Doubling the Signal Quality of Smartphone Camera Pulse Oximetry Using the Display Screen as a Controllable Selective Light Source

Christian Holz, *Member, IEEE* and Eyal Ofek, *Member, IEEE*

Abstract—Recent smartphones have the potential to bring camera oximetry to everyone using their powerful sensors and the capability to process measurements in real-time, potentially augmenting people's lives through always-available oximetry monitoring everywhere. The challenge of camera oximetry on smartphones is the low contrast between reflections from oxyhemoglobin and deoxyhemoglobin. In this paper, we show that this is the result of using the camera flash for illumination, which illuminates evenly across bands and thus leads to the diminished contrast in reflections. Instead, we propose capturing pulse using the front-facing camera and illuminating with the phone's display, a selective illuminant in the red, green, and blue band. We evaluate the spectral characteristics of the phone display using a spectroradiometer in a controlled experiment, convolve them with the sensitivity curves of the phone's camera, and show that the screen's narrow-band display illumination increases the contrast between the reflections in the desired bands by a factor of two compared to flash illumination. Our preliminary evaluation showed further support for our approach and findings.

I. Introduction

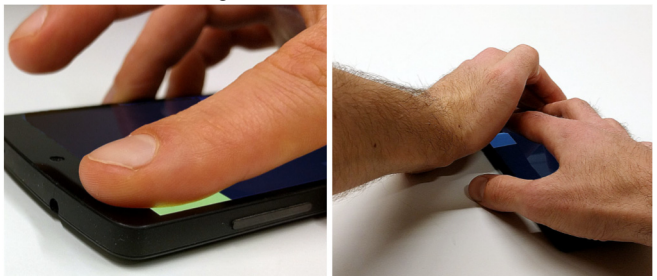
Regularly monitoring blood oxygenation levels can help detecting cardiac and pulmonary conditions, such as hypoxemia or sleep apnea [1]. It can also help athletes monitor their performance levels during endurance training [2]. Pulse oximetry makes monitoring one's blood oxygenation levels easy-to-operate, non-invasive and nearly ubiquitous, typically using a small measurement device clipped to the finger to measure the peripheral oxygen saturation.

Since smartphones now accompany users virtually all of the time, researchers have investigated them for always-available pulse oximetry sensing [3]. Users commonly place their finger on the phone's rear camera as the sensor while the adjacent flash acts as the illuminant, which has been shown to capture accurate heartrates [4]. However, extracting pulse oxygenation from the same signal is an ongoing challenge [5]. The main difficulty lies in the camera's limited optical sensitivity in the near-infrared region due to an integrated IR block filter and the fact that several isosbestic points reside in the visible spectrum, leading to a low contrast between flash-light reflections from oxyhemoglobin and deoxyhemoglobin. Several smartphone-based solutions have thus equipped the phone itself with *additional* illuminants [6].

In this paper, we overcome the challenge of requiring an illuminant at a *controlled* wavelength by repurposing the smartphone's display itself as the light source. Unlike the flash illuminant, the light from the display illuminates a *subset* of the spectrum, which allows us to extract a robust contrast between reflections from oxyhemoglobin and deoxyhemoglobin. Fig. 1 shows our phone application: The user places their finger on the touchscreen, such that the fingertip covers the front-facing camera. The touch event is detected and starts the data collection process, during which the touchscreen lights up in yellow to simultaneously illuminate the red and green band. In our controlled experiment, we demonstrate how display illuminations at various colors impact the absorption rates of a finger when placed on the display using a spectroradiometer. We thereby compare the configurations for transmissive and reflective sensing. Our results show that using the display of a commodity phone as a selective illuminant produces oxyhemoglobin and deoxyhemoglobin reflections in the required bands of the spectrum and that our selective illumination yields twice as strong of a contrast between these reflections compared to existing approaches that utilize the phone's flash for illumination.

C. Holz* and E. Ofek are with Microsoft Research, Redmond, WA 98052, USA. {cholz,eyalofek}@microsoft.com. *Corresponding author.

Figure 1. Our Android app captures oximetry reflections from the finger using the display as an illuminant in *solely* the red and green spectrum (thus appearing yellow). This produces significantly more accurate oximetry values than when using the rear camera and the flash for illumination.



II. Background

Smartphones have become frequent tools for physiological sensing due to the sensors they include, such as accelerometers and cameras, and their capability of processing signals in real-time. Researchers have used inertial sensors to detect ballistocardiographs [6] or extracted heart rates from the optical reflections recorded by the camera (e.g., by placing a finger on the camera [4][7] or from remote captures [8]). Several approaches to extract heart rates have been demonstrated, such as fusing the brightness information of all three channels [4] or extracting them solely from the green channel with higher stability [7]. Kurylyak et al. showed the amount of information each of the channels contributes for both, reflected and transmitted light intensities [9].

Beyond heartrate and pulse characteristics, mobile phones have been adapted for pulse oximetry. Measuring blood oxygenation poses the challenge to sense signals at *two* wavelengths: one at which oxygenated hemoglobin absorbs less light than deoxyhemoglobin (red) and another that shows the inverse behavior (near-infrared). Since many phone cameras feature near-IR block filters to produce better photos, smartphone oximetry has frequently included additional low-cost illuminants and photo sensors [3][10] [11][12] to replicate the functionality of commercial pulse oximeters.

For sensing oxygenation on an out-of-the box mobile device, researchers have examined the camera's color channels to record the two levels of light reflected by the finger using the built-in flash as the illuminant. This is reminiscent of the very beginnings of non-invasive pulse oximetry, which used red and green illumination [13]. Scully et al. extracted oxygenation from the ratio of red and blue reflections and show a correlation with a medical oximeter [14]. Verkruysse et al. reported that green illumination is absorbed more than blue in non-contact configurations [8]. Kanva et al. use the blue channel to sense near-IR reflections and estimate oxygenation using a white LED or flash background [6].

Though not intended for physiological sensing, phone manufacturers, such as Apple and Oppo, have been using the display for flash-like illumination in photography. To our knowledge, no prior work has tied the illumination spectrum to the spectral sensitivity of the camera sensor for physiological sensing. In this paper, we contribute this analysis and show that the flash light source diminishes the resolution of reflection ratios due to illumination in undesirable areas.

III. Methods

A. Apparatus

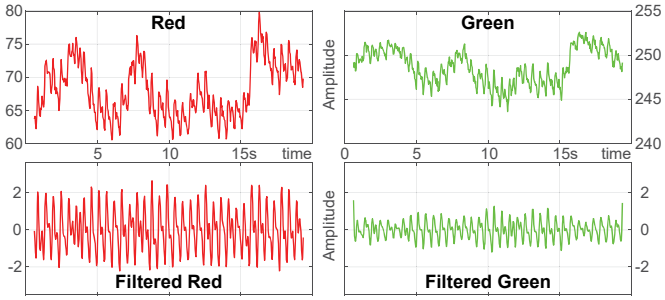
In this work, we use an LG Nexus 5 phone to illuminate the finger and record images through the front-facing camera. The choice of phone was deliberate: Introduced in 2013 as an affordable commodity phone, the Nexus 5 has capable components, which at this point all have substantially reduced in cost. The 4.95″ LCD display has a resolution of 1920x1080 pixels with a maximum brightness of 485 nits, which is around half the brightness current smartphones provide (e.g., Samsung Note 5 or 7). The front-facing camera is a ON Semiconductor MT9M114, which we run at a resolution of 320x240 pixels at 30 Hz. To ensure no crossover of measurements between the camera channels while recording, we disabled all automatic white-balancing, exposure, and gains functionality using the Camera2 API. Importantly, to ensure controlled illumination *solely* through the display, the finger needs to be shielded while recording to prevent light transmission from surrounding light sources or daylight, for example using the other hand as shown in Fig. 1. For comparison, we implemented a second interface for the back-facing Sony IMX179 camera (also 320x240 pixels, 30 Hz) with all auto compensation disabled as explained above.

Our Android app activates the display for controlled illumination of the finger upon touch and records a 20-second video from the front camera. The app then uploads the video to our backend service, which extracts pulse rates and oximetry ratios as described below. During our evaluation of display and flash spectra, we measured light intensities with an ORB SP-200 spectrometer. We then compared our measurements with the camera's response curves in the RGB bands [15]. During our preliminary evaluation, we collected oximetry levels using a Nonin Onyx II oximeter for ground truth.

B. Signal Processing

A video of 20 s contains around 16–20 heartbeats. To extract the amplitude of the signal, we separately analyze the intensity levels of the red and green channel from the region that is closest to the light source in the image. We use 1/3 of the image width for this region and we derive the raw value

Figure 2. Red and green intensity values before and after processing.



from the region's average intensity. Fig. 2 (top) shows the signal change over time: the red band under red illumination and the green band under green illumination. The low frequency changes can stem from the finger slightly moving during acquisition, changing touch pressure, or breathing motions. We thus remove low frequency changes by applying a Gaussian filter of *width* = 1 second. Fig. 2 (bottom) shows the resulting signal, which maintains the heartbeat details. We apply another Gaussian low pass filter of *width* = 0.2 s to filter noise.

From the resulting signals, we extract the *DC* (mean amplitude) and *AC* (root mean square amplitude) values for the red and green band, respectively, to calculate the oximeter ratio *R* as done in the literature [3]. The final mapping of the values we obtain to blood oxygenation can be implemented with a lookup table created in a clinical study [14].

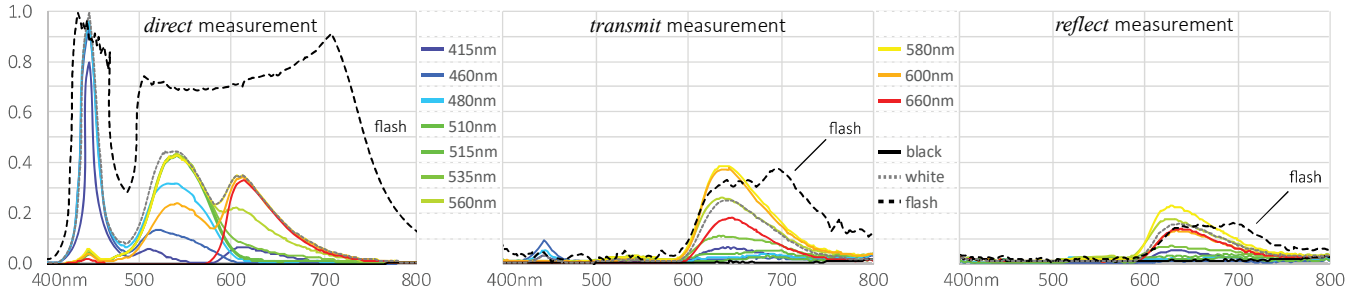
C. Experimental Protocol: Spectrum Analysis

The purpose of our experiment was to measure the spectrum emitted by the display depending on presented colors (*direct*), the spectrum when transmitted through a finger (*transmit*), and the spectrum when reflected inside (*reflect*). In all conditions, the display was set to maximum brightness. To obtain a measurement, the spectrometer pointed directly at the phone's display, at the finger from above as the palmar side was in contact with the illuminated area on the screen (Fig. 1), and at the side of the finger just above the display to measure reflection, respectively. During each recording, 5 consecutive measurements were averaged and we repeated each recording three times. Integration times were 8.5 ms for *direct* and 250 ms for *transmit* and *reflect*. Our test app on the phone mapped output wavelengths to RGB values. Finally, we selected wavelengths so as to best cover the areas between the isosbestic points of the absorbance curves of oxyhemoglobin and deoxyhemoglobin: 415nm, 460nm, 480nm, 515nm, 535nm, 560nm, 580nm, 600nm, 660nm. We also measured the spectral intensities of a black screen, white screen, and the flash illuminant. Since the display cannot act as a near-IR illuminant, our intention was to find an illumination range in which oxyhemoglobin absorbs light more strongly than deoxyhemoglobin to obtain substitute reflections for the typically used near-IR range. For comparison, we repeated these measurements with a Samsung Galaxy S6 with an OLED display.

D. Experimental Protocol: Preliminary Evaluation

For a preliminary validation of the stability of the phone signal, we compared the ranges of *R* estimations produced by the front-facing camera using the display as the illuminant (*display*) with those of the back-facing camera using the flash illuminant (*flash*), grouped by the SpO_2 measurements reported by the pulse oximeter. The front-facing measurements recorded each subject's right index finger while the subject

Figure 3. Spectral distribution of intensities of the LCD screen under different illumination colors (simulated wavelenghts) and the phone camera flash.



covered the finger from incident light with their left hand. The pulse oximeter was clipped to the subject's other index finger to record heartrate and blood oxygenation. Subjects then placed their finger on the back-facing camera while simultaneously covering the flash to record a second measurement. A valid front or back measurement was recorded only if the value on the oximeter did not change throughout the period of collecting video data, which took about a minute for both measurements. Each collection was repeated five times.

IV. Results

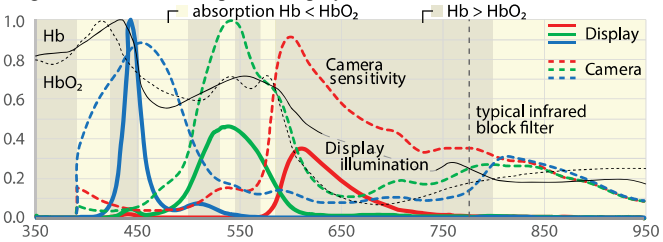
A. Light spectrum of the LCD RGB display and the flash

Fig. 3 shows the results of the spectrum measurements grouped by *direct*, *transmit*, and *reflect*. Graphs are normalized to the maximum intensity recorded in the *direct* condition. Curves illustrating *flash* illumination are normalized separately from those depicting *display* illumination. It is evident that while the flash light illuminates the entire visible spectrum at a comparable intensity apart from a drop in the teal range, the LCD produced peaks of intensities in *only* the red, green, and blue bands. The different illumination colors tested during the experiment resulted in a more or less pronounced intensity of each of these distributions, but did not change illumination peaks *along* the spectrum. Fig. 4 also reveals that the green illumination peak largely intersects with an area in which deoxyhemoglobin reflects and lets more light pass than oxyhemoglobin, similar to the near-IR spectrum. Areas in which this is the case are highlighted yellow, whereas the opposite areas are highlighted in beige. As shown in Fig. 3, the flash light illuminates both types of areas, thus reducing the relative intensity of light reflected by deoxyhemoglobin over that reflected by oxyhemoglobin, which diminishes the contrast between both. We also see that in the red spectrum, the illuminant creates intensities in a band in which oxyhemoglobin reflects more light than deoxyhemoglobin, ideal for sensing the former.

B. Light spectrum intensities vs. camera response curves

Fig. 4 contrasts the response curves of the smartphone's camera to the spectral intensities produced by the display. We again compare these to the overlaid absorbance curves of oxyhemoglobin and deoxyhemoglobin and highlight the areas between isosbestic points to juxtapose areas of desired reflections (i.e., those resembling the ratios in the near-IR range) and undesirable reflections, which reduce contrast and thus diminish the quality of the signal.

Figure 4. Normalized spectral display intensities and camera sensitivities.



The results of our measurements now allow us to compute the contrast between light intensities reflected by oxyhemoglobin and deoxyhemoglobin, contrasting the flash illuminant with the LCD illuminant. The light intensities captured by the camera result from the illumination profile I, which is affected by the transmission profile of the finger T, multiplied by the sensitivity profile of the camera C. We can therefore simulate the response of the camera under different illuminations by integrating over all wavelengths λ:

$$v = \int I(\lambda)T(\lambda)C(\lambda)\, d\lambda$$

where v is the average value of the captured frame. When calculating the oximeter ratio R, the quality of the signal depends on the *relative* change of signal in two different bands. When we apply the equation above to different illuminants and camera bands, we can determine the optimal setups for measurement given the available illuminants.

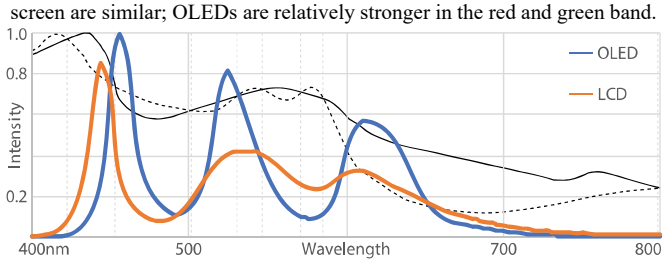
Table 1. The ratio between light reflections from deoxyhemoglobin and oxyhemoglobin in different simultaneous illumination and capture bands.

illumination and capture bands							oxy/deoxy difference
W_{OLED}	&	R_{camera}	/ W_{OLED}	&	G_{camera}	=	0.63%
$R_{display}$	&	R_{camera}	/ $G_{display}$	&	G_{camera}	=	0.40%
Flash	&	R_{camera}	/ Flash	&	G_{camera}	=	0.17%

This table assumes that level of illumination is sufficient to be resolved by the camera. Our tests have shown that the camera observes no reflections in the blue band, neither for the *display* illuminant nor the *flash* illuminant, due to the tissue's absorption of blue light [6][14]. The ratios listed above show that signal quality using *flash* as the illuminant is lower than *display* due to the flash's wide illumination across bands. The more narrow-band *display* illumination generates more than twice the difference in reflections between oxyhemoglobin and deoxyhemoglobin and thus a better signal.

Our measurements also reveal another insight for camera oximetry using flash illuminants: The strong light intensity of a flash saturates the red channel quickly, which requires the camera to reduce its sensitivity to resolve a signal in the green band. Since the digitizer has to perform tone mapping across the *entire* sensor, not for individual color bands, as the fundamental camera sensor is a gray level sensor with a corresponding color-band filter atop each pixel [15]. Therefore, the red signal gets diminished by the amplification of the green signal, which requires a trade-off in sensitivity. Unlike the flash, the display produces brighter illumination in the green than in

Figure 5. The normalized light intensities of an OLED screen and an LCD screen are similar; OLEDs are relatively stronger in the red and green band.



the red band, causing the resulting recording to contain a bigger signal-to-noise ratio in *both*, the red and the green signal.

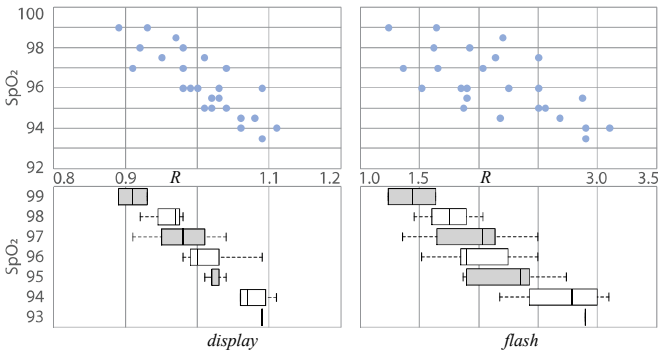
C. Comparison of LCD and OLED screen illumination

As shown in Fig. 5, the LCD screen on the Nexus 5 and the OLED screen on the Galaxy S6 produced comparable spectra. Importantly, the intensity of the illumination of the OLED screen is higher, showing red and green illuminations that are twice as strong compared to the Nexus 5 LCD screen. This is due to a brighter display in the S6 [16], which comes at an increased price, but would boost our signal quality due to the stronger illumination in the appropriate bands. Table 1 also shows that using the OLED for illumination produces a 3.7x higher contrast in the camera signal (0.63% vs. 0.17%) than the signal recorded from reflections using the flash.

D. Correlation of oximeter ratios and SpO_2 measurements

Processing our measurements separately for *display* and *flash* recordings produced the *R–SpO₂* plots shown in Fig. 6. The lower spread of *R* values using the controlled *display* illuminant is evident (Fig. 6, left) compared to using the *flash* (right). The box plots shown in the same figure illustrate the spread of *R* values calculated by either method for the same ranges of blood oxygenation. While these regions overlap substantially for flash illumination, they are more distinct for the display illuminant. These results support the calculations we demonstrated above and confirm results of our spectrum analysis that a signal might be more robust when *selective* illumination is used instead of the broad flash illumination. We also analyzed the blue camera channel of all recordings, but could not find a signal in either the videos with *display* or *flash* illumination. According to the camera's datasheet [15], we suspect that the signal observed in related efforts might have originated from near-IR illumination, in which range the blue channel also exhibits some sensitivity, or automatic white-balancing applied by the camera.

Figure 6. Correlation plot of calculated oximeter ratios *R* for the *display* and *flash* illuminant and the SpO_2 values from the Onyx II oximeter. The box plot illustrates the spread of computed *R* values per SpO2 value.



V. Conclusion

We presented a novel approach for camera oximetry on commodity smartphones, requiring no changes or added components. Instead of using the flash for illuminating the finger, the key idea of our approach is to use the display light, which illuminates *narrower* bands that are better suited for the camera to resolve reflections from deoxyhemoglobin—something that typically requires a near-infrared illuminant for robust signals. We evaluated the spectrum produced by smartphone displays and intersected them with the sensitivity bands of the camera to determine optimal illumination bands. We found that switching to the display as the illuminant has the potential to double the contrast between reflections from oxygenated and deoxygenated hemoglobin. Our preliminary evaluation showed support that our method obtains more robust oximeter ratios. We believe that our approach has the potential to be applicable on all kinds of mobile devices, as our findings transfer to future phones with bright OLED displays, tablets and laptops, all of which incorporate a user-facing camera close to the display, providing the opportunity to bring always-available camera oximetry to everyone. We also hope that our findings will contribute to the progress of *continuous* and less obtrusive sensing for physiological metrics [17].

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