A Remote Monitoring of Photoplethysmography signals and spo2 in COVID wards using visible light communication

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Abstract:

Mobile phones and Radio Frequency energy sources in hospitals produce RF interference with medical devices, brings a threat to the health of the patients. Pulse Oximetry is a non invasive method which generates the PPG signals that are transferred wirelessly inside hospitals that enable quick action to provide oxygenation to the patients. But the RF sources and mobile phones produce RF interference with PPG signals and spo2 values. The operation of Pulse Oximeters fails near RF sources and displays a fault spo2 value for the patients due to radiofrequency interferences in hospitals. This interference can be avoided by utilizing the visible light spectrum for communication inside the health care units. This paper focuses on pulse oximetry in COVID wards to avoid physical interaction, for real time transmission of PPG signals and spo2 using visible light communication. The proposed method eliminates radiofrequency interference with pulse oximeters by utilizing the light spectrum to transmit the spo2 and PPG signals. The proposed work also incorporates bootstrapping action in the photodiode at the receiver to eliminate noise and to improve bandwidth of the system. Using this method, the noise gain has been reduced to ten times in the proposed system. The experimental results produce a communication range of 80 cm at maximum baud rate of 19200 bits per second with a mean square error of 1.2e-^{11}.

Keywords: *Radio frequency interference, Pulse Oximetry in COVID ward, Visible light communication,VLC, Photoplethysmography, spo2,Percentage of peripheral oxygen.*

Introduction

Pulse Oximeter is a non invasive method used to estimate the blood oxygen saturation, pulse rate and heart rate. It is mainly used to measure the saturation of peripheral oxygen (spo2), i.e. the amount of oxygen dissolved in the blood [8]. The spo2 value for a normal well being should be in the range of 95% to 100%.In hospitals.

COVID-19 is rapidly spreading across the world wide and health care units are under tremendous pressure to reduce the mortality rate. Every Health care units have isolated COVID wards where a group of patients are allotted to each healthcare professional, to be monitored remotely. A continuous wireless spo2 monitoring in health care wards has become mandatory to avoid physical interaction[14]. The early signs in patients with suspected COVID-19 can be identified by decreased oxygen saturation levels which are much vital to recognize before the patient becomes symptotic. Pulse Oximeters plays a vital role in current situation where spo2 and PPG signals are monitored in the COVID wards frequently. As the nature of the COVID is contagious, remote monitoring is the only mechanism to provide primary healthcare.

Many wireless monitoring methods that use radio waves for monitoring of Oxygen saturation levels may produce Radiofrequency interference leading to an inaccurate reading of spo2.

In operation theaters, patients are given anesthesia before surgery. The amount of anesthesia delivered to a patient before surgery can be judged by oxygen saturation. Patients who have spo2 level greater than 90% are permitted for surgery [1]. These Pulse Oximeters may fail to operate near RF sources due to electromagnetic interference in hospitals and healthcare units. The electronic circuitry

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of pulse oximeters is sensitive to the RF interferences. A pulse oximeters may display spo2 hemoglobin saturation level of 100 % for a diseased patient[6].This may be because of placement of mobile phones, telemetry transceivers too close to the pulse oximeters. The RF interference produced contributes a huge error to the pulse oximetry[6].

Pulse oximeters are also used to determine patient's heart rate during MRI scan. Sedated patients are monitored using pulse oximeters during MRI procedures. The working of Pulse oximeters has become unsteady due to interference from RF magnetic fields during MRI procedure. Pulse Oximeters using fiber optic technology have been developed to transmit the photoplethysmograph signals without any interference from the electromagnetic fields of MRI procedure. But the fiber optic cables are very delicate and can be broken easily [6].

This problem can be eliminated by Visible light communication (VLC).VLC is a rapid growing technology which uses visible light (400nm to 780 nm) as a medium for data transmission [4].Hence Visible light communication can be used not only in MRI compatible pulse oximetry and operation theaters, to monitor heart rate and but also in COVID WARDS to monitor oxygen saturation for patients, without any electromagnetic interference [12].

VLC uses Light emitting diodes (LEDs) to transmit data wirelessly.LEDs have numerous advantages compared to incandescent lamps in terms of power consumption, operational life time and energy efficiency[13].The method of embedding a digital signal into the highly switching characteristic of LED is known as Visible light communication[13]. In this paper, the RF interference with pulse oximeter was eliminated by transmitting the PPG signals and spo2 value in COVID wards using visible light.

Material and Methods

In the proposed method, real time PPG signals and spo2 were transmitted using visible light communication. The spo2 sensor used is Nellcor ds-100A sensor which consists of two LEDs, Red, IR LED and a photodiode. The Red and IR LEDs emit a wavelength of 660nm and 940 nm respectively. This spo2 sensor is connected to DAQ for signal acquisition into the labVIEW.The timing for switching both the LEDs on and off is controlled by DAQ card (NImyDAQ) through labVIEW in the transmitter. The time interval between the switching off LEDs is set to 250µs.

Oxygen plays a vital role for aerobic respiration. The body cells require oxygen to gain energy by respiration. The oxygen is circulated in the body by blood. The Red blood cells of the blood has a protein known as hemoglobin[9].Oxygen gets attached with hemoglobin to produce oxy hemoglobin(HbO2).When blood comes in contact with a body cell, the oxygen from the hemoglobin gets released to energize the cell and becomes deoxygenated hemoglobin(Hb) known as Deoxyhemoglobin. Based on the amount of Oxyhemoglobin and Deoxyhemoglobin, the amount of oxygen dissolved in the blood can be measured .This is known as Oxygen saturation which is given by equation (1)

$$\mathrm{spo2} = \frac{\mathrm{Hbo2}}{\mathrm{Hbo2+Hb}} * 100 \qquad (1)$$

This non-invasive measurement of Oxygen saturation is known as Pulse oximetry [9].The absorption of Oxyhemoglobin and Deoxyhemoglobin can be measured at two wavelengths, 660nm and 940 nm. The Red light spectrum corresponds to 940 nm. The Infra red light spectrum corresponds to 660nm. At 660nm, deoxygenated hemoglobin has maximum absorption and at 940 nm, Oxyhemoglobin has maximum absorption [9].

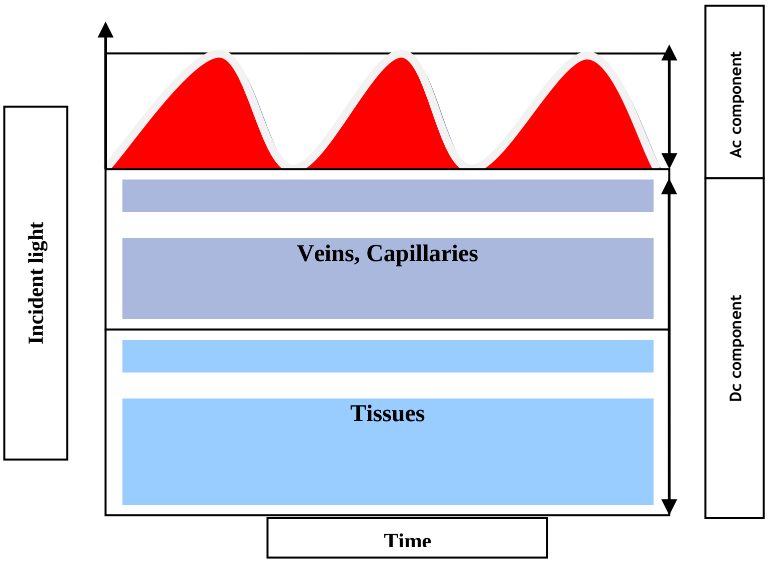

Figure 1.Light aborption in finger

Blood is pumped through arteries and veins.PPG (photoplethysmograph) is a voltage signal that measures the intensity of the light that is transmitted through blood with respect to systole and diastole of the heart beat. The finger is placed between the IR,Red LEDs and the photodiode. The pulse oximeter designed in this experiment is of transmittance type. The Light from the LED is absorbed by the blood. This absorbed light contributes to the 'AC component 'and the 'DC component'. Blood through the arteries will be pulsatile in nature, known as the 'AC component'. Blood through the veins and capillaries will be a constant [7], i.e. will not be with respect to systole and diastole of the heart beat. This is the 'DC component 'of the blood. The intensity of the light is decreased as the volume of the blood increases in the arteries during a systole. The Intensity of the light increases as the volume of the blood in the arteries decreases. Hence a PPG signal is pulsatile with the heart rate[7].The process of light absorption through the finger is shown in the figure 1.

The pulse oximetry is based on Beer Lambert's law. This law states that when a light is transmitted through a medium, based on the intensity of the light transmitted, the concentration of the absorbing substance in the medium can be determined. The specific concentration of the medium is given by 'C' .Absorptivity or extinction coefficient is ε(γ) at a particular wavelength. I is the intensity of the transmitted light. The relationship between the transmitted and incident light[3] is given by equation (2)

$$I = I_N e^{-\varepsilon(\gamma)}.C.L$$

$$\frac{I}{I_N} = e^{-\varepsilon(\gamma)}.C.L$$

$$T = e^{-\varepsilon(\gamma)}.C.L \qquad (2)$$

where $T=I/I_N$ is the ratio of the transmitted to the incident light travelling through a medium given by equation (2).

The exponential function is eliminated by taking negative natural logarithm for the transmittance[3]

$$A = -\ln T = -\ln\left(\frac{I}{I_N}\right) = e^{-\varepsilon(\gamma)}.C.L \qquad (3)$$

where A=Optical density of the medium or the Absorbance given by equation (3).Therefore by Beer lamberts' law, the concentration of the absorbing substance can be determined, by measuring the absorbance of light and by knowing the optical Distance and Extinction coefficient[3].The Absorbance Ratio 'R' is calculated by equation (4)

$$R = \frac{ACred/DCred}{AC\,ir/DCir} \quad (4)$$

where AC_{red},DC_{red},AC_{IR},DC_{IR} are the peak to peak and Average values of PPG signals obtained from Red and IR LEDs respectively.spo2 value[10] is calculated from the absorption ratio R by equation (5),

$$spo2 = K * R \quad (5)$$

where K is the proportionality constant[10] obtained by calibration from the standard pulse oximeters.

The spo2 sensor used in the proposed method is of transmittance type. The Light from the LED is detected by the photodiode. The photodiode converts the intensity of the light into photocurrent which in turn is converted into voltage by an amplifier. This voltage signal is forwarded to LabVIEW for further processing through DAQ card.

Two waveforms, one from Red LED and the other from IR LED are generated. The waveforms acquired through DAQ card are sampled (100 samples) at a frequency of 300 Hz and forwarded to LabVIEW of the transmitter.

AC (peak to peak) and DC (average) values are measured from the signal and the percentage of oxygenation (spo2) is calculated. The Absorbance ratio R which is the ratio of the magnitude of RED to that of IR waveforms is calculated using (4). The spo2 value is obtained using (5).The Noise in the waveforms is eliminated using a Low pass filter with a cut off frequency of 6 Hz. To remove the unwanted ripples the signals are forwarded to a Band pass filter that passes a set of frequencies from 1-6 Hz. The above operations are performed using flat sequence structure in LabVIEW .The Flow diagram for transmission and reception of spo2 and PPG signal are shown in figure 2 and figure 4.

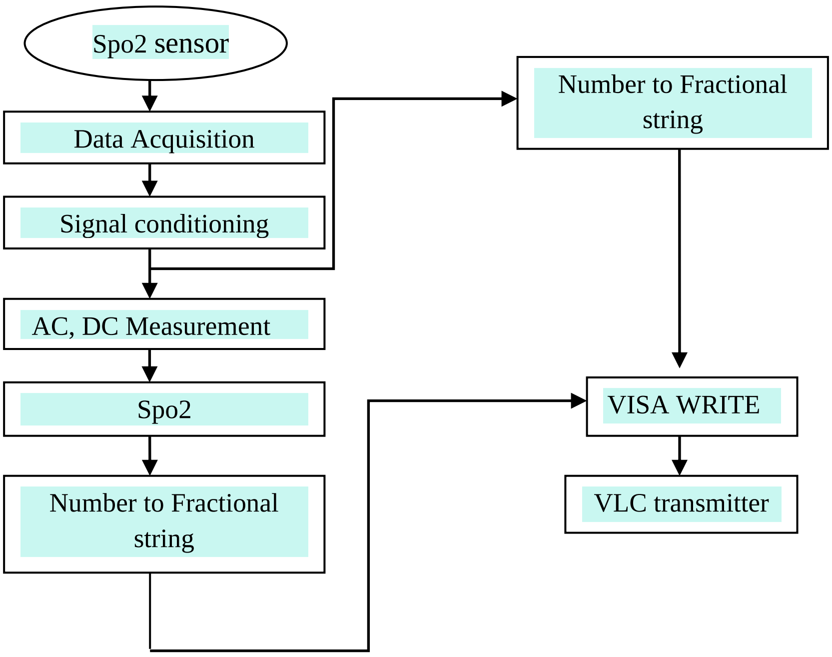

Figure 2.Flowchart for PPG signal and spo2 transmission

In LabVIEW, VISA serial port is configured for transmission. The filtered waveforms and calculated spo2 value are converted into fractional string and written into VISA serial port for VLC transmission. The incoming strings at the receiver contain both spo2 and PPG waveform. The proposed model uses On-Off keying modulation for PPG and spo2 transmission. On-Off keying modulation is one of the simplest modulation techniques used for IM/DD(Intensity Modulation/Direct detection) in optical communication[5]. The Transmitter unit has 555 timer that switches the signal at 100KHz frequency. This 100 KHz signal acts as a carrier for PPG and spo2.This frequency will make the LED to glow constantly, inorder to avoid interference from the ambient light.

The VLC receiver circuit has a photodiode and a transimpedance amplifier. The photodiode used in our proposed work is s1223 Hamamatsu photodiode that has a junction capacitance of 10pf and peak sensitivity of 960nm.This photodiode has high sensitivity in visible to near infrared range with high reliability. The photocurrent produced by the photodiode depends on the intensity of the LED light. This photocurrent is converted into voltage by transimpedance amplifier.LTC6244 is used as transimpedance amplifier which has a wide supply range operation with an offset voltage of 100µV which makes it suitable for fast signal processing for photodiode amplifiers.

The proposed VLC model uses bootstrapping method in a photodiode circuit with JFET. The Bootstrapped photodiode circuit is shown in the figure 3.A large active area photodiode has high input resistance and capacitance that decreases the response of the photodiode. This ac response of the photodiode will be improved by using a JFET in the circuit which acts as a voltage follower in the cathode of the photodiode circuit.

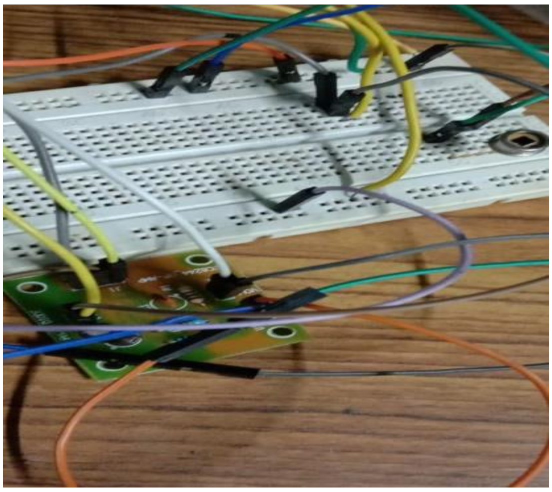

Figure 3. Bootstrapped photodiode circuit

The strings corresponding to the PPG signal are converted into number and plotted on a waveform graph. These operations are performed using a flat sequence structure. The remaining strings containing the spo2 value is displayed. From the figure 6 and 7, it is observed that the spo2 value after transmission and reception remain the same. This means that the pulse oximeter is unaffected by any RF interference and visible light communication is the most desirable communication to transmit PPG signals and spo2 in hospitals and healthcare units.

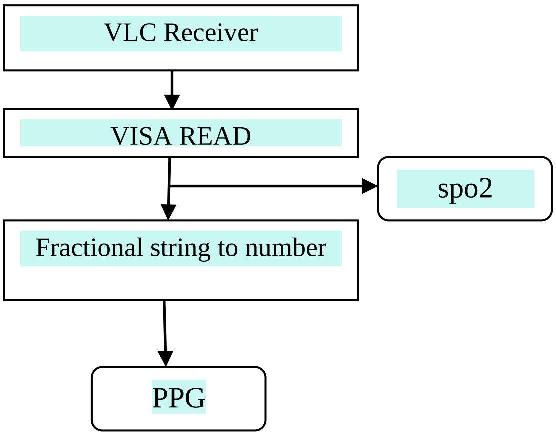

Figure 4.Flowchart for PPG signal and spo2 reception

The presence of bootstrap action of the JFET will not affect the photocurrent generated by the photodiode. This not only eliminates the resistance and the capacitance of the photodiode, but also improves the bandwidth and decreases the noise of the circuit.

Results and discussion

A prototype pulse oximeter has been used for measurement of spo2. The proposed prototype uses a 3watt LED which is attached along with the transmitter consisting of DAQ to the patient bed. The PPG signals from Red and IR LED has been controlled by DAQ which has been processed using LabVIEW.The peak to peak and average values from the signal has been measured and spo2 has been calculated. The sampled waveform and spo2 value has been converted into fractional string and transmitted over VLC link using On-Off keying modulation through VISA port in LabVIEW.The received sample values are shown in the figure 5.The LED is ON when it receives a logic 1 and switches off when it receives a logic 0.This method of embedding data into LED by making it On and Off is known as On-Off keying modulation.

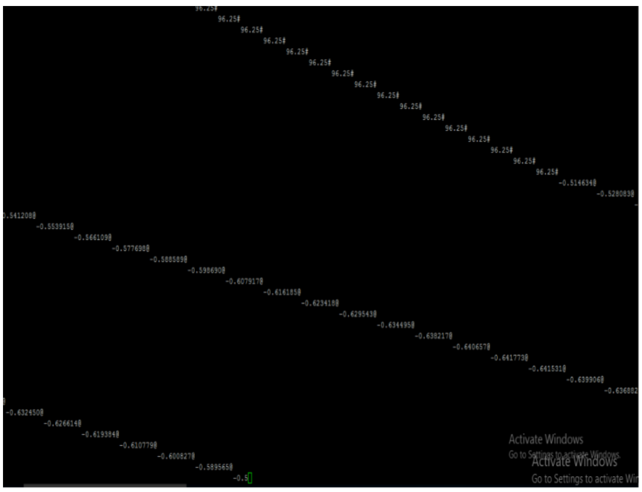

Figure 5. Received samples in the receiver

On-Off keying modulation consumes less power compared to other types of modulation. The PPG with spo2 has been recorded continuously and sent to the receiver circuit embedded in the nurse station,where the healthcare professional assigned for a group of patients will observe and check for the spo2 inside the COVID ward. This avoids direct physical interaction with the patient and maintains social distancing.

The incoming strings at the receiver containing the PPG signal and spo2 has been read using VISA port in LabVIEW.The strings containing the PPG signal has been converted into number and plotted on a waveform graph and the remaining strings containing spo2 has been displayed. Both PPG waveform and spo2 value were transmitted using VLC so that the spo2 value will be devoid of electromagnetic interference leading to erroneous value. The received spo2 value shows the errorless transmission as shown in the figure 6 and figure 7.The proposed pulse oximeter is calibrated using standard pulse oximeters and experimental values are shown in table 1.

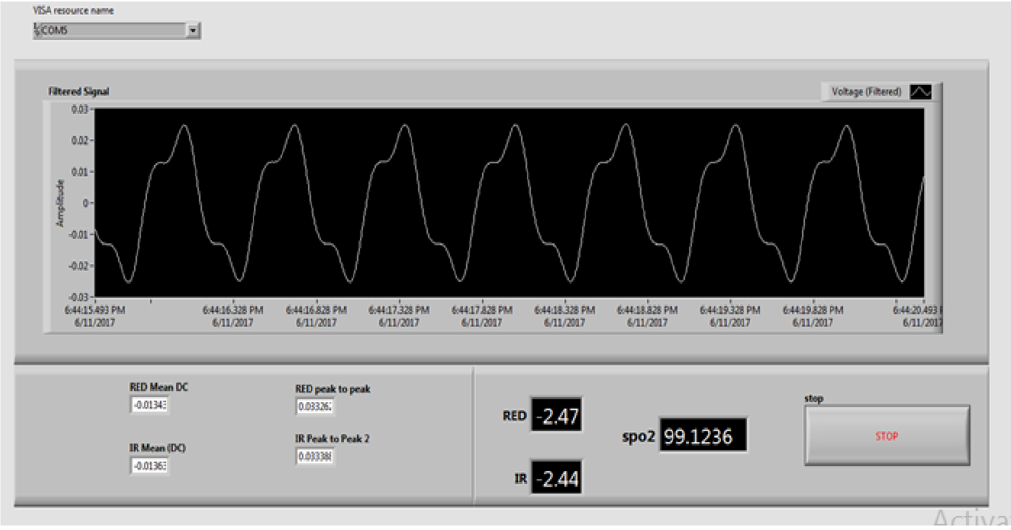

Figure 6. Transmitted PPG signal and spo2

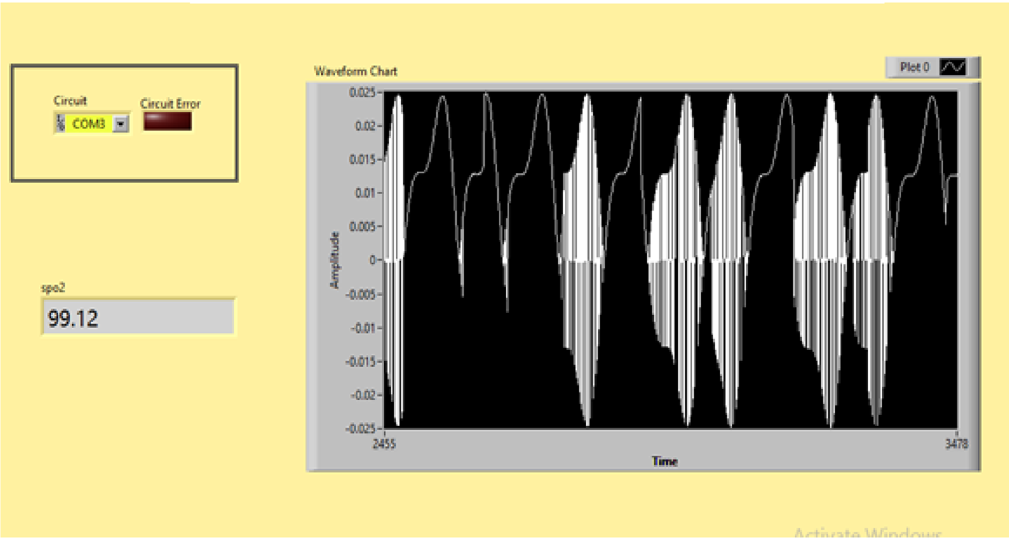

Figure 7. Received PPG signal and spo2

The obtained PPG signal is transmitted along with spo2 using VLC link in an indoor environment. The maximum distance achieved is 80 cm up to a baud rate of 19200 bits per second. The PPG signal and spo2 values are analyzed at various baud rates. Mean square error has been calculated and plotted against distance as shown in the figure 8.At 80 cm a mean square error of $1.211e^{-11}$ with baud rate of 19200 bps was achieved. This shows that data transmission at highest baud rate gives rise to increased mean square value at 60 cm compared to other baudrates as shown in figure 8. The proposed method has been tested on 5 different people with a span of 5 minutes for each individual as shown in table1.

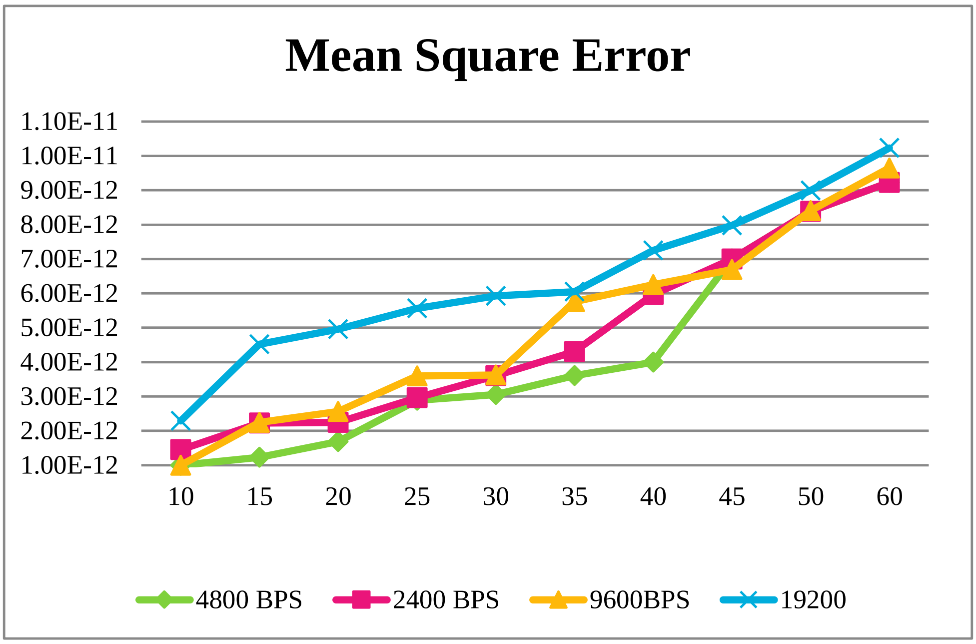

Figure 8.Mean Square error Vs distance

Table 1:SpO2 calculation

Test Analysis	Red Signal Mean DC	Red signal Peak to Peak AC	IR signal Mean DC	IR peak to peak AC	$(AC/DC)_{RED}$	$(AC/DC)_{IR}$	Spo2	Standard Spo2
Patient 1	-0.01357	0.03313	-0.0134	0.0337	-2.44	-2.47	99.4	98
Patient 2	-0.00099	0.00136	-0.0013	0.00213	-3.35	-3.35	100	99
Patient 3	-0.01338	0.03772	-0.0133	0.0327	-2.44	-2.44	98.6	97
Patient 4	-0.01319	0.03307	-0.0131	0.0323	-2.50	-2.50	99.7	98
Patient 5	-0.01318	0.00313	-0.0134	0.0337	-2.44	-2.47	99.4	98

The Hamamatsu photodiode s1223 has a junction capacitance of 10pF.At the amplifier input; bootstrapping makes a photodiode internal capacitance to be zero. Hence a small compensation capacitor of 0.25pF is used to extend the frequency response of the circuit.

The Noise combination of the photodiode with amplifier consists of diode noise, amplifier's current noise, voltage noise and thermal noise of the feedback resistor. The dc noise gain is given by equation (6)

$$1 + \left(\frac{R_F}{R_N}\right) \quad (6)$$

Where R_F is the feedback resistance and R_N is the input resistance.

The ac noise gain is given by equation (7)

$$1+\left(\frac{C_N}{C_F}\right) \quad (7)$$

Where C_F is the feedback resistance and C_N is the input resistance. The photodiode resistance becomes infinite after bootstrapping and hence the dc noise gain is unity, which indicates that there is no multiplication of noise gain with amplifier's offset and input equivalent voltage noise.

In a photodiode–transimpedance amplifier circuit,the input capacitance is the combination of the input capacitance of the photodiode and the capacitance of the amplifier plus the stray capacitance of the printed circuit board.s1223 has a junction capacitance of 10pF.The transimpedance amplifier used is LTC6244 input capacitance in differential mode and common mode id 3.5pf and 2.1pf.Therefore the total input capacitance of the photodiode transimpedance amplifier without JFET is given by equation (8)

$$1 + \left(\frac{10}{0.25}\right) = 41 \quad (8)$$

The circuit input capacitance with JFET is the addition of JFET and amplifier's input capacitance .The JFET BF862 has a input capacitance of 1.9pf.Hence the total input capacitance of the photodiode-transimpedance amplifier circuit is 7.5pf.Hence the ac noise gain of the circuit with JFET is

$$1 + \left(\frac{7.5}{0.25}\right) = 31 \quad (9)$$

Hence it is inferred that the ac-noise gain of the photodiode-transimpedance amplifier is decreased from 41 to 31 by bootstrapping the circuit with JFET. Therefore wireless monitoring of spo2 and PPG signals were achieved without radiofrequency interference up to a baud rate of 19200 bits per second with a mean square error $1.211e^{-11}$.

Conclusion:

Thus the Radiofrequency interference produced by the usage of Radio waves for communication in the presence of RF sources has been eliminated by visible light communication. The unsteady working of pulse oximeters due to interference from Radiofrequency magnetic fields during wireless monitoring in COVID wards has been overcome by the above proposed method. The results show that PPG signals can be transmitted in real time over a VLC link at a distance of 80 cm with a baud rate of 19200 bits per second and the ac noise gain of the amplifier has been reduced by 10 times by bootstrapping the transimpedance amplifier. As a result the received spo2 is accurate for patients. In future, the noise in received PPG signal can be reduced by filtering techniques and the range can be enhanced by using automatic gain control (AGC) in the receiver.

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