



- (51) **International Patent Classification:**
A61B 5/024 (2006.01) *A61B 5/1455* (2006.01)
- (21) **International Application Number:**
PCT/IB2015/052579
- (22) **International Filing Date:**
9 April 2015 (09.04.2015)
- (25) **Filing Language:** English
- (26) **Publication Language:** English
- (30) **Priority Data:**
1979/CHE/2014 16 April 2014 (16.04.2014) IN
- (71) **Applicant:** INDIAN INSTITUTE OF SCIENCE
[IN/IN]; C V Raman Ave, Bangalore 560012 (IN).
- (72) **Inventors:** AMRUTUR, Bharadwaj; Department Of
Electrical Communication Engineering, Indian Institute Of
Science, Bangalore, Karnataka 560012 (IN). GUBBI,
Sagar, Venkatesh; Department Of Electrical Communica-
tion Engineering, Indian Institute Of Science, Bangalore,
Karnataka 560012 (IN).
- (74) **Agents:** RAGHAVENDRA, Ramya, Rao et al.; K&S
Partners, Intellectual Property, Attorneys, 4121/B, 6th
Cross, 19A Main, HAL II Stage (Extension), Bangalore
560038 (IN).
- (81) **Designated States** (*unless otherwise indicated, for every
kind of national protection available*): AE, AG, AL, AM,

AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY,
BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM,
DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT,
HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR,
KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG,
MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM,
PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC,
SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN,
TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

- (84) **Designated States** (*unless otherwise indicated, for every
kind of regional protection available*): ARIPO (BW, GH,
GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ,
TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU,
TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE,
DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU,
LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK,
SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ,
GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

- *as to the applicant's entitlement to claim the priority of the
earlier application (Rule 4.17(iii))*
- *of inventorship (Rule 4.17(iv))*

Published:

- *with international search report (Art. 21(3))*

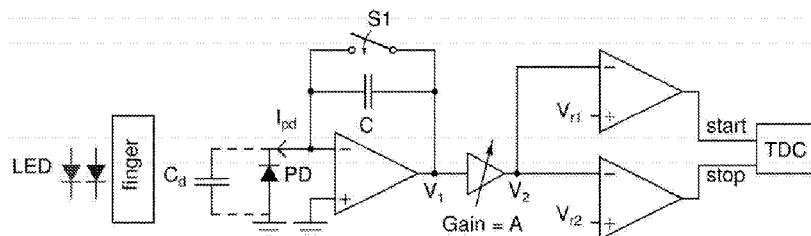
(54) Title: LOW POWER PULSE OXIMETER AND A METHOD THEREOF

Fig. 2

(57) **Abstract:** Embodiments of the present disclosure relates to a pulse oximeter and method of reducing power consumption in the pulse oximeter. The oximeter comprises a transducer, having a plurality of light sources to generate light pulses to be incident on a subject and a 5 photo-detector to receive the transmitted light pulses from the subject to generate a photocurrent. Also, the oximeter comprises an integrator to convert the photocurrent into monotonically changing voltage signals. An amplifier coupled to the integrator amplifies the voltage signals. Further, a threshold circuit identifies time duration for which the amplified voltage signal is present within predetermined reference voltage levels. Further, 10 the oximeter comprises a time to digital convertor (TDC) to provide digital signal equivalent to the time duration. Furthermore, a control unit controls operations of all the blocks of the oximeter by estimating signal to noise ratio from the time duration, thereby reducing power consumption.

LOW POWER PULSE OXIMETER AND A METHOD THEREOF

TECHNICAL FIELD

5 Embodiments of the present disclosure relate to low power pulse oximeter. More particularly, the embodiments relate to power optimization in low power pulse oximeter.

BACKGROUND

10 Presently, there exist some devices which provide affordable health care in rural areas by monitoring various physiological parameters of a subject remotely. To remotely monitor physiological parameters, it is desirable to have sensor nodes that are small and discreet, which means that the battery powering the node will be of limited capacity. So, to reduce the frequency of battery replacement, the sensor node has to be designed to consume
15 as little power as possible. Arterial oxygen saturation is an important physiological parameter in modern medicine. Pulse oximeters are commonly used in intensive care units, sleep studies, neonatal care, etc. Low-power pulse oximeters are useful for remotely monitoring heart rate and oxygen saturation.

20 Conventional low-power oximeters use energy efficient transimpedance amplifiers. These circuits are completely based on analog design. Also there exist compressive sensing circuits, which are used to minimize power consumption by reducing the number of samples taken. However, existing photodiode interface circuits use analog band pass filters which do not easily permit sub-Nyquist sparse random sampling which is necessary for compressive
25 sensing to effectively reduce power.

Fig. 1 shows a conventional oximeter, which is a photocurrent detector based on transimpedance amplifier. In order to deal with low perfusion, oximeters use AC coupled amplifiers to separate the large DC level and amplify the AC component only. Thereafter,
30 the amplified AC signal is fed to analog to digital converter (ADC). However, the use of AC coupled amplifiers and low pass filters in the pipeline as shown in Fig. 1 makes the process of turning ON the LED and sparsely sampling the photocurrent at arbitrary time instants harder to implement because the low pass filter does not allow the plethysmogram to change rapidly as would happen if the LED is turned ON at arbitrary time instants and

will also need to have a sample and hold circuit that droops, voltage by no more than a few hundred microvolts over the duration when samples are not taken.

An oximeter works based on the oxygen saturation present in the subject. The oxygen saturation is the percentage of haemoglobin in the blood that is oxygenated. If $[Hb]$ is the concentration of de-oxygenated haemoglobin in the blood and $[HbO_2]$ is the concentration of oxygenated haemoglobin,

$$SpO_2 = \frac{[HbO_2]}{[Hb] + [HbO_2]} \quad (1)$$

Pulse oximetry is an optical technique that takes advantage of volumetric pulsations in the arteries as the heart pumps blood to measure arterial oxygen saturation. When light from an LED is transmitted through the human body part, generally a finger or an ear lobe and the intensity of the light that passes through to the other side is measured using a photodiode. The normalized absorption ratio R is calculated as,

$$R = \frac{P_R}{P_{IR}} \quad (2)$$

where perfusion P is the ratio of alternate current (AC) to direct current (DC) of the corresponding plethysmogram for red and infra-red wavelengths.

$$P = \frac{I_{pd(ac)}}{I_{pd(dc)}} \quad (3)$$

where I_{pd} is photocurrent generated by the photodiode. Based on the known absorption coefficient values, the concentration of oxygenated haemoglobin is represented as:

$$SpO_2 = \frac{0.81 - 0.18R}{0.63 + 0.11R} \times 100\% \quad (4)$$

However, SpO_2 is assumed to be a linear function of R as in

$$SpO_2 = a - bR \quad (5)$$

where a and b are constants obtained by calibration.

Accordingly, a need exists for a device and method which provides reduces power consumption of the battery used in the oximeters. Thereby, improving battery life, this in turn reduces the frequent changing of batteries in oximeters which are used to remotely

monitor physiological parameters of a subject.

REFERENCES

- [1] D. G. Bassani, R. Kumar, S. Awasthi, S. K. Morris, V. K. Paul, A. Shet, U. Ram, M. F. Gaffey, R. E. Black, P. Jha et al., "Causes of neonatal and child mortality in india: a nationally representative mortality survey." *Lancet*, vol. 376, no. 9755, p. 1853, 2010.
- [2] H. Rao, D. Saxena, S. Kumar, S. V. Gubbi, B. Amrutur, P. Mony, P. Thankachan, K. Shankar, S. Rao, and S. R. Bhat, "Low power remote neonatal temperature monitoring device," in *BIODEVICES 2014, 7th International Conference on Biomedical Electronics and Systems*, 2014.
- [3] J. Webster, *Design of Pulse Oximeters*, 1997.
- [4] N. Netzer, A. H. Eliasson, C. Netzer, and D. A. Kristo, "Overnight pulse oximetry for sleep-disordered breathing in adults a review," *CHEST Journal*, vol. 120, no. 2, pp. 625–633, 2001.
- [5] Z. Zhu, R. K. Barnette, K. M. Fussell, R. Michael Rodriguez, A. Canonico, and R. W. Light, "Continuous oxygen monitoring a better way to prescribe long-term oxygen therapy," *Respiratory medicine*, vol. 99, no. 11, pp. 1386–1392, 2005.
- [6] A. K. Simonds, "Oximetry feedback flow control simulation for oxygen therapy," *Journal of clinical monitoring and computing*, vol. 21, no. 2, pp. 115–123, 2007.
- [7] R. Haahr, S. Duun, M. Toft, B. Belhage, J. Larsen, K. Birkelund, and E. Thomsen, "An electronic patch for wearable health monitoring by reflectance pulse oximetry," *Biomedical Circuits and Systems, IEEE Transactions on*, vol. 6, no. 1, pp. 45–53, 2012.
- [8] F. Adochiei, C. Rotariu, R. Ciobotariu, and H. Costin, "A wireless lowpower pulse oximetry system for patient telemonitoring," in *Advanced Topics in Electrical Engineering (ATEE), 2011 7th International Symposium on*, 2011, pp. 1–4.
- [9] W.-Y. Chung, Y.-D. Lee, and S.-J. Jung, "A wireless sensor network compatible wearable u-healthcare monitoring system using integrated ecg, accelerometer and spo2," in *Engineering in Medicine and Biology Society, 2008. EMBS 2008. 30th Annual International Conference of the IEEE*, 2008, pp. 1529–1532.
- [10] P. Shaltis, S. Rhee, and H. Asada, "Implementation and validation of a power-efficient, high-speed modulation design for wireless oxygen saturation measurement systems," in *Bioengineering Conference*, 2002.

- [1] E. Hughes, M. Masilela, P. Eddings, A. Raflq, C. Boanca, and R. Merrell, "Vmote: A wearable wireless health monitoring system," in e-Health Networking, Application and Services, 2007 9th International Conference on, 2007, pp. 330–331.
- [11] N. Watthanawisuth, T. Lomas, A. Wisitsoraat, and A. Tuantranont, "Wireless wearable pulse oximeter for health monitoring using zigbee wireless sensor network," in Electrical Engineering/Electronics Computer Telecommunications and Information Technology (ECTI-CON), 2010 International Conference on, 2010, pp. 575–579.
- 5 [12] T. Torfs, V. Leonov, C. Van Hoof, and B. Gyselinckx, "Body-heat powered autonomous pulse oximeter," in Sensors, 2006. 5th IEEE Conference on, 2006, pp. 427–430.
- [13] Y. Mendelson, R. J. Duckworth, and G. Comtois, "A wearable reflectance pulse oximeter for remote physiological monitoring," in Engineering in Medicine and Biology Society, 2006. EMBS '06. 28th Annual International Conference of the IEEE, 2006, pp. 912–915.
- 10 [14] R. Haahr, S. Duun, K. Birkelund, P. Raahauge, P. Petersen, H. Dam, L. Norgaard, and E. Thomsen, "A novel photodiode for reflectance pulse oximetry in low-power applications," in Engineering in Medicine and Biology Society, 2007. EMBS 2007. 29th Annual International Conference of the IEEE, 2007, pp. 2350–2353.
- 15 [15] C. Pujary, M. Savage, and Y. Mendelson, "Photodetector size considerations in the design of a noninvasive reflectance pulse oximeter for telemedicine applications," in Bioengineering Conference, 2003 IEEE 29th Annual, Proceedings of, 2003, pp. 148–149.
- 20 [16] R. Sarpeshkar, "Ultra low power electronics for medicine," in Wearable and Implantable Body Sensor Networks, 2006. BSN 2006. International Workshop on, 2006, pp. 1 pp.–37.
- [17] L. Turicchia, S. Mandal, M. Tavakoli, L. Fay, V. Misra, J. Bohorquez, W. Sanchez, and R. Sarpeshkar, "Ultra-low-power electronics for noninvasive medical monitoring," in Custom Integrated Circuits Conference, 2009. CICC '09. IEEE, 2009, pp. 85–92.
- 25 [18] M. Tavakoli, L. Turicchia, and R. Sarpeshkar, "An ultra-low-power pulse oximeter implemented with an energy-efficient transimpedance amplifier," IEEE Transactions on Biomedical Circuits and Systems, vol. 4, no. 1, pp. 27–38, feb. 2010.

- [19] K. Glaros and E. Drakakis, "A sub-mw fully-integrated pulse oximeter front-end," Biomedical Circuits and Systems, IEEE Transactions on, vol. 7, no. 3, pp. 363–375, 2013.
- [21] P. Baheti and H. Garudadri, "An ultra-low power pulse oximeter sensor based on compressed sensing," in Wearable and Implantable Body Sensor Networks, 2009. BSN 2009. Sixth International Workshop on, june 2009, pp. 144 –148.
- [22] E. Pelaez and E. Villegas, "Led power reduction trade-offs for ambulatory pulse oximetry," in Engineering in Medicine and Biology Society, 2007. EMBS 2007. 29th Annual International Conference of the IEEE, 2007, pp. 2296–2299.
- [23] K. Glaros and E. Drakakis, "Trade-offs for low power integrated pulse oximeters," in Biomedical Circuits and Systems Conference, 2009. BioCAS 2009. IEEE, 2009, pp. 245–248.
- [24] (2013) Precision switched integrator transimpedance amplifier. [Online]. Available: <http://www.ti.com/lit/ds/symlink/ivc102.pdf>
- [25] C. Enz and G. Temes, "Circuit techniques for reducing the effects of op-amp imperfections: autozeroing, correlated double sampling, and chopper stabilization," Proceedings of the IEEE, vol. 84, no. 11, pp. 1584–1614, 1996.
- [26] E. Klumperink, S. L. J. Gierink, A. Van Der Wel, and B. Nauta, "Reducing mosfet 1/f noise and power consumption by switched biasing," Solid-State Circuits, IEEE Journal of, vol. 35, no. 7, pp. 994–1001, 2000.
- [27] S. Lopez. (2012) Application note 4327, pulse oximeter fundamentals and design. [Online]. Available: http://www.freescale.com/files/32bit/doc/app_note/AN4327.pdf
- [28] J. Guo and S. Sonkusale, "A 22-bit 110ps time-interpolated timeto-digital converter," in Circuits and Systems (ISCAS), 2012 IEEE International Symposium on, 2012, pp. 3166–3169.
- [29] T. Sepke, P. Holloway, C. Sodini, and H.-S. Lee, "Noise analysis for comparator-based circuits," Circuits and Systems I: Regular Papers, IEEE Transactions on, vol. 56, no. 3, pp. 541–553, 2009.
- [30] B. Razavi, "Design of analog cmos integrated circuits," Tata McGrawHill Edition, 2002.
- [31] (2013) Data sheets from texas instruments.

[Online]. Available: <http://www.ti.com/lscs/ti/amplifiers-linear/operational-amplifier-op-amp-products.page>

[32] J. Immerkar, "Fast noise variance estimation," *Computer Vision and Image Understanding*, vol. 64, no. 2, pp. 300 – 302, 1996.

5 [33] J. Patterson and G.-Z. Yang, "Ratiometric artifact reduction in low power reflective photoplethysmography," *Biomedical Circuits and Systems, IEEE Transactions on*, vol. 5, no. 4, pp. 330–338, 2011.

[34] S. Rhee, B.-H. Yang, and H. Asada, "Artifact-resistant power-efficient design of finger-ring plethysmographic sensors," *Biomedical Engineering, IEEE Transactions on*,
10 vol. 48, no. 7, pp. 795–805, 2001.

[35] B. E. Sueppel and D. W. Mortara, "Low power pulse oximeter," Feb. 24 2004, uS Patent 6,697,655.

SUMMARY

15 The shortcomings of the prior art are overcome and additional advantages are provided through the provision of systems and methods of the present disclosure.

Additional features and advantages are realized through various techniques provided in the present disclosure. Other embodiments and aspects of the disclosure are described in
20 detail herein and are considered as part of the claimed disclosure.

In one embodiment, the present disclosure provides a pulse oximeter comprising a physiological-pulse transducer. This transducer comprises one or more light sources to generate pulses of light at predetermined wavelengths, but with controllable pulse durations
25 and intervals to be incident on a subject and a photo-detector is configured to receive the pulses of light passing through the subject to generate photocurrent. The transducer further comprises one or more light emitting diodes (LED) configured as light sources to generate pulses of light at predetermined wavelengths, to be incident on the subject. Also, the pulse oximeter comprises an integrator coupled to the photo detector to convert photocurrent into
30 monotonically changing voltage signals. Further, the pulse oximeter comprises an amplifier coupled to the integrator to amplify the voltage signal. Further, the pulse oximeter comprises a threshold circuit to identify time duration for which the amplified voltage signal is present within predetermined reference voltage levels. A time to digital convertor

(TDC) is coupled to the threshold circuit to provide digital signal equivalent to the time duration. A control unit is included to control operation of at least one of the integrator, the amplifier, the threshold circuit, the time to digital converter, the light sources and the photodetector. The control unit optimizes the gain of the amplifier, thereby reducing the time required to keep the light sources, the photo detector, the integrator, the amplifier, the threshold circuit and the TDC ON, thereby reducing power consumption during any sample acquisition. Furthermore, the control unit controls acquiring of samples only at peaks and troughs of the photocurrent generated by the photodetector using a phased locked loop, thereby further reducing power consumption of the pulse oximeter.

In one embodiment, the disclosure provides a method of reducing power consumption in a pulse oximeter. The method comprises generating successive pulses for powering one of plurality of light emitting diodes (LEDs) of the photo sensor to generate photocurrent. Next receiving, by a control unit, a time difference signal generated by time to digital control (TDC), said TDC generates the time difference signal from the photocurrent. Also, the method comprises controlling predetermined parameters of all components of the pulse oximeter, thereby reducing power consumption in the pulse oximeter. The predetermined parameters are at least one of gain of amplifier, duty cycle of the LEDs and signal to noise ratio (SNR) being obtained from the photocurrent.

The foregoing summary is illustrative only and is not intended to be in any way limiting. In addition to the illustrative aspects, embodiments, and features described above, further aspects, embodiments, and features will become apparent by reference to the drawings and the following detailed description.

BRIEF DESCRIPTION OF THE ACCOMPANYING DRAWINGS

The novel features and characteristic of the disclosure are set forth in the appended claims. The embodiments of the disclosure itself, however, as well as a preferred mode of use, further objectives and advantages thereof, will best be understood by reference to the following detailed description of an illustrative embodiment when read in conjunction with the accompanying drawings. One or more embodiments are now described, by way of example only, with reference to the accompanying drawings wherein like reference numerals represent like elements and in which:

Fig. 1 shows a conventional oximeter, which is a photocurrent detector based on transimpedance amplifier;

Fig. 2 shows a low-power pulse oximeter, in accordance with an embodiment of the present disclosure;

Fig. 3 illustrates pulses generated by two LEDs of the oximeter, in accordance with an embodiment of the present disclosure;

Fig. 4 illustrates a plot showing output from a TDC for one of the channels (red or IR), in accordance with an embodiment of the present disclosure;

Fig. 5 illustrates the ramp output from the TDC in which noise is reflecting as a jitter, in accordance with an embodiment of the present disclosure;

Fig. 6 illustrates output of the switched integrator, in accordance with an embodiment of the present disclosure;

Fig. 7 illustrates a scatter plot showing supply current in terms of bandwidth in the log-log scale for discrete op-amps, with a value of $K1 = 1.32 \cdot 10^{10}$;

Fig. 8 illustrates a scatterplot of supply current in terms of bandwidth per input referred noise for discrete op-amps, with a value of $K2 = 3.02 \cdot 10^{-27}$;

Fig. 9 illustrates a plot showing a trade-off between amplifier power and LED power;

Fig. 10 illustrates a plot showing SNR in terms of LED on-time of the oximeter placed on different fingers of the human, in accordance with an embodiment of the present disclosure;

Fig. 11 illustrates a flowchart of the dynamic adaptation techniques, in accordance with another embodiment of the present disclosure;

Fig. 12 illustrates captured photoplethysmogram from the prototype oximeter, in accordance with an embodiment of the present disclosure;

Fig. 13 illustrates performance of minimum SNR tracking in the presence of motion artifacts, in accordance with an embodiment of the present disclosure;

5 Fig. 14 illustrates performance of PLL tracking in the presence of motion artifacts, in accordance with an embodiment of the present disclosure; and

Fig. 15 illustrates a graph showing power divided into LED power, analog power and processor or control unit power for different fingers, in one embodiment of the present
10 disclosure.

The figures depict embodiments of the disclosure for purposes of illustration only. One skilled in the art will readily recognize from the following description that alternative embodiments of the structures and methods illustrated herein may be employed without
15 departing from the principles of the disclosure described herein.

DETAILED DESCRIPTION

The foregoing has broadly outlined the features and technical advantages of the
20 present disclosure in order that the detailed description of the disclosure that follows may be better understood. Additional features and advantages of the disclosure will be described hereinafter which form the subject of the claims of the disclosure. It should be appreciated by those skilled in the art that the conception and specific embodiment disclosed may be readily utilized as a basis for modifying or designing other structures for carrying out the
25 same purposes of the present disclosure. It should also be realized by those skilled in the art that such equivalent constructions do not depart from the spirit and scope of the disclosure as set forth in the appended claims. The novel features which are believed to be characteristic of the disclosure, both as to its organization and method of operation, together with further objects and advantages will be better understood from the following description
30 when considered in connection with the accompanying figures. It is to be expressly understood, however, that each of the figures is provided for the purpose of illustration and description only and is not intended as a definition of the limits of the present disclosure.

Exemplary embodiments of the present disclosure provide a low power pulse
35 oximeter and method for reducing power consumption in the pulse oximeter.

One embodiment of the present disclosure is a pulse oximeter comprising a photo sensor or a physiological-pulse transducer. The physiological-pulse transducer comprising one or more light sources to generate pulses of light of predetermined wavelengths at controllable intervals and with controllable pulse duration to be incident on a subject and a photo-detector configured to receive the pulses of light incident of the subject to generate corresponding photocurrent. Also, the pulse oximeter comprises an integrator coupled to the photo detector to convert photocurrent into voltage signals. The integrator is a switched integrator used to reduce noise. Further an amplifier with digital gain control is used to amplify the output of the integrator. Further, the pulse oximeter comprises a threshold circuit to identify time duration for which the amplified voltage signal is present within predetermined reference voltage levels. A time to digital convertor (TDC) is coupled to the threshold circuit to provide digital signal equivalent to the time duration. Furthermore, the pulse oximeter comprises a power supply unit to power up the light sources, the photodetector, the integrator, the amplifier, the threshold circuit and the TDC. The pulse oximeter further comprises a control unit to control operation of the integrator, the light sources, the photodetector, the amplifier, the threshold circuit and the TDC. The control unit estimates SNR from the output of the TDC, which is obtained based on the captured photoplethysmogram using the transducer. This information is used by the control unit to dynamically adjust the gain of the amplifier as well as the light emitting diode (LED) ON time, and the ON time of the photo detector, the integrator, the amplifier, the threshold circuit and the TDC, thereby reducing power consumption by operating the sensor at just sufficient SNR. Also, the control unit reduces the number of samples required, thereby reducing power consumption. The processing unit obtains the physiologically relevant parameters like oxygen saturation and pulse rate from the raw TDC samples, using well known algorithms.

In one embodiment, the disclosure provides a method of reducing power consumption in a pulse oximeter. The method comprises generating successive pulses for powering one of plurality of light emitting diodes (LEDs) of the photo sensor to generate photocurrent. Next receiving, by a control unit, a time difference signal generated by time to digital control (TDC), said TDC generates the time difference signal from the photocurrent. Also, the method comprises controlling predetermined parameters of all components of the pulse oximeter, thereby reducing power consumption in the pulse oximeter. The

predetermined parameters are at least one of gain of amplifier, duty cycle of the LEDs and signal to noise ratio (SNR) being obtained from the photocurrent.

In one embodiment, the pulse oximeter acquires samples at arbitrary time instants. A trade-off between noise performances required for the photo-detector circuit and the duration for which the LED is turned ON for each measurement, which also achieves a noise performance.

Fig. 2 shows a low-power pulse oximeter, in accordance with an embodiment of the present disclosure. The oximeter comprises two LEDs and a photo-detector. When one of the LEDs is turned ON and the switch S1 of the integrator is opened, light from the LED is transmitted through the human body part such as a finger or an ear lobe. The intensity of the light that passes through to the other side is measured using a photodiode. As shown in the Fig. 2, the first stage of the low-power pulse oximeter is a current integrator, which converts the photocurrent of the photo diode into a voltage ramp. An amplifier is coupled to the integrator as shown in the Fig. 2, which amplifies the ramp signal from the integrator. The amplified is thresholded against two voltage references. Thereafter, a time to-digital converter (TDC) measures the difference between the times when the amplified ramp hits a two reference voltages. A control unit (not shown in figure) controls the operation of at least one of the integrator, the amplifier, the threshold circuit and the light sources. A processing unit processes the digital output of the TDC to determine oxygen saturation and pulse rate of the human. After the measurement is recorded, the LED, the entire analog circuitry and the TDC are powered down to save power.

Fig. 3 illustrates pulses generated by two LEDs, red and IR LEDs which are alternately flashed once every 5 ms and for each photocurrent measurement, in accordance with an embodiment of the present disclosure. One of the LEDs is kept ON for a duration t_{on} whose precise value depends on the photocurrent at that time.

Fig. 4 illustrates a plot showing output from a TDC for one of the channels (red or IR), in accordance with an embodiment of the present disclosure. As shown in Fig. 4, a discrete time waveform is having plurality of samples separated by 10 ms. To acquire each sample, the switched integrator of the pulse-oximeter accumulates photocurrent for a duration that typically lasts a few hundred microseconds and the measurement made by the

TDC is recorded. As illustrated in Fig. 3, the recorded plethysmogram has a large DC component $t_{dc(dc)}$ and a small AC component $t_{dc(ac)}$.

In an example embodiment, let the circuit starts acquiring a sample at $t = 0$. The output of the first stage is,

$$V_1(t) = \frac{I_{pd}}{C}t \quad (6)$$

where I_{pd} is the photocurrent. I_{pd} is passed through integrator to obtain a ramp signal, which is amplified by the second stage i.e. the amplifier to produce an output voltage,

$$V_2(t) = A \frac{I_{pd}}{C}t \quad (7)$$

where A is a gain of the second stage, which can be digitally controlled. The obtained amplified output voltage is thresholded against two references and the difference between the times when the ramp crosses these two references is measured. After thresholding, the TDC measures the time,

$$t_{tdc} = t_{r2} - t_{r1} = \frac{C}{AI_{pd}}\delta V_r \quad (8)$$

where $\delta V_r = V_{r2} - V_{r1}$, t_{r1} and t_{r2} are the instants when $V_2(t)$ crosses V_{r1} and V_{r2} respectively. The measured t_{tdc} is inversely proportional to the photocurrent. The perfusion is represented as:

$$P = \frac{t_{tdc(ac)}}{t_{tdc(dc)}} \quad (9)$$

Fig. 5 illustrates the ramp output from the TDC in which noise is reflecting as a jitter, in accordance with an embodiment of the present disclosure. In one example embodiment, if the photocurrent I_{pd} is a constant then the output of the TDC will exhibit variance due to noise, which is illustrated in Fig. 5. To quantify the effect of noise, signal-to-noise ratio (SNR) of the acquired plethysmogram is defined as:

$$SNR = \frac{t_{tdc(ac)}}{\sigma_{tdc}} \quad (10)$$

where σ_{tdc} is a standard deviation of the jitter in the output of the TDC due to noise. The signal-to-noise ratio (SNR) can be represented as,

$$SNR^2 = \frac{I_{pd(ac)}^2}{A^2 \left(\frac{2v_{in,n}^2 A_N^2 I_{pd(ac)}^2 \omega_{nb}}{\delta V_r^2} \right) + A \left(\frac{I_{pd(ac)}^2}{C \delta V_r} \right)} \quad (11)$$

5 where $A_N = 1 + \frac{C}{C_d}$ is noise gain of the first stage, $v_{in,n}^2$ is the input referred noise spectral density of the op-amp used for the switched integrator, $\omega_{nb} = \frac{\omega_{ugb}}{A_N}$ is noise bandwidth, ω_{ugb} is a unity gain bandwidth and $i_{pd,n}^2$ is photocurrent noise spectral density.

In one embodiment of the present disclosure, a pulse oximeter comprises a switched integrator front-end which provides a simple way to control the duration of photocurrent measurement. The gain of the second stage i.e. amplifier can be digitally controlled, but the two reference voltages are constants. This allows a control unit to analyze the acquired photoplethysmogram and adjust the gain of the amplifier A to dynamically trade-off SNR for measurement duration as shown in Eq. (11) and (8). Thereby, reduces power consumption as the measurement duration determines the percentage of time for which the LED and the circuitry are powered.

The amplified ramp, which is the output of amplifier, is thresholded against two references. The difference between the times when the ramp crosses these two references is measured. This suppresses the effect of 1/f noise in the integrator stage which can be severe because of the very low signal frequency involved (0.5-6Hz). This is similar to correlated double sampling. However, only the 1/f noise from the amplifiers is suppressed and not the 1/f noise due to the comparator. The comparator 1/f noise has a smaller effect on SNR because the signal may have undergone substantial amplification before reaching the comparator. Since the power supply to the entire analog circuit is duty cycled, 1/f noise gets further suppressed. Also, TDC measurements are subtracted at the peak and trough to obtain $t_{tdc(ac)}$ which suppresses comparator 1/f noise below the heart rate.

In the pulse oximeter, the control unit operates the LEDs at their highest efficiency (luminosity per unit current) so that, LED current is constant. This is in contrast to implementations such as that control the current so that the DC value of the red and IR photoplethysmogram are equal to some pre-determined value. By operating each LED at its maximum efficiency point and controlling only the duty cycle, the power consumption is reduced. Also, this eliminates the need of one more amplifier that may be used to control the LED current. The low-power pulse oximeter uses a time-to-digital converter (TDC) as opposed to an ADC used in the conventional oximeters. This is because it is relatively easier to obtain large dynamic range in TDCs as opposed ADCs, particularly as the supply voltage shrinks.

In one embodiment of the present disclosure, in order to obtain low perfusion, current oximeter implementations use AC coupled amplifiers to separate the large DC level and amplify only the AC component and feed the amplified AC signal to the ADC to make the best use of their dynamic range. The TDCs provide very large dynamic range, thereby permitting the photocurrent to be digitized directly without having to separate the AC signal from the DC. With TDCs with such a large dynamic range, even under low perfusion, quantization noise is sufficiently small. Furthermore, because samples are separated by a relatively large interval of 5 ms, the TDCs may comfortably take more time than the sampling duration to resolve the time difference.

One embodiment of the present disclosure is obtaining suitable parameters of the low power pulse oximeter circuit to reduce power consumption. The parameters are such as, but not limited to, the gain, bandwidth and noise performance of the amplifier and a trade-off. The higher the gain-bandwidth and lower the input referred noise level of the amplifier, the larger will be its bias current and lower will be the necessary measurement duration to achieve a target SNR leading to smaller power burnt in the LED because it can be shut off sooner. Conversely, using an amplifier with smaller gain-bandwidth and poorer noise performance will lead to lower power burnt in the amplifier. However, the duration of measurement will now have to be longer to achieve the desired SNR that is more power is burnt in powering the LED while the photocurrent is being measured. For optimally obtaining the parameters of the amplifier, a power model for op-amps in terms of bandwidth and noise performance are analyzed, and then design-space analysis is performed.

One embodiment of the present disclosure is interface circuit design. Let the photocurrent $I_{pd(dc)}$, perfusion P , the photodiode capacitance C_d and photocurrent noise spectral density $i_{pd,n}$, the circuit parameters C , V_{r1} , V_{r2} , the gain, bandwidth and input referred noise levels of the op-amps as shown in Fig. 1. This is performed so that the total power consumption of the LED and the interface circuit is minimized. For this analysis, only the noise from the first stage is considered and the second stage is assumed to have unity gain. In an example embodiment, let the voltages V_{r1} and V_{r2} be constant or fixed.

One embodiment of the present disclosure is obtaining a circuit parameter gain, which is obtained by knowing the average duration for which the LED is turned ON, to acquire a sample is $t_{on(avg)}$,

$$C = \frac{I_{pd(dc)} t_{on(avg)}}{V_{r2}} \quad (12)$$

The equation (12) sets the noise gain A_N at $(1 + \frac{C_d}{C})$.

One embodiment of the present disclosure is obtaining a parameter Bandwidth. The output of the switched integrator $V_1(t)$ of the Fig. 1, may not be a perfect ramp because of the limited bandwidth of the op-amp. In order to obtain the minimum bandwidth which keeps non-linearity at an acceptable level, the op-amp Bandwidth may satisfy the below equation:

$$\frac{\omega_{nb} \left(\frac{\delta V_r}{V_{r2}} \right) t_{on(avg)}}{e^{-\left(\frac{C \omega_{nb} V_{r2}}{I_{pd(dc)}} \right)} - e^{-\left(\frac{C \omega_{nb} V_{r1}}{I_{pd(dc)}} \right)}} \geq SNR_r \quad (13)$$

where SNR_r is the minimum SNR necessary to make sufficiently accurate SpO_2 calculations, $\omega_{nb} = \frac{\omega_{ugb}}{A_N}$, is the noise bandwidth and ω_{ugb} is the unity gain bandwidth. Using the equation (13), the minimum acceptable bandwidth is obtained for a given $t_{on(avg)}$. Also, equation (13) indicates that $t_{on(avg)}$ may be increased, to reduce the required bandwidth.

One embodiment of the present disclosure is obtaining a parameter Input referred noise. Referring the jitter in the output of TDC (σ_{tdc}) back to the input of the op-amp, the

maximum permissible input referred noise spectral density of the op-amp. So that, the SNR of the acquired plethysmogram is greater than SNR_r can be shown to be

$$v_{in,n}^2 = \frac{\delta V_r I_{pd(dc)}^2 t_{on(avg)}}{2V_{r2} A_N^2 C^2 \omega_{nb}} \left[\frac{P^2 \delta V_r t_{on(avg)}}{SNR_r^2 V_{r2}} - \frac{i_{pd,n}^2}{I_{pd(dc)}^2} \right] \quad (14)$$

Equation (14) shows that as $t_{on(avg)}$ is increased and the input referred noise requirement gets relaxed.

One embodiment of the present disclosure is obtaining a parameter reference voltage. Let the voltage V_{r1} and V_{r2} that are as high as possible within the input common mode range of the comparator so that the noise performance of the comparator is maximized. If V_{r1} and V_{r2} are close to each other, δV_r becomes small and from Eq. (14), the permissible input referred noise of the op-amp reduces which in turn causes an increase in the op-amp power consumption. From Equation (13), the bandwidth required increases which also cause an increase in the power consumption of the op-amp, as shown in Fig. 6. As shown in Fig. 6 which illustrates the output of the switched integrator. In an example embodiment, if δV_r is small the output is closer to a straight line between V_{r1} and V_{r2} . If δV_r is large, a larger portion of non-linearity gets captured. To avoid the extremes the voltages are chosen as $V_{r1} = 1.25$ V and $V_{r2} = 2.5$ V. A small variation in the reference voltages due to comparator offset or reference generator offset are insignificant because only the ratio of readings and the voltage reference terms get cancelled.

One embodiment of the present disclosure is an op-amp power model. The power consumption of an op-amp is estimated for op-amp parameters such as, but not limited to gain, bandwidth and input referred noise level. In an example embodiment, the op-amp may be assumed to be constructed by cascading a number of simple amplifiers each having a gain of 10. The required number of stages is $\log_{10}(A_{V(total)})$ where $A_{V(total)}$ is the required op-amp gain. Hence, the current consumption of the op-amp is

$$I_D(total) = \log_{10}(A_{V(total)}) \times I_{Dps} \quad (15)$$

where I_{Dps} is the current per stage. The bandwidth is represented as,

$$BW = K_1 I_{Dps} \quad (16)$$

where K_1 is a model parameter.

The 1/f noise in the example model is ignored because the circuit is designed to be resistant to 1/f noise and approximate input referred noise as,

$$v_{in,n}^2 = K_2 \frac{BW}{I_{Dps}} \quad (17)$$

where K_2 is a model parameter. In one example embodiment, for a given input referred noise and bandwidth, I_{Dps} is represented as,

$$I_{Dps} = \max\left(\frac{BW}{K_1}, \frac{K_2 \cdot BW}{v_{in,n}^2}\right) \quad (18)$$

Therefore, the current consumption of the op-amp to the equation (15) to (18) is

$$I_{D(total)} = \log_{10}(A_{V(total)}) \times \max\left(\frac{BW}{K_1}, \frac{K_2 \cdot BW}{v_{in,n}^2}\right) \quad (19)$$

In an example embodiment, the parameters K_1 and K_2 in the equations (18) and (19) may be obtained from least mean squares fits, for the data of about 35 discrete op-amps, which may have an input bias current below 50 pA. Figs. 7 and 8 illustrate scatterplots of supply current against op-amp parameters and the least mean squares fit. The mean of the absolute relative errors is about 57.3%. Fig. 7 illustrates a scatter plot showing supply current in terms of bandwidth in the log-log scale for discrete op-amps, with a value of $K_1 = 1.32 \cdot 10^{10}$.

Fig. 8 illustrates a scatterplot of supply current in terms of bandwidth per input referred noise for discrete op-amps. The one extreme point in the plot of Fig. 8 may be ignored during fitting with a value of $K_2 = 3.02 \cdot 10^{-27}$.

Fig. 9 illustrates a plot showing a trade-off between amplifier power and LED power. For example, let SNR be 100 for the perfusion of 1.5%, the photodiode junction

capacitance is 1nF and the DC value of the photocurrent is 100nA. The LED is turn ON with on-time ($t_{on(avg)}$), the op-amp parameters needed for each $t_{on(avg)}$, power for the op-amp from the power model are computed. The power consumption based on the LED ON time is obtained which is shown as a plot in Fig. 9. The optimal ON time for the probe used corresponds to 237 μs which requires a gain of 106, closed-loop $\sqrt{}$ bandwidth of 1 MHz and an input referred noise of 2 nV/Hz.

Fig. 10 illustrates a plot showing SNR in terms of LED on-time of the oximeter placed on different fingers of the human, in accordance with an embodiment of the present disclosure. The below is a Table I illustrating noise estimation performance of oximeter.

σ of added noise	Estimated σ	SNR	SNR
(a.u.)	(a.u.)	actual	calculated
1000	1004	2.2	2.19
100	99.83	22	22.03
50	50.69	44	43.4
25	25.53	88	86.17
10	11.67	220	188.5
5	7.57	440	290.62

Table 1

An example embodiment of the present disclosure is about Minimum SNR tracking. For optimizing the amplifier parameters of the oximeter, by assuming that the perfusion is 1.5% and that the average photocurrent is 100 nA. The average photocurrent depends on the parameters such as, but not limited to, the thickness of the finger, amount of oil on the skin surface and an order of magnitude. Also, the perfusion exhibits considerable variance and is in the range of 0.1% and 5% and also depends on ambient temperature. Furthermore, the noise input into the oximeter system depends on ambient lighting and the extent to which ambient light reaches the photodiode. The pulse oximeter has to provide widely varying SNR levels, because of which, the optimal amplifier parameters determined should be treated as a guiding value rather than precise targets to achieve. Fig. 10 shows variation of SNR with measurement duration for three fingers of a human. For example as shown in Fig.

10, to achieve a SNR value of 100, the duration for which the LED needs to be turned ON, and hence power is 2.5 times higher for the middle finger than for the forefinger. The pulse oximeter as shown in Fig. 2 measures the SNR of the acquired photoplethysmogram continuously and dynamically adjusts LED on-time, and hence power consumption so that
 5 the oximeter operates at a sufficient SNR, which is called as minimum SNR tracking.

The signal level may be estimated by measuring the AC value of the plethysmogram. Since, the plethysmogram is known to be low pass in nature that is signals are in the frequency band 0.5Hz to 6Hz, filtering is performed to remove all low-frequency content which is less than 10Hz. In an example embodiment, assuming that the input noise
 10 is white noise, the filtered waveform may contain only pink noise. The variance of the noise is calculated and scaled to obtain the noise variance of the acquired photoplethysmogram, thereby SNR is obtained.

In another example embodiment of the present disclosure, 400 samples are recorded at high SNR, by keeping measurement duration above 1ms. The high SNR recording was
 15 deemed to have infinite SNR. Additive White Gaussian Noise (AWGN) may be added to the recording and an estimate of the AWGN is obtained. Table I shows the performance of blind estimation of noise with a fourth order butterworth high pass filter, in accordance with an embodiment of the present disclosure. The mean of the estimated noise over 1000 realizations of pseudo-random noise is reported. The blind estimation method may work
 20 well at low to medium SNR and underestimates high SNRs. It is able to compute SNR readings below 100 satisfactorily with a fourth order butterworth high-pass filter.

Fig. 11 illustrates a flowchart of the dynamic adaptation techniques, according to an embodiment of the present disclosure. The acquiring samples involve powering an LED, which power consumption in the pulse oximeter and to reduce the power consumption the
 25 duration for which the LED is turned ON is reduced for each measurement. In another embodiment, a method of reducing power is performed by taking fewer samples from the oximeter which translates to turning or switching ON the LED fewer times on average compared to the conventional way of switching ON the LED. The samples that may be used in computing SpO_2 are the peaks and troughs of the photoplethysmogram. So, by estimating
 30 when the peaks or troughs happen, sampling can be performed just before the time when these events are expected to occur. This is similar to the working of phase locked loop

(PLL), hence this may be called as PLL tracking. After detecting occurrence of a peak in the photoplethysmogram, the oximeter device or system skips sampling for duration equal to 50% of the expected peak-to-peak interval.

In one embodiment of the present disclosure, the oximeter system resets the loop for every 10 cycles and forces the same to re-lock. The result of this is that it takes much longer to be confident of heart rate measurements. A flowchart describing both the “Minimum SNR tracking” and “PLL tracking” techniques is shown in Fig. 11.

In some example embodiment of the present disclosure, a fingertip probe may be used and reference values are taken as shown in Table. II: (components used in the prototype)

Component	Part Used
Opamps	OPA2314
Comparators	TLV3202
Reference generators (V_{r1} , V_{r2})	REF3312, REF3325
Switch (S1)	MAX4594
Power Gate	TS3A4751
Digital Potentiometer (gain A)	TPL0501-100
C (integration capacitor)	100 pF
TDC	Timer1 (16-bit) of CC2540

Fig. 12 illustrates captured photoplethysmogram from the prototype oximeter, in accordance with an embodiment of the present disclosure. As shown in Fig. 12, plotted on the y-axis are measurements made by the TDC of Fig. 2. First, the control unit, with control algorithm recognizes that the SNR of the acquired plethysmogram is higher than necessary and the step like reduction indicates the decrease in LED on-time, increase in the gain of the second stage in Fig. 2. Next, the PLL tracking algorithm may skip samples between peaks.

After the reduction of LED on-time, the PLL tracker is reset and then re-locks to the heart rate.

One example embodiment of the present disclosure shows that the minimum SNR tracking loop settled to a steady state within 25 seconds after the finger is inserted into the probe, of the pulse oximeter. The time taken may be acceptable as SpO_2 is remotely monitored continuously for hours at a time. Furthermore, since each peak-trough measurement is tagged with SNR, SpO_2 may be confidently measured even if the loop is not in steady state.

One embodiment of the present disclosure is calibration of the pulse oximeter. The calibration is performed using finger simulators from BC Biomedical group. The finger simulators had known SpO_2 levels of 80%, 90% and 97%. Performing linear regression on the acquired readings gave $a = 112.8$ and $b = 24$ in Equation (5). The accuracy of the pulse oximeter may be verified by comparing the readings from the oximeter with readings from a commercial finger-tip oximeter. In an example embodiment, an accuracy test is performed on an arbitrary number of humans, let the number be 10, the highest measured SpO_2 was 99% and the lowest was 93%. In 9 cases, the difference between reported SpO_2 readings from the prototype oximeter and the commercial oximeter was no more than 1%. In one case, the difference was 2%, which is acceptable because the oximeter prototype is designed with a target of 3% accuracy and the commercial oximeter also had an accuracy of 3%.

In one embodiment, the minimum SNR tracking approach may have motion artifacts and deteriorate the performance of the oximeter. To reduce chances of motion artifacts affecting signal level measurement, the signal level from the past 5 peaks is averaged after removing the maximum and minimum signal level and then SNR is computed. In the event that an erroneous signal level measurement creeps in through this check, one of two things can happen. Either the SNR is underestimated or it is overestimated. If the SNR is underestimated, the loop increases the measurement duration and burns more power for a while before reducing the measurement duration. For this case, the readings are unaffected and the only impact is that the pulse oximeter system consumes higher power than necessary for a short while. On the other hand, if the SNR is overestimated, the loop reduces the measurement duration and the SNR of the acquired readings will be lower than acceptable. This is because each signal measurement is tagged with SNR and the readings

with below acceptable SNR get rejected and are not reported to the user. After detecting that the SNR is lower than necessary, the measurement duration is increased. A sample waveform where the loop erroneously chooses a lower than acceptable LED ON-time because of motion artifacts and then recovers after the transient artifact has passed is shown in Fig. 13. Since SpO_2 changes relatively slowly, the occasional loss of readings will not affect system operation. Furthermore, power consumption may be avoided by setting the target SNR of the loop to be slightly higher than the minimum required SNR. Then, even if the loop occasionally acquires readings at SNR below its target, the SNR still remains higher than that is necessary and the readings continues to be valid. The impact of motion artifacts would have been worse if a proportional controller approach has been used to set the measurement duration. The motion artifacts are transient, which when coupled with the constant step approach to changing the measurement duration, reduces the impact of such artifacts.

Also, the PLL tracking algorithm is affected by motion artifacts but in a more benign manner. The rapid occurrence of edge like features in the plethysmogram during motion artifacts can cause the PLL tracking algorithm to underestimate the peak to peak interval. Once the transient artifact has passed, the tracking algorithm which now expects a short peak to peak interval will wait until the next peak due to a heartbeat and relock to the heart rate. A recording that demonstrates the performance of the PLL tracking in the presence of artifacts is shown in Fig. 14. Even in the extraordinary event that the motion artifact causes the algorithm to lock onto an integral fraction of the heart rate, the duration for which the heart rate is misreported is controlled. This is because the tracking loop is forced to relock once every 10 cycles.

Fig. 15 illustrates a graph showing power divided into LED power, analog power and processor or control unit power for different fingers, in one embodiment of the present disclosure. A microcontroller and analog components are powered by separate channels and the power for each was thus measured. The LEDs were powered from the microcontroller IO pins. Since, the duration for which the LEDs were powered is measured and the LED current was kept at a fixed level, we could compute the LED power and subtract it from the total power consumed by the microcontroller to separate LED power from processing power. The plot in Fig. 15 shows the impact of each of the proposed dynamic adaptation

techniques and also how they work in tandem to reduce power. Analog power is the total power consumed by the analog parts of the system which includes op-amps, comparators and reference generators. The processor power refers to the power consumed by the digital parts of the oximeter including the power consumed by the TDC, oscillator for the system clock, the processor which runs control algorithms and calculates SpO₂, heart rate from the waveforms. The power for the entire platform i.e. the pulse oximeter is reported. All the elements of the platform including analog circuitry, TDC, processor and the system clock generator, with the exception of the 32 kHz sleep timer are duty cycled. When the minimum SNR tracking is enabled and the LED ON-time reduces, the fraction of the time for which the entire platform is active also reduces and hence the processor power reduces.

Similarly, when PLL tracking is enabled, the entire platform, again with the exception of the 32 kHz sleep timer, sleeps for approximately 0.5 seconds when samples are skipped and thus the average power goes down. The PLL tracking usage cuts the number of samples acquired by 35% and as we expected, the power consumption gets cut by the same percentage. On average, Minimum SNR tracking reduces power consumption by a factor 3.9. Furthermore, the power consumption varies from one finger to the other while the SNR is held constant. The PLL tracking and Minimum SNR tracking in tandem reduce power consumption by 6 times on average compared to when both techniques are disabled.

In one embodiment, remotely sensing the physiological parameters may reduce mortality while lowering the cost of health care and low-power sensors are essential for remote sensing. In building a low-power oximeter, design-space analysis was performed to explore the trade-off between spending power in the LED and burning power in a higher performance amplifier. Dynamic adaptation techniques lower power considerably by operating the sensor at the edge of the SNR requirement and acquiring samples only when necessary.

The terms "an embodiment", "embodiment", "embodiments", "the embodiment", "the embodiments", "one or more embodiments", "some embodiments", and "one embodiment" mean "one or more (but not all) embodiments of the invention(s)" unless expressly specified otherwise.

The terms "including", "comprising", "having" and variations thereof mean "including but not limited to", unless expressly specified otherwise.

The enumerated listing of items does not imply that any or all of the items are
5 mutually exclusive, unless expressly specified otherwise.

The terms "a", "an" and "the" mean "one or more", unless expressly specified otherwise.

10 Devices that are in communication with each other need not be in continuous communication with each other, unless expressly specified otherwise. In addition, devices that are in communication with each other may communicate directly or indirectly through one or more intermediaries.

15 A description of an embodiment with several components in communication with each other does not imply that all such components are required. On the contrary a variety of optional components are described to illustrate the wide variety of possible embodiments of the invention.

20 Further, although process steps, method steps, algorithms or the like may be described in a sequential order, such processes, methods and algorithms may be configured to work in alternate orders. In other words, any sequence or order of steps that may be described does not necessarily indicate a requirement that the steps be performed in that order. The steps of processes described herein may be performed in any order practical.
25 Further, some steps may be performed simultaneously.

When a single device or article is described herein, it will be readily apparent that more than one device/article (whether or not they cooperate) may be used in place of a single device/article. Similarly, where more than one device or article is described herein
30 (whether or not they cooperate), it will be readily apparent that a single device/article may be used in place of the more than one device or article or a different number of devices/articles may be used instead of the shown number of devices or programs. The functionality and/or the features of a device may be alternatively embodied by one or more other devices which are not explicitly described as having such functionality/features. Thus,
35 other embodiments of the invention need not include the device itself.

The illustrated operations of Fig. 11 show certain events occurring in a certain order. In alternative embodiments, certain operations may be performed in a different order, modified or removed. Moreover, steps may be added to the above described logic and still conform to the described embodiments. Further, operations described herein may occur sequentially or certain operations may be processed in parallel. Yet further, operations may be performed by a single processor or by distributed processing units.

The foregoing description of various embodiments of the invention has been presented for the purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed. Many modifications and variations are possible in light of the above teaching. It is intended that the scope of the invention be limited not by this detailed description, but rather by the claims appended hereto. The above specification, examples and data provide a complete description of the manufacture and use of the composition of the invention. Since many embodiments of the invention can be made without departing from the spirit and scope of the invention, the invention resides in the claims hereinafter appended.

Finally, the language used in the specification has been principally selected for readability and instructional purposes, and it may not have been selected to delineate or circumscribe the inventive subject matter. It is therefore intended that the scope of the invention be limited not by this detailed description, but rather by any claims that issue on an application based here on. Accordingly, the disclosure of the embodiments of the invention is intended to be illustrative, but not limiting, of the scope of the invention, which is set forth in the following claims.

With respect to the use of substantially any plural and/or singular terms herein, those having skill in the art can translate from the plural to the singular and/or from the singular to the plural as is appropriate to the context and/or application. The various singular/plural permutations may be expressly set forth herein for sake of clarity.

In addition, where features or aspects of the disclosure are described in terms of Markush groups, those skilled in the art will recognize that the disclosure is also thereby

described in terms of any individual member or subgroup of members of the Markush group.

5 While various aspects and embodiments have been disclosed herein, other aspects and embodiments will be apparent to those skilled in the art. The various aspects and embodiments disclosed herein are for purposes of illustration and are not intended to be limiting, with the true scope and spirit being indicated by the following claims.

Claims:

1. A pulse oximeter comprising:

5 a physiological-pulse transducer comprising one or more light sources to generate pulses of light of predetermined wavelengths at controllable intervals with controllable pulse duration to be incident on a subject; and a photodetector configured to receive the pulses of light which passes through the subject to generate a corresponding photocurrent;

10 an integrator coupled to the photodetector to convert the photocurrent into a monotonically changing voltage signal;

an amplifier with controllable gain to amplify the voltage signal generated by the integrator;

a threshold circuit to indicate a time duration for which the amplified voltage signal is present within predetermined reference voltages;

15 a time to digital converter coupled to the threshold circuit to provide a digital value equivalent to the time duration;

a control unit to control the operation of at least one of the integrator, the amplifier, the threshold circuit and the light sources; and

20 a processing unit to process the digital output of the TDC to determine oxygen saturation and pulse rate of the subject.

2. The pulse oximeter as claimed in claim 1, wherein the physiological-pulse transducer further comprises one or more light emitting diodes (LED) configured as light sources to generate pulses of light at predetermined wavelengths at controllable intervals and with controllable pulse duration, to be incident on the subject.

3. The pulse oximeter as claimed in claim 1 further comprising at least one amplifier coupled to the integrator to amplify the voltage signals, with at least one amplifier being digitally controlled to adjust the gain.

30 4. The pulse oximeter as claimed in claim 1, wherein the integrator is a switch integrator.

5. The pulse oximeter as claimed in claim 1, wherein the TDC provides a large dynamic range compared to an analog to digital converter.

6. The pulse oximeter as claimed in claim 1, wherein the control unit controls the acquisition of a sample by controlling the turning ON one or more light sources, the photo detector, the integrator, the amplifier, the threshold circuit and the TDC
7. The pulse oximeter as claimed in claim 1, wherein the control unit determines the signal to noise ratio of the measured signals, determines the optimal gain of the amplifier and the optimal duration of the ON time of the light sources, the photo detector, the integrator, the threshold circuit and the TDC, thereby saving power consumption.
8. The pulse oximeter as claimed in claim 7, wherein the control unit digitally controls gain of the at least one amplifier to dynamically adjust signal to noise ratio (SNR) to achieve minimum power with good measurement fidelity compared with the conventional pulse oximeters.
9. The pulse oximeter as claimed in claim 7, wherein the control unit controls the pulse duration and the duty cycle of the light sources dynamically based on the predefined signal to noise ratio to achieve good fidelity measurement when compared with the conventional pulse oximeters.
10. The pulse oximeter as claimed in claim 1, wherein the control unit controls acquisition of samples so that samples are acquired only where peaks and troughs of the photocurrent generated by the photodetector are expected to occur, thereby reducing power consumption of the pulse oximeter.
11. The pulse oximeter as claimed in claim 3, wherein the control unit controls the acquisition of samples using a phased locked loop to keep track of the peaks and troughs in the photocurrent.
12. The pulse oximeter as claimed in claim 1, wherein the threshold circuit converts the voltages signals into time domain signals.
13. The pulse oximeter as claimed in claim 1, wherein the control unit performs at least one of controlling duration of photocurrent measurement by the integrator, controlling gain of the at least one amplifier, controlling the reference voltages of the threshold circuit

and operating each of the LEDs at a predetermined duty cycle to reduce power consumption of the pulse oximeter.

14. A method of reducing power consumption in a pulse oximeter, the method comprising:

5 generating successive pulses for powering one of plurality of light emitting diodes (LEDs) of the physiological-pulse transducer to generate photocurrent;

 receiving, by a control unit, a time difference signal generated by time to digital control (TDC), said TDC generates the time difference signal from the photocurrent; and

10 controlling predetermined parameters of all components of the pulse oximeter, thereby reducing power consumption in the pulse oximeter.

15. The method as claimed in claim 14, the predetermined parameters are at least one of gain of amplifier, duty cycle of the LEDs and signal to noise ratio (SNR) being obtained
15 from the photocurrent.

16. The method as claimed in claim 14, wherein acquiring of samples at peaks and troughs of the photocurrent is controlled by the control unit controls, thereby reducing power consumption of the pulse oximeter.

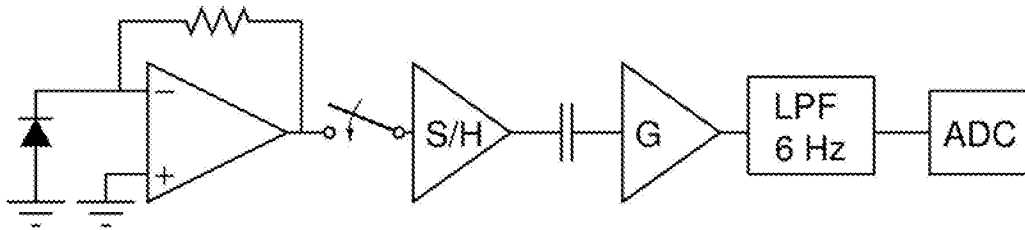


Fig. 1 (Prior Art)

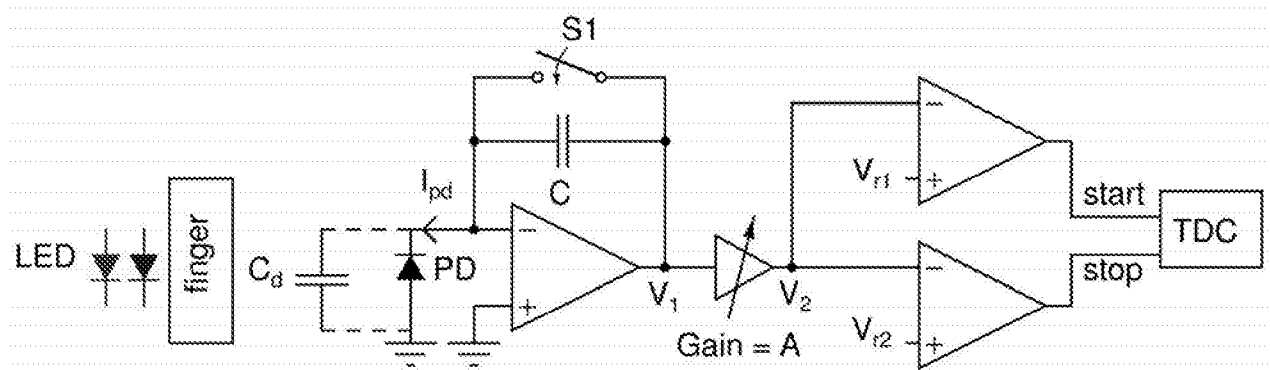


Fig. 2

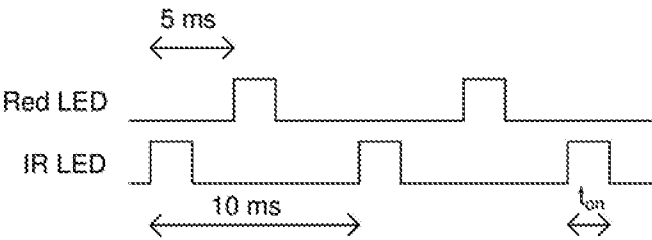


Fig. 3

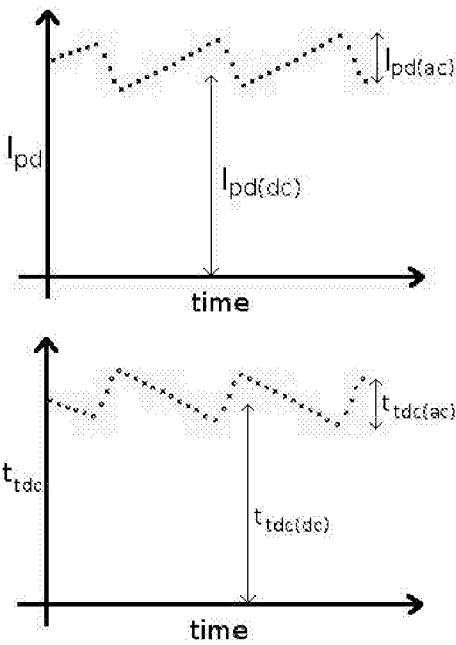


Fig. 4

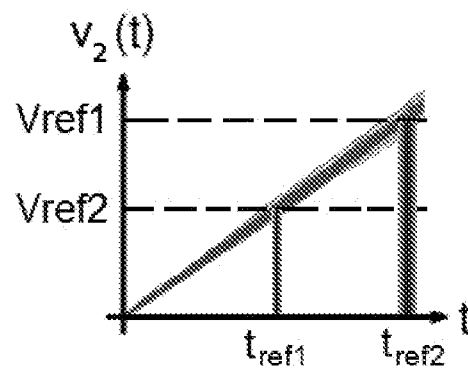


Fig. 5

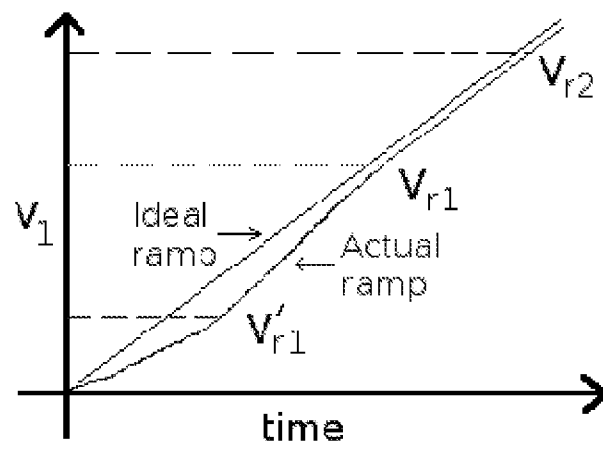


Fig. 6

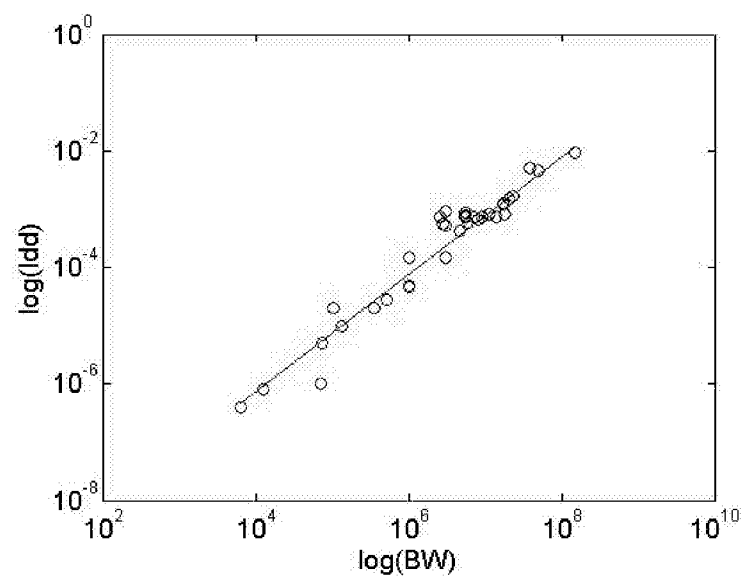


Fig. 7

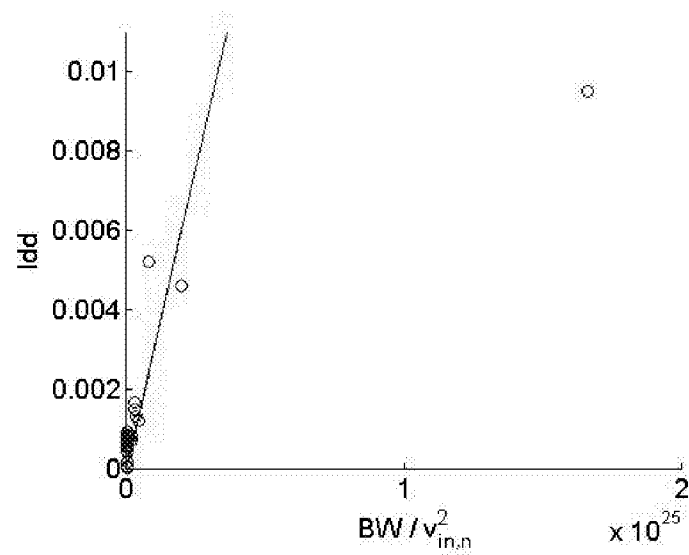


Fig. 8

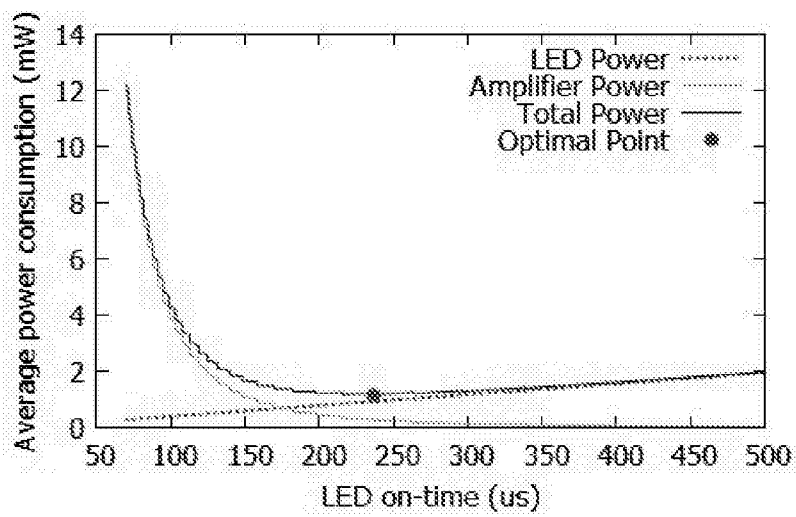


Fig. 9

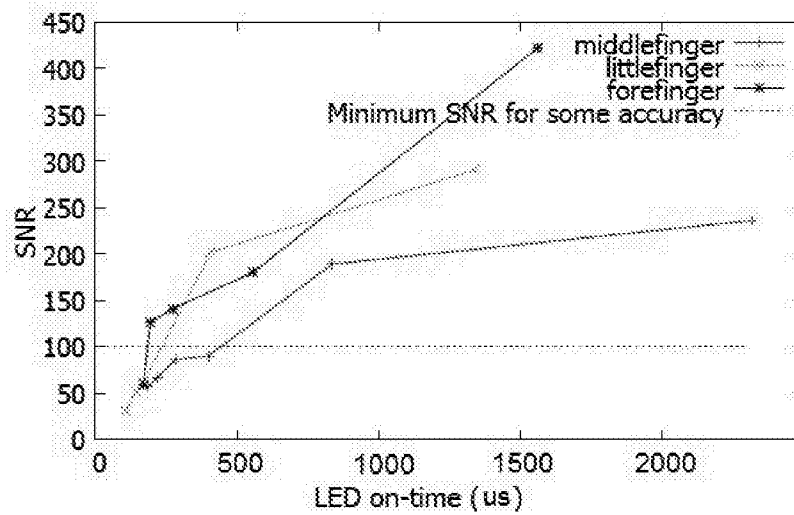


Fig. 10

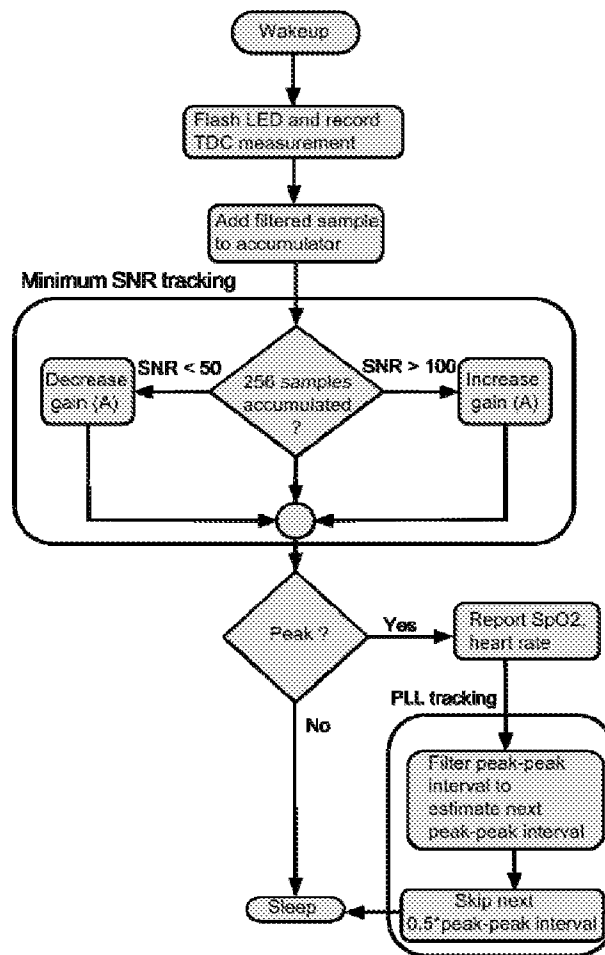


Fig. 11

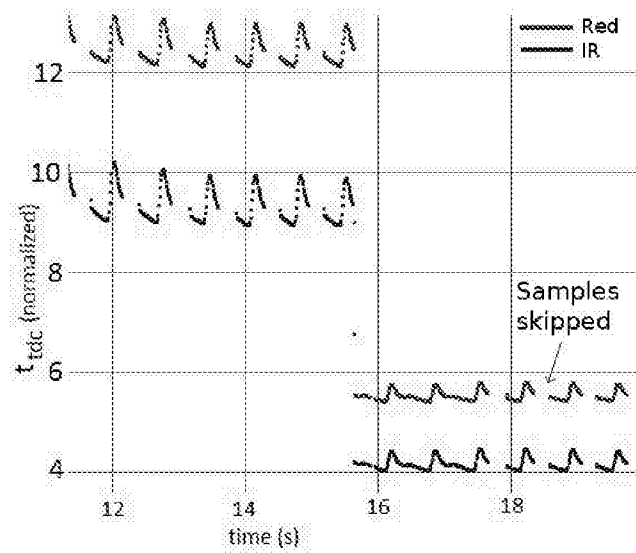


Fig. 12

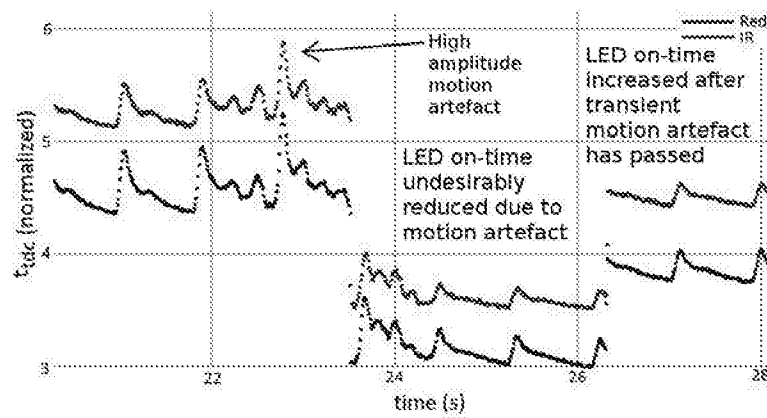


Fig. 13

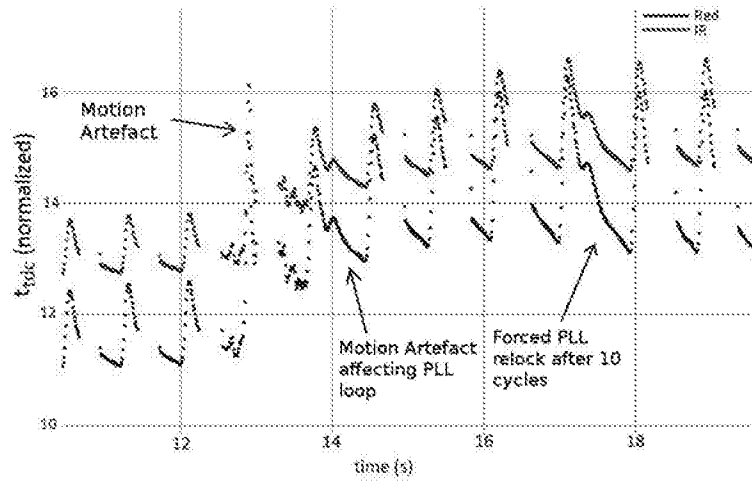


Fig. 14

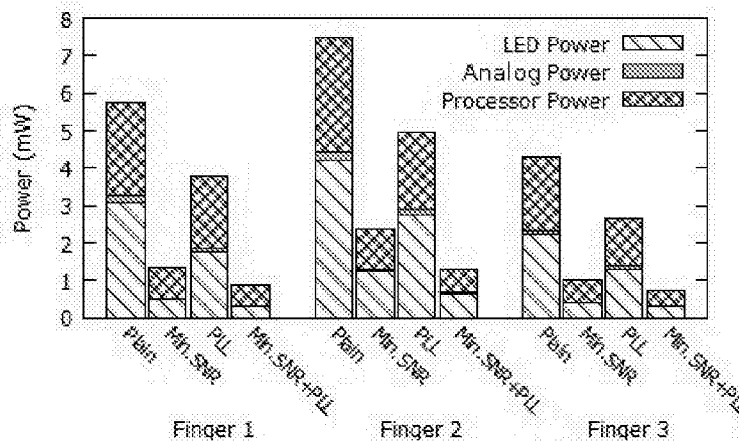


Fig. 15

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2015/052579

A. CLASSIFICATION OF SUBJECT MATTER

INV. A61B5/024 A61B5/1455
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

A61B H03M

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EP0-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2012/232354 A1 (ECKER ROBERT MICHAEL [US] ET AL) 13 September 2012 (2012-09-13) paragraphs [0002], [0019], [0021] - [0025], [0028], [0030], [0033], [0034], [0043] - [0045], [0047]; figures 1-4	1-16
A	US 8 643 526 B1 (DEY SANJOY K [IN] ET AL) 4 February 2014 (2014-02-04) column 1, lines 5-21 column 3, line 63 - column 4, line 16 figure 1	1-16
A	US 2012/157861 A1 (JARVERUD KARIN [SE] ET AL) 21 June 2012 (2012-06-21) paragraph [0064]; figure 3	1-16
	----- -/--	



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

6 July 2015

Date of mailing of the international search report

14/07/2015

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Authorized officer

Mecking, Nikolai

INTERNATIONAL SEARCH REPORT

International application No

PCT/IB2015/052579

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2010/079322 A1 (GLADSHEIN VICTOR [IL] ET AL) 1 April 2010 (2010-04-01) paragraph [0044]; figure 4A -----	1-16
X,P	GUBBI SAGAR VENKATESH ET AL: "Adaptive Pulse Width Control and Sampling for Low Power Pulse Oximetry", IEEE TRANSACTIONS ON BIOMEDICAL CIRCUITS AND SYSTEMS, IEEE, US, vol. 9, no. 2, 30 June 2014 (2014-06-30), pages 272-283, XP011579742, ISSN: 1932-4545, DOI: 10.1109/TBCAS.2014.2326712 [retrieved on 2015-04-29] the whole document -----	1-16

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/IB2015/052579

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
US 2012232354	A1	13-09-2012	NONE	

US 8643526	B1	04-02-2014	NONE	

US 2012157861	A1	21-06-2012	US 2012157861 A1	21-06-2012
			US 2015173653 A1	25-06-2015
			WO 2011025415 A1	03-03-2011

US 2010079322	A1	01-04-2010	NONE	
