DESIGN AND IMPLEMENTATION OF A MICROCONTROLLER PULSE OXIMETER WITH MULTIPLE EMERGENCY NOTIFICATION CHANNELS

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Abstract: A pulse oximeter is an electronic device that is used to noninvasively analyse the Saturated Peripheral Oxygen level (SpO_2) of arterial blood and the pulse rate of cardiac activity in Beats per Minute (BPM) of the user of the device. This paper presents a cost-effective design and development of a microcontroller pulse oximeter with multiple emergency notification channels. The aim of this paper focuses on key challenges of this electronic device by firstly addressing the problems associated with motion and varying ambient light artifacts by using a variable width window filter algorithm. Secondly, it also addressed the problem associated with failure in transmission of notification signal to a third party through the incorporation of a multiple emergency notification channel. The results obtained from this research were compared to that of an already existing clinical model. Three key performance metrics were used to validate the results obtained from the research. These include Root Mean Square Error (RMSE), Pulsatile Signal Quality Index (P_{SQI}) and the Probability of Successful Message Delivery (PSMD). The result obtained from the research gave rise to an RMSE value of 1.0488 for the SpO_2, 1.7748% for the Pulse Rate as against the 3.0 and 3.5% thresholds set by the international organization for standard. Also, the P_{SQI} was found to be 1.2723 while the PSMD was pegged at 0.93, indicating a very good value. As such, these results indicate that the developed pulse oximeter can be deployed in practical field where it is required.

Keywords: Pulse, Oximeter, Microcontroller, Channels

Introduction

Technological advancement in the field of disease monitoring prevention and maintenance of patient health have enabled the evolution of fields such as monitoring systems Heart rate monitoring is a very vital process that can be used to improve the quality of health of individuals especially amongst the elderly where the chances of developing a heart attack are higher. In order to do this, a pulse sensor is used to measure an individual's heart rate and a hardware processor is then used to analyze the quality of health of the individual so that necessary actions can be triggered when the heart-rate falls outside the specified critical limits based on the design of the monitoring system. The triggered action in the event of a fall out from the specified threshold can range from: sounding a beeping alarm, sending an email to a relative of the user, updating the cloud server of a medical monitoring repository or even sending a Short Message Service (SMS) notification to other close affiliates of the user (Pendurthi et al., 2021).

Pulse oximetry is the science that involves the use of a non-invasive approach in the analysis of the heart rate and oxygen saturation of arterial peripheral blood. At the heart of its working principle are two main principles which are Photoplethysmography and Spectroscopy (Tsiakaka et al., 2020). Photoplethysmography (PPG) is the aspect of the pulse oximetry working principle that involves the generation and transmission of optical sources of specific spectral wavelength. It also involves the use of a low-cost optical technique for the detection of volumetric changes of blood in vascular tissues. A typical PPG signal, consists of two major subcomponents namely i) the pulsatile ("AC") component that originates from the synchronous vacillations in blood volume with each heartbeat, ii) the second component is the slowly changing ("DC") baseline with accompanying lower frequency components stemming from respiratory and sympathetic nervous system's activities (Stylogiannis et al., 2020).

Spectroscopy on the other hand, deals with the analysis of the spectral wavelengths generated during the PPG phase (Han et al., 2020). It adopts the use of mathematical models that touches on the analysis of the spectral characteristics of matter in a bid to establish the theory behind the dynamics of their atomic structures (Thiele et al., 2020). In generic terms, spectroscopy can be said to be the branch of science that deals with the study of electromagnetic spectra and interaction between electromagnetic radiation and matter as a reflection of the wavelength or frequency of the radiation.

Apart from the heart-rate monitoring, other vital health parameters like the saturated peripheral oxygen concentration of the blood, blood pressure, sugar levels, temperature etc., can also be monitored through the use of suitable sensors. These sensors can be embedded in wearable fabrics of the user or other utilities like wearable bracelets to facilitate continuous monitoring and updating of a second party with the vital health information that the wearable device of the user is designed to monitor (Yadav & Gowda, 2016). A key concern that is often considered in the design of these devices: is the reliability of detection of these critical thresholds, the seamlessness of the adopted notification channel(s), the robustness of the device to mitigate the influence of distorting bionic artefacts which can adversely affect the quality of the sampled data and hence leading to error in measurement and triggering of false alarms (Ufoaroh et al., 2015).

As a rule of thumb, for better performance of the designed system, the consideration of what notification channel to be utilized is of core importance. This can be attributed to the fact that the availability of one notification channel may vary remarkable from one geographical location to the other. For smaller devices on the other hand, the power consumption of the system is a key performance parameter that must be considered for prolonged operational lifetime. In lieu of this, communication channels that warrant an upsurge of power consumption are often exempted. In another vein, especially where the design of the device is intended for constant monitoring against an emergency situation so as to enhance the quickest response, a multipath notification channels must be selected in consideration to their availability within the area where the device will be deployed for use (Sharma & Sebastian, 2019). As such, these aforementioned discussions formed the basis of the developed oximeter presented in this write-up.

Research efforts tailored towards the provisioning of constant heart rate monitoring has been a top notch in the recent decade. This is partly due to emerging illnesses affecting the heart functions which often lead to heart attack and other critical health conditions (Virani et al., 2020). If nothing is done to proactively salvage the problem, it will pose a serious threat to the survival of the victims of such illnesses. Most electronic heart rate monitoring devices available now, utilizes a single notification channel in the transmission of distress signals in the event that the patient encounters critical health challenge. This however comes with a drawback especially when the network availability of the selected notification channel is on downtime. Another key problem that often affects the fidelity of the bionic signal sampled from the monitoring device is the bionic signal distorting artefacts (Yang et al., 2020).

Pulse rate monitoring has become a very important medical procedure in the assessment of the state of health of an individual. This is because many vital deductions can be made from the quality of the heart's function profile as recorded by these monitoring systems. A major challenge that often affects the quality of the signal sampled by these devices stems from the myriads of bionic signal distorting artefacts. A notable problem amongst the list of the different artefacts that impairs the quality of the bionic signals is the motion artefact. In another vein, the choice of the notification channel to use in sending distress alarms in the event of an emergency detected by the monitoring device is of pertinent importance. This is largely because the mean availability of this communication channel may vary from one geographical location to another.

Pulse oximeter remains a key medical device whose uses and applications finds immense usefulness in the medical profession. Its importance stems from the fact that it allows the medical practitioners to monitor some key health parameters majorly the saturated peripheral oxygen concentration SpO_2 and the pulse rate of the patients in a medical ward or other users via remote monitoring. Some of the key challenges affecting the functionality of this important medical device are subsumed in a phenomenon known as artefacts which can emanate from a myriad of sources. Another key problem often encountered is the choice of reliable notification channel(s) that will help ensure that at least a third party is notified about the state of health of a remote user of the device in the event of an emergency. This is solely due to the fact that especially in developing countries like Nigeria, the availability of the network coverage needed to create the wireless communication channel for the relay of the notification message may vary from one geographical location to another.

In lieu of the peculiarity of the geographical location where this research work was conducted, a pulse rate monitoring system with a multichannel notification frame work was used to ensure that the distress notification packets, gets to the desired quarters so that the user can secure the needed help in the event of an emergency. As such, the aim of this research work was to design a pulse rate monitoring system with multiple notification channels. This aim was achieved through the design and implementation of the Pulse Oximeter hardware architecture with an embedded multiple channel notification module. Furthermore, the results of the developed system were compared with that of an already existing clinical model. Finally, the effectiveness of the developed system was validated using the probability of successful notification packets delivery and signal quality index of the pulse oximeter measurement as performance metrics.

Materials and Method

Materials Used

The lists of the materials used for the implementation of this research work are:16 by 2 green LCD display, PIC16f887 Microcontroller unit, LM7805 +5V voltage regulator, M29150 +3.3V voltage regulator, Level shifter module, C1815 transistors, Diodes, Soldering Iron, Soldering Led, Led sucker, Jumper wires, Arduino Serial Plotter terminal, Buzzer, LDR , Small red-LED, 12V DC adapter socket, Push buttons, 9V battery socket, Crystal Oscillator, Capacitor, Perspect plastic casing, Resistors, IC sockets, Male and female socket header, Pickit 3 Programmer, Proteus Circuit Development suite, Proton Compiler Software, Matlab

Overview of the Methodology

The methodology that was used in carrying out the research is described in details under this subheading as follows:

1. Design and implementation of the pulse oximeter hardware architecture with the embedded multiple notification channels which was achieved through the following steps:
    a) Implementation of the hardware subcomponents using a Proteus computer aided (CAD) design suite and a breadboard for preliminary test.
    b) Transferring the design to a permanent Vero-board and linking the various subcomponents so that they work together as a system.
    c) Programming of the microcontrollers using Proton Integrated Development Environment (IDE).
    d) Incorporation of GSM module for multiple channel notification in the event of the occurrence of an emergency.
2. Development and Incorporation of variable window filter algorithm to mitigate the effect of motion artefact through the following steps:
    a) Acquisition of the raw bionic signal samples from the developed pulse oximeter sensor.
    b) Establishment of the new window width based on the lowest and highest bionic signal samples recorded from the latest n samples.
    c) Mitigation of noisy perturbations occasioned by the artefact through the use of the newly established window.
    d) Incorporation of the algorithm into the developed pulse oximeter system via programming.
3. Assessment of the performance of the developed pulse oximeter model in comparison with an existing clinical model through the following steps:
    a) Measurement of the Heart rate and SpO_2 values by both the developed model and an existing clinical model.
    b) Tabulating the measured values of the Heart rate and SpO_2 readings in a well-organized form.
    c) Using the data obtained in b) to compute the root mean square error and the signal quality index which

will be used as the performance metrics.

A panoramic description of the implementation of this research is shown using the block diagram shown in Figure 1.

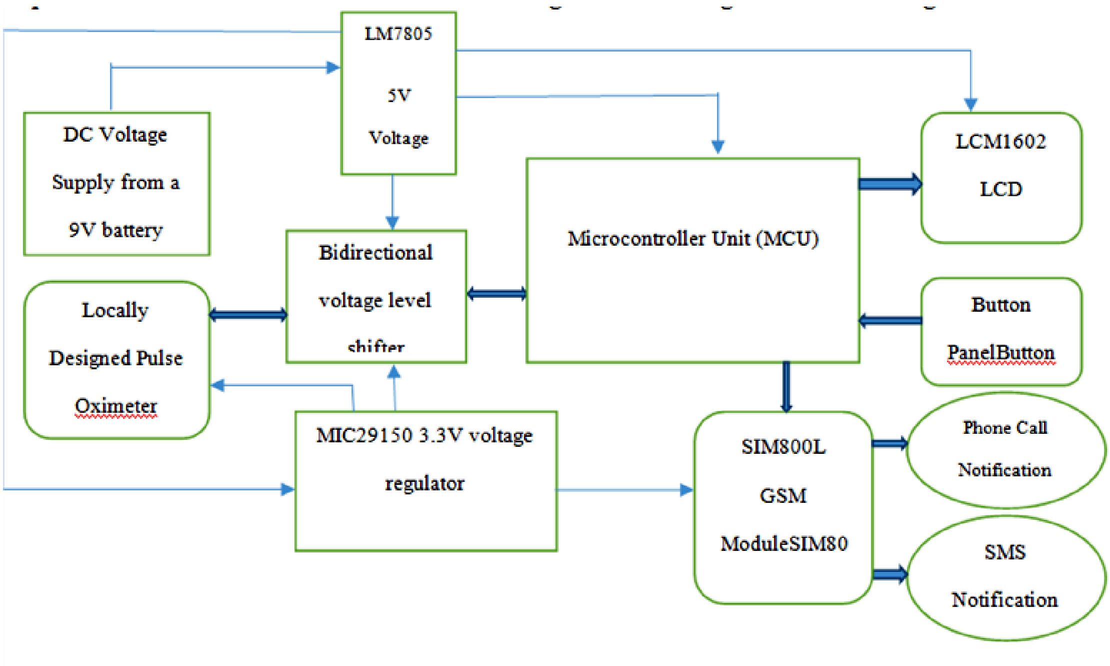

Figure 1: Block Diagram of the Pulse Oximeter Design

The detail schematic diagram of the entire design is given on Figure 2. It encapsulates all the various sections of the design.

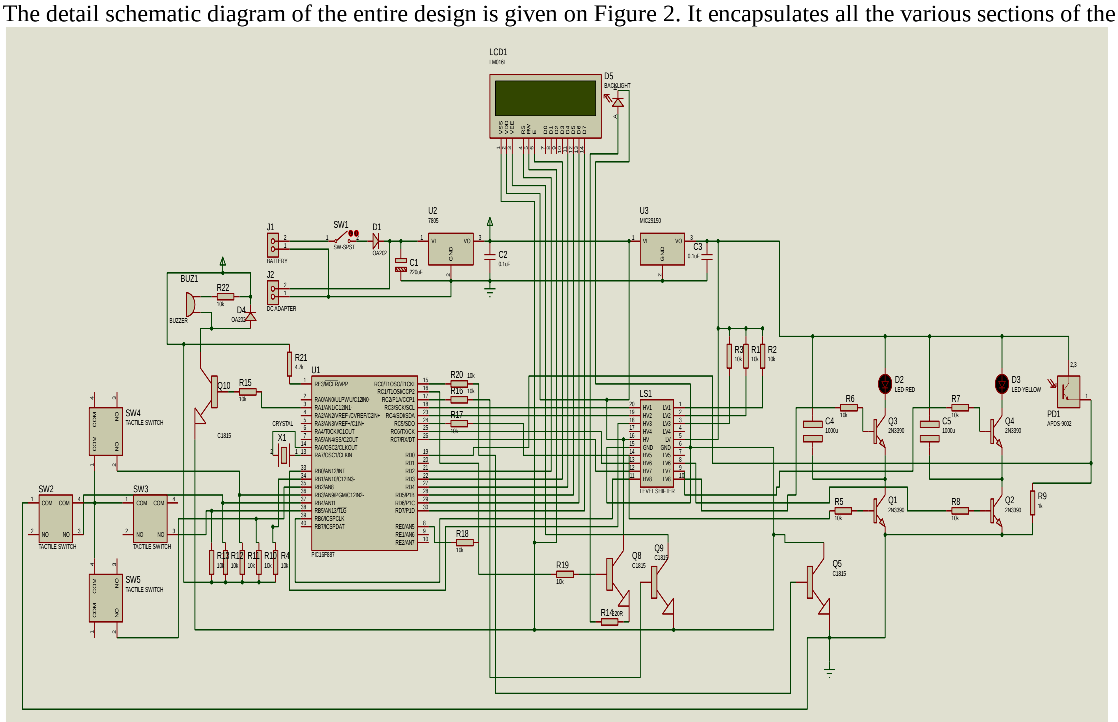

Figure 2: Detail Schematic Diagram of the Complete Circuit Design

The incorporation of the SIM800L GSM module allows for the multiple channel communication link with a third party in order to allow them of an eventual critical health situation that may be encountered by the user during the period of usage of the pulse oximeter device. To achieve this feat, a threshold value for the Saturated Peripheral Oxygen (SpO_2) level and the pulse rate in bpm is set during the programming phase of the design. During the course of usage of the device, the microcontroller is programmed to constantly compare the measured value of the two parameters with this predefined threshold. Immediately the microcontroller detects a fall in the measured value below any of the threshold, a delay count-up timer is set to start counting as far as this low value persists. If the count up timer reaches a predefined delay value, then the distress SMS message will be sent to the destination message phone number while at the same time, a phone call alert will be forwarded to the designated phone call number of the third party to be notified.

In the event that the microcontroller measures a higher value above the set threshold before the expiration of the delay time, the count up timer will be reset and deactivated until another lower value than the set threshold is detected again. This measure was put in place in order to mitigate the problem of false alarm. As it was earlier mentioned, the communication protocol that the microcontroller uses to communicate with the GSM module is the UART communication protocol and

the command type that the Module understands is the AT command.
Based on the findings obtained during the course of the paper reviewed on this research area, it was found that the measurement of the health parameters by a pulse oximeter device would be grossly without the use of suitable filters. In fact, the uses of filter techniques to mitigate the effects of these artefacts form one of the major top notches in this research area. Many filter techniques have been utilized by many researchers in a bid to combat the effects of these artefacts which can emanate from variation in ambient conditions of the immediate environment where the pulse oximeter device is deployed for use, motion artefacts, physiological variations due to underlining changes in the constituents of the blood etc. If these discrepancies are not tackled, the measurement results obtained from the pulse oximeter design will be erratic. A window filter algorithm is a digital signal processing technique used in pulse oximeter design to improve the accuracy and reliability of oxygen saturation (SpO_2) measurements.

Results and Discussion

The acquisition of the bionic signal samples that was used in producing the photoplethysmographic plot shown on Plate 4 was obtain via the UART interface of the microcontroller. This signal samples were rerouted to the the arduino serial plotter to produce the PPG plot. As it can be seen, clear profiling of the PPG plot was achieve because of the efficacy of the variable filter algorithm. This algorithm was used to smoothen out the effect of the distortions observed due to the artifact. Plate 1a shows a picture of the finished design while Plate 1b shows a screenshot of the clinical model that was used for comparison.

(a) (b)

Plate 1: (a) Screenshot of the Finished Design and Plate (b) the Screenshot of the Clinical Model Used for Comparison. Table 1 gives the values of the SpO_2 readings for the measurement obtained using the developed model and an existing clinical model.

Table 1: Table of Result for Clinical and Model Device SpO2 Measurements

S/No	Clinical SpO2 (X_1) in %	Model SpO2(Y_1) in %	(X_1-Y_1)	Square Error $(X_1-Y_1)^2$
1	96	95	1	1
2	94	93	1	1
3	95	95	0	0
4	93	93	0	0
5	97	96	1	1
6	96	95	1	1
7	92	92	0	0
8	94	93	1	1
9	95	94	1	1
10	96	96	0	0
11	90	92	-2	4
12	98	96	2	4
13	96	95	1	1
14	94	93	1	1
15	95	96	-1	1
16	96	97	-1	1
17	99	98	1	1
18	93	94	-1	1
19	96	97	-1	1
20	96	95	1	1
TOTAL				22

In this research, the Matrix Laboratory (MATLAB) application was used to compute the root mean square error of the result obtained from the developed model and an already existing clinical model. Thus, the comparison based on the tabulated result in Table 1 and Table 2 for the SpO_2 and Pulse Rate respectively is given by Equation (1).

$$RMSE = \sqrt{\frac{\sum(X_1 - Y_1)^2}{N}} \quad (1)$$

where: RMSE is the root mean square error,N is the number of sample, and $\sum(X_1 - Y_1)^2$ is the summation of all the square errors.By using Equation (1), the RMSE was found to be 1.0488

Table 1: Table of Result for Clinical and Model Device BPM Measurements

S/No	Clinical Pulse Rate (A_1) in BPM	Model P. Rate (B_1) in BPM	(A_1-B_1)	Square Error $(A_1-B_1)^2$
1	70	69	1	4
2	65	68	-3	9
3	67	65	2	4
4	73	72	1	4
5	74	76	-2	4
6	65	65	0	1
7	67	68	-1	1
8	69	70	-1	1
9	66	67	-1	1
10	75	73	2	4
11	70	69	1	1
12	67	65	2	4
13	68	66	2	4
14	70	70	0	0
15	71	72	-1	1
16	64	63	1	1
17	69	68	1	1
18	65	66	-1	1
19	67	63	4	16
20	70	69	1	1
TOTAL				63

Thus, the value of the RMSE obtained from Table 1 was less than 3 which is the allowable maximum set by the internal organization for standardization.Hence the designed model performance for the measurement of SpO_2 proved to be reliable. In a similar vein, the RMSE for the heart rate reading was calculated using the same Equation (1) but with respect to the data presented on Table 2 which gave rise to a value of 1.7748.A careful study of the results obtained from Table 1 and Table 2 using Equation (1) reveals that both the RMSE values of the SpO_2 and Pulse Rate false below a value of 4%. This conote the fact that the performance of the developed model is within the acceptable limit as specified by the organisation of standardization within a margin of 90.04% for SpO_2 and 62.84bpm for the Pulse Rate. Figure 3, gives the visual plot of the SpO_2 reading of the Clinical and Designed model reading while Figure 4 gives the plot of the Heart rate reading of the two devices respectively.

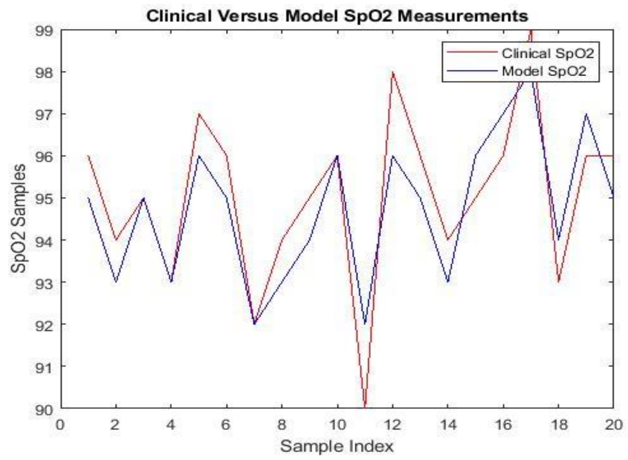

Figure 3: Visual Plot of the SpO2 Reading for the Pulse Oximeters

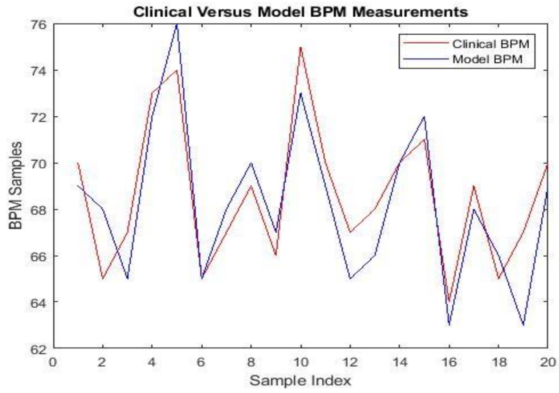

Figure 4: Visual Plot of the BPM Reading of the Pulse Oximeters

As it can be seen from Figure 8, there is some measure of correlation between the result obtained using the clinic oximeter and the readings obtained using the designed model which gives rise to an approximate root mean square error of about 1.0488 for the SpO_2. Similarly, The plot of the BPM readings using the clinical and the designed model also show a measure of correlation which gives an approximate root mean square error of 1.7748 which is below the 4% maximum limit set by the international organization for standardization.Table 3 shows the raw data of the bionic signal obtained from the designed model with and without the implementation of the variable window filter algorithm.

Table 3: Raw Bionic Signal Data with and Without the Implementation of the Variable Filter Algorithm

S/No	Raw Bionic Signal Data with Filter Algorithm Implemented	Raw Bionic Signal Data without the Implementation of the Filter Algorithm
1	70	118
2	96	115
3	118	117
4	114	115
5	118	111
6	114	172
7	110	151
8	103	142
9	211	142
10	47	136
11	98	129
12	49	123
13	41	159
14	36	63
15	55	108
16	62	61
17	55	152
18	55	65
19	59	88
20	76	91
TOTAL		2358

From Table 3, the mean of the raw bionic data obtained without the filter algorithm $\hat{x}$, was calculated by dividing the total of the unfiltered data samples by the total number of samples. This gives$[\hat{x}] = 117.9$. On the other hand, the maximum value of the filtered data as can be seen from Table 3 is$y_{max} = 211$,while the minimum of the filtered data is $y_{min} = 61$. The mathematical relationship for computing the SQI in terms of the perfusion $P_{SQI}$is given by Equation (2).

$$P_{SQI} = [(y_{max} - y_{min})/|\hat{x}|] \quad (2)$$

Where: P_{SQI} is the signal quality index in terms of the perfusion, $y_{max}$is the peak of the filtered signal, $y_{min}$is the low of the filtered signal, $\hat{x}$is the statistical mean of the raw signal. By substituting these parameters into Equation (2) to get the perfusive signal quality index $P_{SQI} = 1.2723$. Table 4 shows the total number of Short Message Service (SMS) sent from the designed model GSM module and total number of SMS messages received at the destination terminal equipment for three different network providers in Nigeria. Namely: GLO, MTN and 9Mobile.

Table 4 Number of Sent and Received SMS Using the Developed Model

Network Providers	**Number of Messages Sent (MS)**	**Number of Messages Received (MR)**
GLO	10	9
MTN	10	9
9MOBILE	10	10
TOTAL	TMS = 30	TMR = 28

As it can be seen from Table 4, the total number of SMS messages sent (TMS) by the developed model using the three different network providers network is 30 while the total number of messages received from the destination terminal equipment (TMR) is 28. The probability of successful message delivery is given by Equation (3).

$$PSMD = TMS/TMR \quad (3)$$

Where: *PSMD* is the probability of successful message delivery, *TMS* is the number of total messages sent, and *TMR* is the number of the total messages received. By using Equation (12), the probability of successful message delivery (PSMD) is 0.93. This result is indicative of a very good message delivery rate, hence signifying the conclusion of overall project achieving its objectives.

Conclusion

In this research work, the focus was zeroed down to the effect of fluctuations in the ambient light conditions, anomalous physiological condition of the patient, and marked temperature changes on the quality of the photoplethysmographic plot thereby increasing the accuracy and reliability of the modified design. All the performance metrics considered proved very satisfactory when compared to recommended standards in literature. Another intriguing contribution made by this research work stems from the incorporation of a multiple emergency notification channel. This feature allows the device to send a distress notification to a third party about the critical state of health of the patient in event that the patient's state of health deteriorates beyond a critical threshold. Finally, this research work also provided a serial communication interface that allows the developed model to transmit the photoplethysmographic (PPG) data from the developed model to a personal computer for real time visual monitoring. In future works, the scope of the coverage of the wireless interface can be expanded using then Internet of Things (IoT) technology; the adoption of a more sophisticated implementation technology for miniaturized design.

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