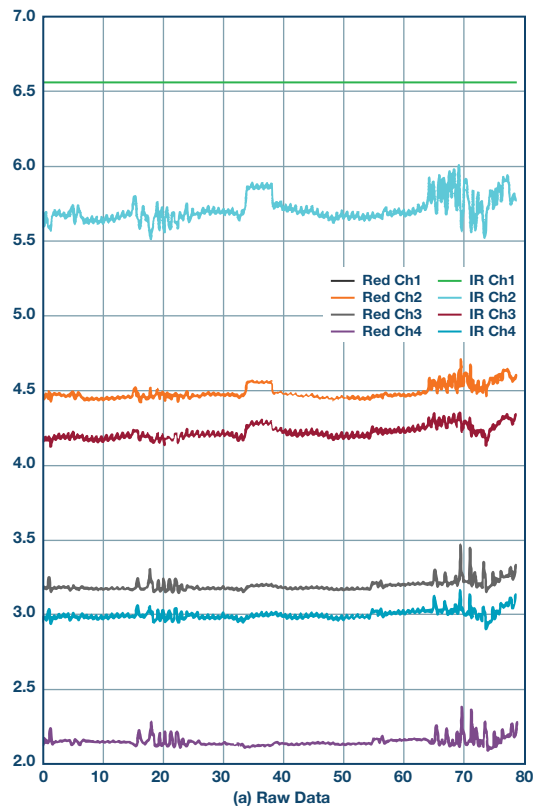
Figure 4. The red region (top) shows a four-channel measurement for standing still and chewing and the infrared region (bottom) shows raw and summed data. The heart rate (black line) can be determined from the summed data by the algorithm, with the color scale indicating the confidence level. The heart rate can be determined without an accelerometer.
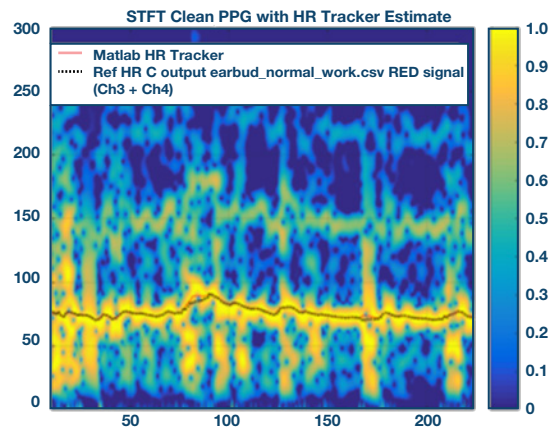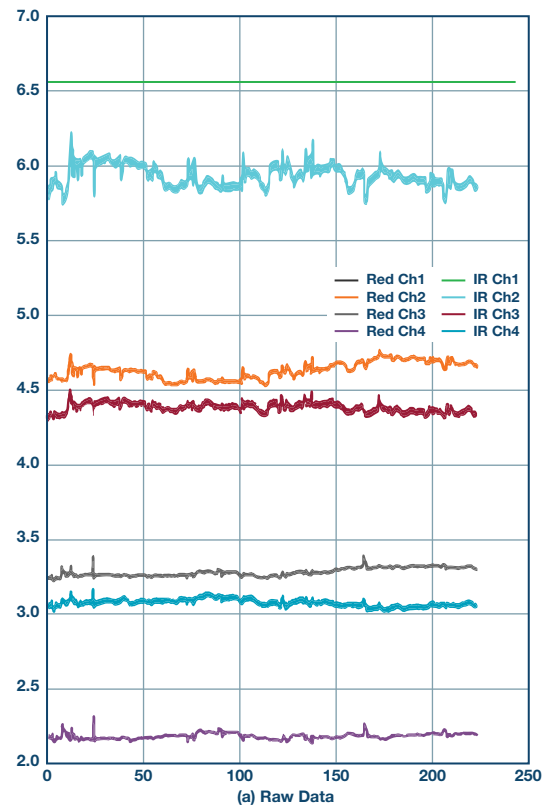
Figure 5. The red region (top) shows a four-channel measurement for working at a desk and the infrared region (bottom) shows raw and summed data. The heart rate (black line) can be determined from the summed data by the algorithm, with the color scale indicating the confidence level. The heart rate can be determined without an accelerometer.
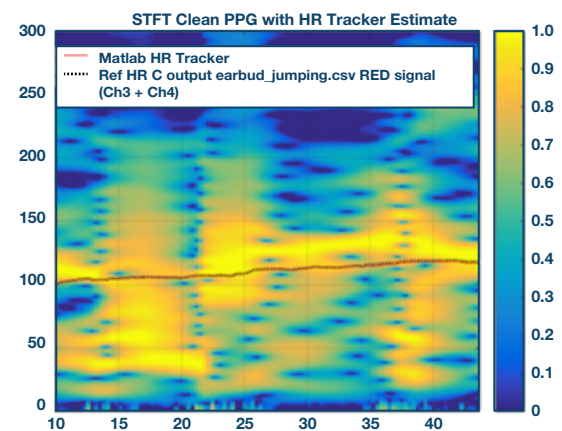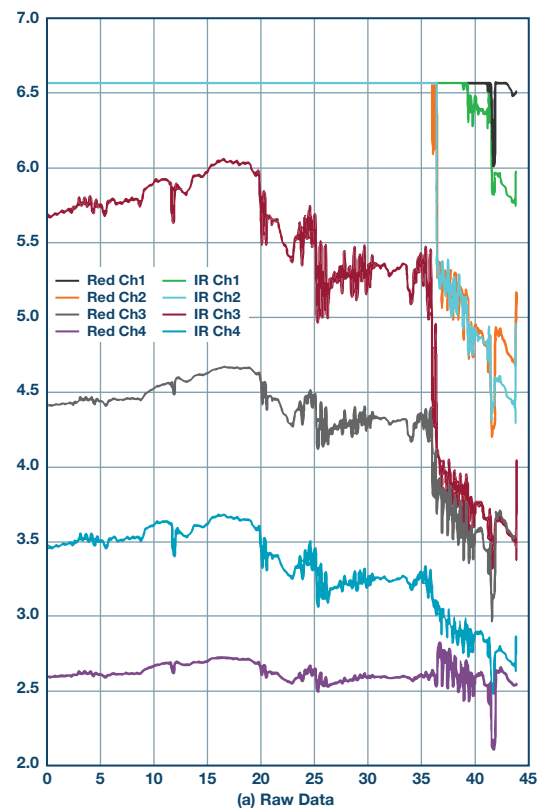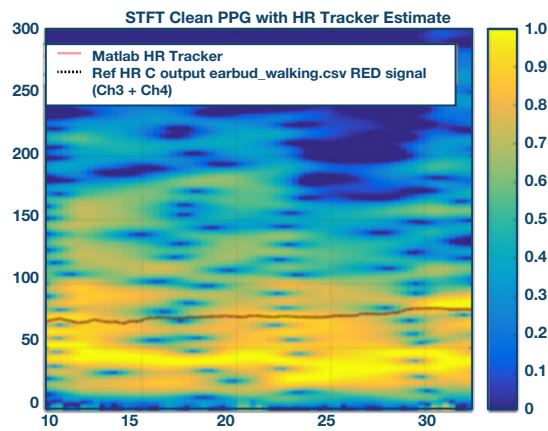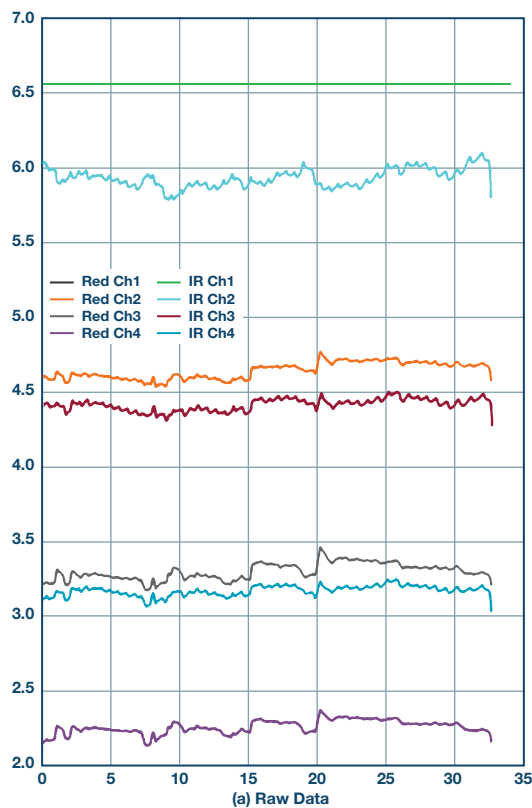
Figure 6. The red region (top) shows a four-channel measurement for walking and the infrared region (bottom) shows raw and summed data. The heart rate (black line) can be determined from the summed data by the algorithm, with the color scale indicating the confidence. The heart rate can be determined without an accelerometer in the infrared case.

Figure 7. The red region (top) shows a four-channel measurement for running and jumping and the infrared region (bottom) shows raw and summed data. The heart rate (black line) can be determined from the summed data by the algorithm, with the color scale indicating the confidence level. The heart rate can hardly be determined without an accelerometer.
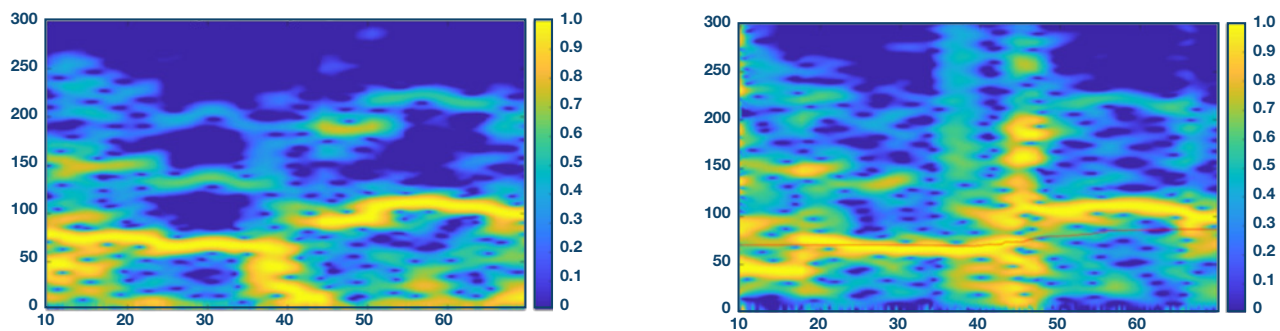
Figure 8. A comparison between additive spectrum without accelerometer data (left) and with accelerometer data (right). With the use of an accelerometer, the user's heart rate can be reconstructed.

Test Scenario 3

Working at a Desk

In Scenario 3, another everyday situation is tested. The test person sits at a desk and carries out normal tasks and the movements associated with them. Similarly to Scenario 2, motion artifacts can be detected, whereby the algorithm can identify the heart rate in both channels. As can be seen in Figure 5, the infrared signals dominate here, too.

Test Scenario 4

Walking

While the previous scenarios addressed stationary measurement conditions, the test person in this case moves uniformly in one direction at a low speed (about 50 steps per minute). As shown in Figure 6, the heart rate mixes with the walking pace in the PPG signal and the sum of the various channels shows a very blurry signal. While no defined heart rate can be calculated in the red signal field, the algorithm finds a fit in the infrared one. As a result of the large fluctuations and the low confidence matrix, however, additional motion data from an accelerometer would be tremendously helpful, especially because, up to now, measurements were only made at a low walking speed.

Test Scenario 5

Running and Jumping

Instead of measuring uniform movement, Scenario 5 introduces alternating sprinting and jumping intervals. The motion artifacts can now be very clearly identified, whereby the algorithm has great difficulty isolating a correct heart rate as shown in Figure 7. The need for motion sensor support seems to be unavoidable.

To better evaluate the need for a motion sensor, Scenario 5 tested measurement technology both with and without an accelerometer. Figure 8 shows a comparison of the additive spectrum without corrected accelerometer data (left) and with corrected accelerometer data (right). The improvement of the signal becomes visible in the identification of the heart rate, which was not possible without an accelerometer's support.

From the test cases, it can be concluded that in most cases, the heart rate can be determined very accurately with an integrated sensor in the earbuds. In the case of local or slow translational motions, the heart rate could even be determined without the use of accelerometer data. However, in the limiting case of abrupt and rapid motions, the comparison with motion-corrected data also permits interpretation of the data. The infrared signals were stronger than the red signals were in all cases.

In comparison to wrist measurements, the signal in the ear is stronger and thus enables more accurate measurements to be made. In addition, the use of red or infrared light allows for measurement of blood oxygen levels.

Conclusion

In conclusion, measurement in the ear is extremely promising, as demonstrated by the functioning test system. The measuring device can also be improved through better mechanical integration and extended to include additional measurements. Thus, the accelerometer can also be used for fall detection and step recognition and hence create an added value for the customer.

About the Author

Christoph Kämmerer has worked at Analog Devices in Germany since February 2015. He graduated in 2014 from Friedrich-Alexander University in Erlangen with a master's degree in physics. In the following year, he worked as an intern in process development at Analog Devices in Limerick. After completion of the trainee program as a field applications engineer in December 2016, he began working at Analog Devices, where he specializes in emerging applications. He can be reached at *christoph.kaemmerer@analog.com*.

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