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Unity in Diversity: Sampling Strategies in Wearable Photoplethysmography

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PHOTOPLETHYSMOGRAPHY OPTICALLY MEASURES the pulsating blood volume flow in the human skin so that primary vital signs such as the heart rate can be determined. Most known is this sensing principle from the mysterious illumination that can sometimes be seen at the back of fitness trackers and smartwatches. Since powering these high-intensity light puts a large dent into a wearable's energy budget, this paper delves into the sampling schemes and strategies used by current off-the-shelf wearables to save energy and yet obtain good readings. As it turns out, the devices are following very different approaches.

Plenty of commercial wearables have been introduced to the general public that benefit their users in terms of personal health care and fitness. Besides the detection of physical activity, these devices can also monitor the user's heartbeat throughout daily life. This initially triggered interest from the quantified-self movement, but recently has been adopted by organizations that use the devices to support and motivate people to practice more physical exercise. The wearables that apply photoplethysmography (PPG) are loosely attached to the body and tend to be more comfortable and less obtrusive to wear long-term than electrocardiogram (ECG) stick-on sensors. While ECG sensing requires perfectly attached electrodes, wearables at the wrist can be as comfortable as traditional watches. Although most PPG research strives to match ECG in terms of accuracy, most devices are still used for fitness instead of medical care.[1]

PPG needs a strong illumination of the skin to capture the pulsating blood just below the human skin. The light-emitting diodes (LEDs) are utilized to generate short flashes to sample the blood volume of the moment, and are turned off

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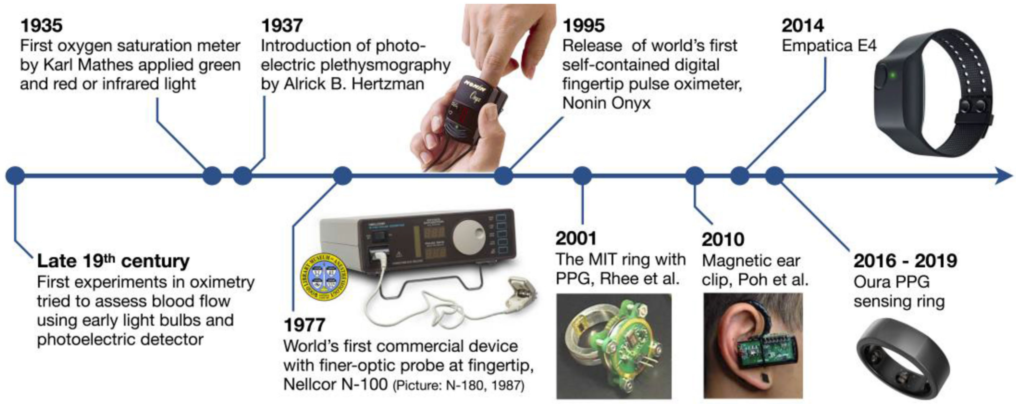

Figure 1. Development of PPG from its fundamental investigation in the late 19th century to modern commercial devices based on reflective mode PPG.

when no measurement takes place to save energy. This begs the question: How often, and in which sampling scheme, should these measurements take place? A recent patent application by Intel mentions that "the LED pulsing consumes approximately 80% of system power in a conventional 32 Hz PPG design".[2] While most research in PPG still concentrates on conventional uniform sampling, some commercial devices seem to use other sampling strategies.

PHOTOPLETHYSMOGRAPHY

With the fundamentals investigated in the late 19th century, the principle of photoelectric plethysmography was introduced in 1937 by Alrick B. Hertzman and is now referred to as Photoplethysmography (PPG). The history from the first experiments to modern commercial devices is depicted in Figure 1. PPG noninvasively measures the pulsating blood volume flow in the microvascular bed of the tissue beneath the skin. In clinical settings, it is known as pulse oximetry and is a proven method to monitor the heart rate and peripheral oxygen saturation (SpO2) of regular ward patients. It is typically applied at the fingertip, with LEDs on one side illuminating the tissue, while a photodetector on the opposite side measures the changes in the light intensity. Today's wearable devices usually apply reflective-mode PPG, where both LEDs and photodiodes are placed nearby and in the same orientation. In this way, the scattered light is measured at the skin surface and its intensity is inversely proportional to the captured blood volume as the incident light is absorbed by a larger volume.[3] Besides being used for estimating heart rate and SpO2, the raw PPG signal is also used to infer respiration rate, emotional state, and stress level, due to phenomena such as the respiratory sinus arrhythmia and the influence of the autonomic nervous system on the blood flow.

Light Wavelengths

The selection of the LED's color has large effects on what is actually measured. Depending on the wavelength, the emitted light penetrates the skin differently and captures information from different layers of the tissue.[4] Blue and green LEDs measure the blood volume changes in the superficial capillaries of the outermost layer of the skin. Yellow light reaches the arterioles in the layer below that. Red and infrared are found to even reach the smaller arteries below that. While the pulsating blood vessels modulate the scattering light, the smaller veins and other nearby tissues just add a dc component, which constitutes about 98% of the detected light. The analog-to-digital converter (ADC) of the PPG front end, which records the signal from the photodetector, needs to provide a large resolution of typically more than 16 bit to be able to sufficiently represent the ac component, the desired 2% of the signal, and its amplitude.[5]

The first wearable heart rate monitors used red and infrared lights. However, because the blood constituents oxyhaemoglobin and deoxyhaemoglobin absorb about seven times more green than red light, most recent modules tend to use green or even yellow lights, which exhibit the largest modulation depth in the detected signal, resulting in a better signal-to-noise ratio.[6] The incident light scatters within the tissue, where

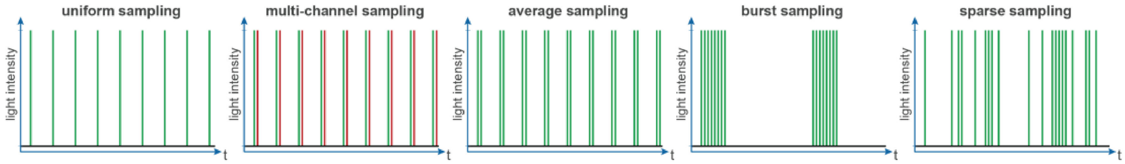

Figure 2. Typical sampling schemes applied in wearable PPG sensing devices. **(1)** Uniform sampling with constant frequency, **(2)** multichannel sampling with multiple subsequent pulses of different wavelengths, **(3)** average sampling with multiple samples per captured value, **(4)** burst sampling with a burst frequency and duty cycle which window captures samples with a specific pulse repetition frequency (PRF), and **(5)** sparse sampling for compressive sensing with a randomized sampling pattern.

most of the optical power follows a curved, banana-shaped path between LED and photodiode that largely depends on the applied light wavelength.[7] The distance of each specific light source and the photodetector thus has to be dimensioned according to the utilized light color to achieve maximum quality and amplitude of the detected signal. With physical activity causing sensor movement and soft tissue deformation, green light has also proven to be more motion tolerant than lights with wavelengths that penetrate the skin deeper and pass through more inhomogeneous textures with different scattering behaviors. Infrared is still used for SpO2 measurements, but also to inconspicuously detect the proximity of the skin and, hence, to verify the device is being worn against the skin.

Sampling Strategies

Sampling is the illumination of the skin with light of a specific wavelength and the measurement of its scattered part with a photodetector. With regard to the characteristics of the light source, the detector, and its analog front-end, different parameters have to be considered in the PPG sampling process. Those are mainly the LED colors, settling time, and intensity on the one hand, and the photodiode's sensitivity, dimensions, capacitance, and the applied ADC's sample and hold time on the other hand. The extended sample and hold time determines the integration time, meaning that the induced signal of the incoming light accumulates and neglects high-frequency distortion through averaging. The dimensions of the photodetector and the sample and hold time determine the quality of the captured measures and their signal-to-noise ratio. However, an extended sample and hold time needs a longer illumination of the skin and, consequently, results in increased energy consumption.

In traditional uniform sampling (see Figure 2.1), which is still the most common scheme, samples are taken continuously at a particular frequency. However, if the device is not worn, many devices resort to a reduced sampling rate with single intermittent samples. Such proximity measurements are often performed with infrared light as it is not visible for the human eye and, thus, not distracting. If multiple channels with different wavelengths are available (see Figure 2.2), those are triggered subsequently with a little gap to permit the photodiode to recover. This gap should not to be too large because otherwise the physiological signal would change during the measurement and the samples would not be comparable anymore. For example, computing the SpO2 requires the ratio of measurements using two different wavelengths taken at nearly the same moment. Sampling can also be reduced in other situations, such as when the user is moving too much to deliver a clean PPG signal. Studies have found the necessary minimum sampling frequency in uniform sampling to enable the reliable determination of heart rate to be at about 10 Hz.[8] To derive heart rate variability, a more advanced measure that is used to infer respiration rate and activity of the autonomic nervous system, the minimum sampling frequency in uniform sampling has been found to be 25 Hz.[9]

Sampling improvements have been achieved by capturing of multiple adjacent samples that are averaged (see Figure 2.3) either in software or, more efficiently, in hardware. This method decimates the amount of data throughput, but also reduces the influence of high-frequency noise because a moving-average, low-pass filter is implemented. This increases the number of samples per averaged value, and consequently, the cost of illumination is increased as well, but the derived values stay at a lower rate and do not require more resources and larger efforts in processing. Another approach reduces the energy consumption through nonaveraged, intermittent burst measurements (see Figure 2.4) at which the duty cycle determines the power dissipation. Similar to continuous sampling, the samples are taken at a specific sampling frequency, the so-called pulse repetition frequency (PRF), but the measurement is limited to a certain time interval. The minimization of this duty cycle reduces the energy demands, but it simultaneously reduces the gathered information. In some approaches, devices only record samples if the user is at rest for a certain time, thus avoiding distortions by motion artifacts.

Yet another strategy uses nonuniform sampling, which is applied for compressed sensing approaches (see Figure 2.5). Raw PPG signals are quasi-periodic pulse signals which are superimposed by nonstationary, chaotic low-frequency baseline wandering and high-frequency noise. Because the desired signal exhibits a low activity and diversity, uniform sampling is delivering data that are redundant and largely predictable. To reduce the dissipation through light flashes of the high-intensity LEDs, the samples are partially omitted and a sparse sampling in a random pattern is applied. Due to the reduced number of samples, less data have to be processed. However, the missing information of the fewer samples has to be reconstructed and estimated through suitable methods, which in turn require computational efforts and energy again. Whereas such algorithms are usually running on larger platforms and result in highly accurate estimates, the performance of wearable devices is limited and such algorithms would need to be highly efficient to outperform conventional uniform sampling.

WHAT DO THE COMMERCIAL WEARABLES DO?

In this paper, the sampling strategies of seven commercial wrist-worn devices are analyzed, specifically not addressing their accuracy and the success of the approaches, but instead investigating what types of sampling schemes and strategies are used in current PPG-based wearables. Our set of devices covers the entire price spectrum, from low-cost wristbands up to expensive lifestyle devices that have appeared over the past years. The oldest device, commonly used in research studies, is the *Empatica E4*, released in November 2014. Next is the consumer product *Samsung Gear S3* from November 2016. The fitness tracker *Polar OH1* was released in September 2017, and the devices *Mobvoi TicWatch E* and *Xiaomi Amazfit Bip* were released late 2017. The most recent devices are the *Fitbit Versa* from March 2018 and the *Apple Watch 4* from September 2018.

The PPG sampling of all wearables was monitored in two common conditions. Figure 3 shows the continuous sampling that is actively triggered through the user interface, for example to monitor physical exercises, whereas Figure 4 shows the incidental measurements that are applied sporadically during normal operation to save energy. Each device's LED activity has been captured with a photodiode and its signal recorded with a digital oscilloscope. The amplitude is normalized and the pulses were identified with a threshold-based peak detector to enable the characterization of all sampling parameters.

The physical appearance of the sensing setup looks similar for most wearables. One or two photodiodes are placed near multiple LEDs. An elaborate configuration with Fresnel lenses is utilized by the *Apple Watch 4*, but all other devices place the photodetectors directly at the skin's surface. The *Empatica E4* and the *Mobvoi TicWatch E* provide a shielded window to the sensor, but the other devices, such as the *Xiaomi Amazfit Bip*, place the sensor closer to the skin by making it protrude from the case. All tested wearables applied green light for the measurements. However, the *Empatica E4* and *Fitbit Versa* utilize green and red light, and the *Apple Watch 4* even used green and infrared light to support the derivation of SpO2.

We found a large diversity of applied sampling schemes. Straightforward uniform sampling is used by the *Xiaomi Amazfit Bip* which simultaneously samples two green LEDs at 25 Hz frequency. The *Samsung Gear S3* and *Polar OH1* also use two green LEDs, but differently. The *Samsung Gear S3* uses consecutive flashing at 1.3 kHz PRF and 20 Hz group frequency (GF). The *Polar OH1* uses 4.8 kHz PRF and 135 Hz GF, probably in an averaging strategy. The most recent devices, the *Fitbit Versa* and the *Apple Watch 4,* are following the approach of multichannel sampling and utilize

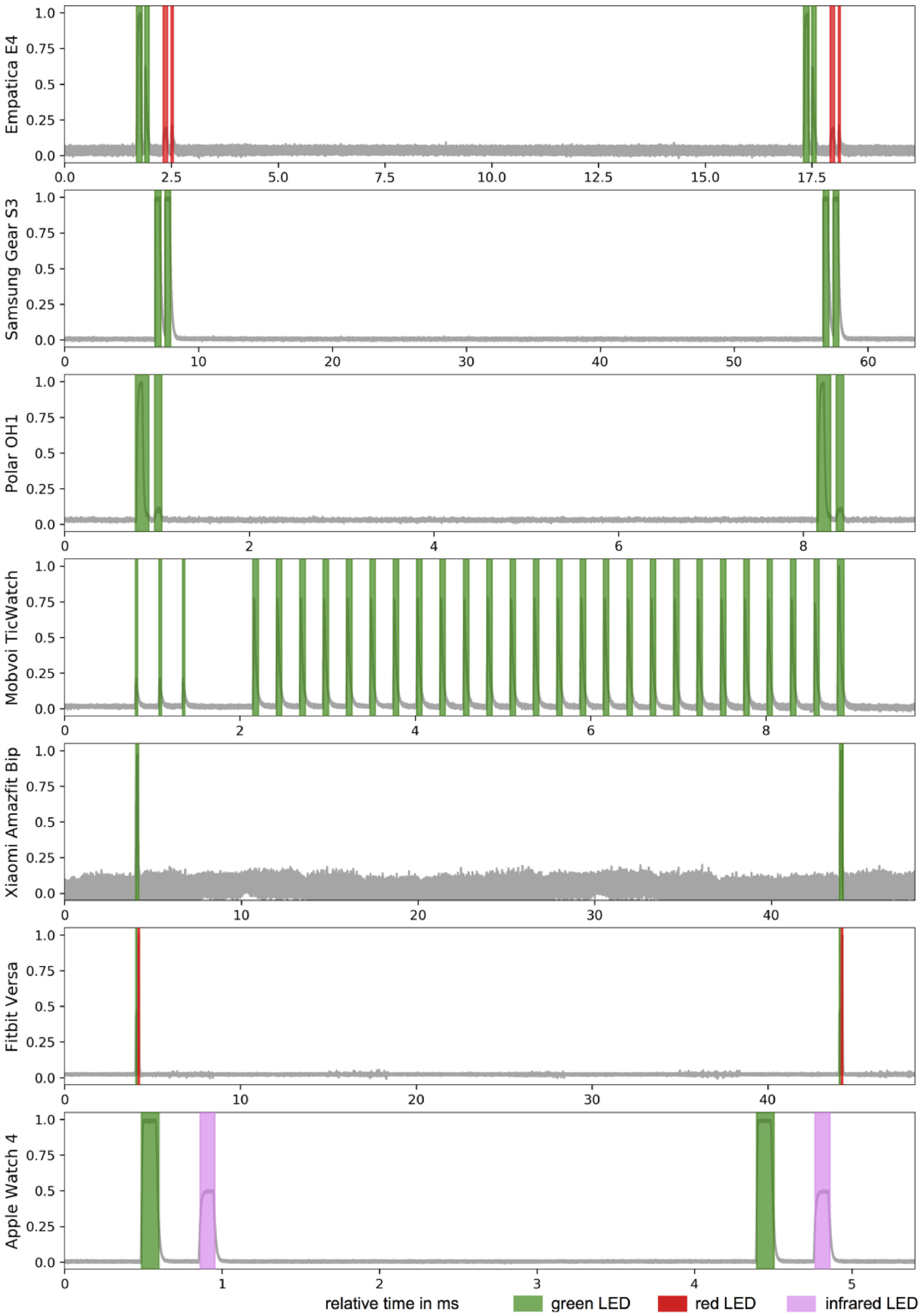

Figure 3. Sampling schemes of seven commercial devices as time series plots with highlighted pulses corresponding to the applied light wavelengths (green, red, and infrared). All devices were put in a mode that enables continuous measurement, for instance for physical activity monitoring.

green light in combination with either red or infrared light. The two channels are likely used to derive the SpO2 ratio. As summarized in Table 1, the PRF and GF are 7.5 kHz and 25 Hz, respectively for the *Fitbit Versa* and 2.7 kHz and 256 Hz for the *Apple Watch 4*. The *Empatica E4* has two green and

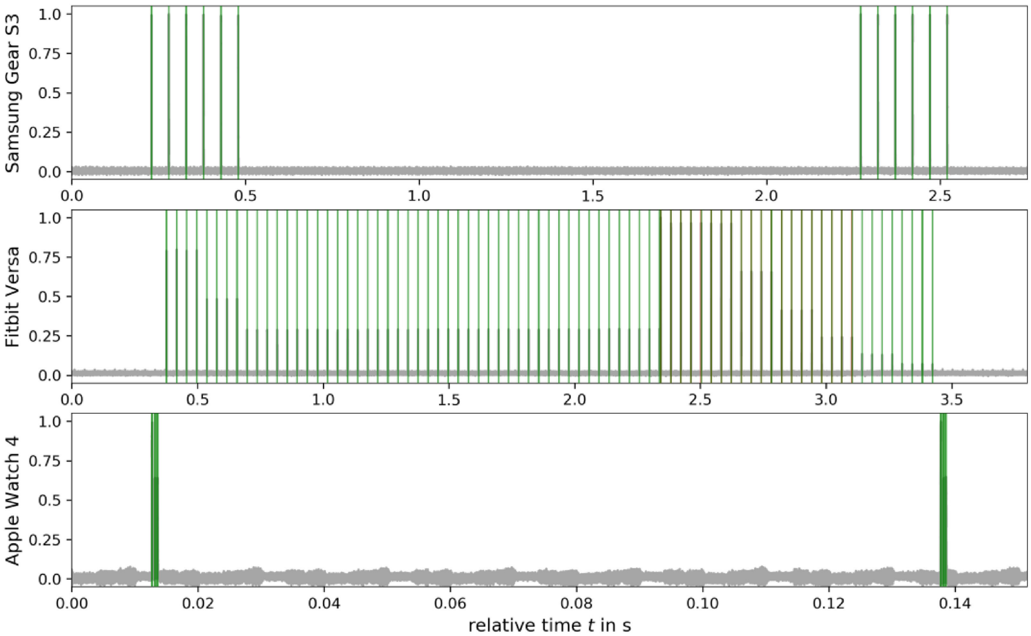

Figure 4. Recorded sampling strategies for three commercial wearables, with sampling highlighted according to the applied light wavelengths (green, red, and infrared). Here, the wearables were put in a sporadic sampling mode, which is usually enabled in casual wearing.

then two red LEDs flashing subsequently, with likely two readings of the same wavelength averaged and then likely used to enable the derivation of the SpO2 ratio. It is the only device that actively regulates the light intensity according to the available body surface. The *Mobvoi TicWatch E* surprisingly applied a totally different scheme at which three pulses are followed by 25 larger pulses and a terminating larger pulse of presumably green light. While the PRF is about 3.8 kHz, the GF is only about 20 Hz.

Sporadic sampling modes were only used by three devices, the *Samsung Gear S3*, the *Fitbit Versa*, and the *Apple Watch 4*. The *Apple Watch 4* uses three consecutive samples from the green LEDs at about 2.5 kHz PRF and 8 Hz GF, and the infrared LEDs seem to be inactive. The *Samsung Gear S3* applies a burst measurement with a PRF of about 20 Hz instead, repeated at a GF of about 0.5 Hz. Finally, the *Fitbit Versa* applies an interesting sampling scheme at a PRF of about 25 Hz in which the amplitudes of the green LED are gradually decreasing. In the first time period, the two treads exhibit four pulses, followed by 42 pulses with a constant amplitude; this is followed by a second time period with 30 adjacent double

Table 1. Overview of the PRFs and GFs for the continuous and sporadic measurement modes of the seven analyzed PPG sensing devices.

		Continuous		Sporadic	
Product	Release	PRF	GF	PRF	GF
Empatica E4	Nov. 2014	5 kHz	64 Hz		
Samsung Gear S3	Nov. 2016	1.3 kHz	20 Hz	20 Hz	0.5 Hz
Polar OH1	Sep. 2017	4.8 kHz	135 Hz		
Mobvoi TicWatch E	Nov. 2017	3.8 kHz	20 Hz		
Xiaomi Amazfit Bip	Dec. 2017		25 Hz		
Fitbit Versa	Mar. 2018	2.7 kHz	256 Hz	25 Hz	unknown
Apple Watch 4	Sep. 2018	7.5 kHz	25 Hz	2.5 kHz	8 Hz

pulses. The latter ones consist of two flashes, alternatingly emitted either from the green or the red LED.

CONCLUSION

Wearable PPG sensors have become a popular way to unobtrusively provide information about the wearer's vital signs, allowing continuous monitoring of fitness and health. Although plenty of research has studied the parameters that such sensors can use to take their readings, we decided in this paper to focus on what measurement strategies can be observed in off-the-shelf wearable products. In recent years, the variety of light wavelength used in current wrist-worn devices has settled on mostly using green light since it is robust against motion artifacts and provides a larger signal amplitude. All other parameters that one might consider in sampling PPG data are less settled. We noticed that some commercial devices apply traditional uniform sampling at a fixed-sampling frequency, but many other wearables follow different strategies as a tradeoff to achieve a good signal while using a minimum of energy. They tend to follow different variations of multichannel sampling, average sampling, and burst sampling strategies at various frequencies, yet only part of this diversity can be explained by the need for different qualities of readings. Even though PPG has been integrated into many commercially available wrist-worn wearable devices, their sampling strategies have thus yet not converged to a single solution.

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