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Real-time Signal-to-Noise Ratio Optimization of Bio-Impedance Signal for Cuffless Blood Pressure Monitoring

Bryant Passage, Bassem Ibrahim, and Roozbeh Jafari, *Senior Member, IEEE*

***Abstract*—Continuous and unobtrusive blood pressure (BP) monitoring provides significant advantages in predicting the onset of cardiovascular disease. Bio-impedance sensing is a prominent method for continuous BP monitoring in a wearable form factor that can effectively measure blood pulsations from the arteries and translate them into BP. However, assessing the quality of the bio-impedance signal captured from small electrodes placed on the skin is required to determine the accuracy of BP estimation. In wearable devices, frequent movements of the electrodes on the skin are expected which cause non-optimal contact quality between the electrodes and the skin. This can lead to high skin-electrode impedance which can cause saturation of the current injection module of the bio-impedance device. This phenomenon degrades the signal quality In this paper, we present an automatic gain control (AGC) circuit that controls the amplitude of the current injection into the body based on sensing the skin-electrode impedance to ensure injection of maximum current to maximize the signal-to-noise ratio (SNR) while avoiding saturation of the current injection module. In this work, the proposed AGC method shows higher quality of blood pulsation from bio-impedance signal measured from a human subject with 1.59 dB improvement in SNR which leads to a better estimation of blood pressure.**

***Clinical Relevance*— The proposed automatic gain control (AGC) circuit establishes a more accurate method of continuous blood pressure monitoring using bio-impedance.**

I. Introduction

Cardiovascular disease (CVD) is the leading cause of death worldwide and accounts for 1 in 4 deaths in the United States [1]. One important biomarker of monitoring cardiovascular disease is blood pressure monitoring [5]. The traditional method of measuring blood pressure utilizes the sphygmomanometer with its inflatable cuff. This method is obtrusive and does not allow for continuous blood pressure monitoring which would be needed in order to continually monitor the health of patients prone to cardiovascular disease [3]. Continuous blood pressure monitoring relies on cuffless methods that can be integrated into a wearable device that is comfortable to always wear and does not require human intervention when taking measurements [10].

Current cuffless blood pressure monitoring techniques utilize multiple sensors placed at different locations on the body to measure the pulse transit time (PTT) which is the time between arterial pulse wave at two different locations. From previous literature, it has been found that the PTT is directly correlated to arterial stiffness and can be used to estimate systolic and diastolic blood pressure by measuring the delay between two points of measurement from an ECG located on the chest to a PPG located on the finger [6]. For a small form-factor device, blood pressure can be monitored by utilizing PTT and pulse morphology features from multiple bio-impedance sensors placed on the wrist arteries (radial and ulnar arteries) as shown in Figure 1 [7],[9]. In this research, bio-impedance is used to measure the changes in impedance within the tissue of the body due to arterial blood flow [2],[8]. Our research utilizes bio-impedance sensors because it is a non-invasive electrical signal which are low cost, low power, and highly configurable in controlling the location of current injection and voltage sensing electrodes [4].

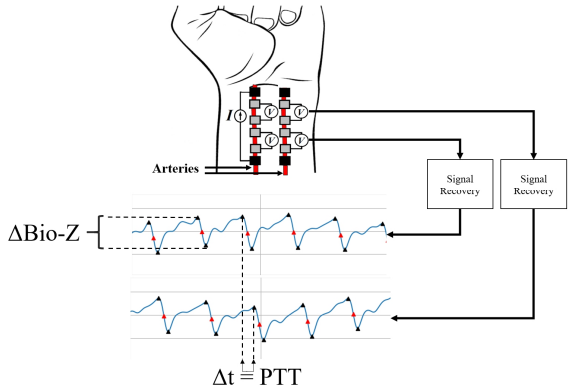

Figure 1. Bio-impedance sensing from an array of sensors on the wrist to measure the arterial pulse (ΔBio-Z) for PTT and blood pressure monitoring.

The bio-impedance sensors can either be wet electrodes that utilize an electrolytic gel material as a conductor between the skin and the electrode, or dry electrodes which consist of a single metal that acts as the conductor between the skin and electrode. Our approach for continuous cuffless blood pressure monitoring relies on an array of bio-impedance (Bio-Z) sensors that can be placed on the wrist using a wristband. The main challenge with continuous cuffless blood pressure monitoring is the noise generated from the imperfect application of the wristband on the skin. Since the device is to be worn comfortably on the wrist, placing sensors on key contact points near the radial and ulnar arteries through a fixed

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B. Passage and B. Ibrahim are with the Department of Electrical and Computer Engineering at Texas A&M University, College Station, Texas, 77843, USA. (e-mail: bryant.passage , bassem@tamu.edu).
R. Jafari is with the Departments of Biomedical, Computer Science and Engineering, and Electrical Engineering at Texas A&M University, College Station, Texas, 77843, USA. (e-mail: rjafari@tamu.edu).

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wristband device is challenging. Furthermore, over time, contact quality between the bio-impedance sensors and skin can vary depending on body movements, causing an increase in noise level and degradation in signal quality.

Imperfections in the application of the wearable device contribute higher noise output in the Bio-Z signals acquired from the wearable device for several reasons. For one, misalignment from the radial and ulnar arteries from the wrist can generate weaker tissue impedance changes which will dampen the Bio-Z signals captured from the cuffless wearable device. Another major source of noise is the saturation of the current injection module due to high skin-electrode impedance. The noise added into the Bio-Z signals can be reduced by a secondary voltage sensing device to optimize the current injection level.

A closed feedback loop should be added to identify signal strength and quality from the sensors and apply necessary changes to the current injection through the skin to optimize signal-to-noise ratio (SNR). Automatic gain control (AGC) circuitry is one possible approach where the controller senses the voltage through the skin and determines whether the current injected needs to increase or decrease in order to maximize the SNR of the bio-impedance readings. The real-time AGC will ensure continuous high-quality bio-impedance signals which will improve the estimation of blood pressure.

The contribution of this paper can be summarized as follows:

- A novel AGC loop is added to the bio-impedance sensor to maximize the SNR and the quality of measured signals.
- The AGC loop operates by controlling the amplitude of the current injection signal based on the sensed skin-electrode impedance.
- Efficient implementation of the AGC algorithm on a microcontroller to be integrated into a wearable device for real-time optimization of the SNR based on the change of skin-electrode impedance over time.

In this paper, a closed feedback loop circuit is added to the current cuffless blood pressure monitoring device prototype which can change the current injection of the device based on skin voltage sensing to maximize the SNR in real-time.

II. Methods

A. Bio-Impedance Sensing Hardware

Bio-impedance is an electrical non-invasive signal measured by injecting AC current in the human body and sensing the voltage difference using separate pairs of electrodes. This is known as four-terminal sensing where two electrodes carry the current injection signal while another pair of electrodes senses voltage and is more accurate than two-terminal sensing where only two electrodes are used for both current injection and voltage sensing which includes the effect of the skin-electrode impedance. The changes in bio-impedance over time (ΔZ) corresponds to the blood volume changes at the sensing location, which is used to sense the arterial pulse through the body. An AC current signal is utilized as the carrier signal, and the variation in impedance due to blood volume changes modulates the amplitude of the resulting signals at the voltage sensing terminals.

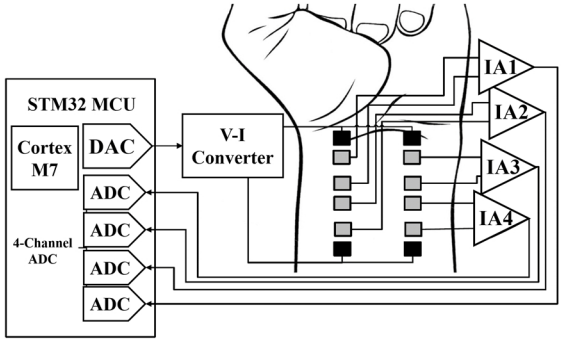

Figure 2. Bio-Impedance Sensing Hardware Overview

Our bio-impedance sensing hardware utilizes the STM32H7 microcontroller (MCU) to generate a digital waveform, read the incoming signals, and process the signals through digital signal processing (DSP). The MCU outputs a digital waveform using its 12-bit DAC to drive the voltage-to-current converter for generating an AC current signal with programmable amplitude and a frequency of 9.765kHz. Each Bio-Z voltage sensing channel is handled by two electrodes connected to a low noise instrumentation amplifier (IA) followed by a low pass filter to obtain an RMS error of less than 1mΩ. There are two pairs of Bio-Z sensors for a total of four sensors in our bio-impedance sensing hardware with each pair to be placed above the radial and ulnar artery to improve BP estimation by combining the BP features from multiple sensors. The current injection circuit is shared between four Bio-Z sensors so that only one voltage-to-current converter is needed for the bio-impedance sensing hardware. Each ADC channel samples the four Bio-Z channels simultaneously at 78.125kSPS with 16-bit resolution to enable accurate Bio-Z signal readings. The Bio-Z signals are then demodulated within the MCU in the digital domain using the envelope detection method. The Bio-Z signals are run through a bandpass filter to only retain frequencies close to the carrier frequency and eliminate DC offset, 60Hz interference, and high-frequency noise. Each Bio-Z signal is then multiplied by itself for envelope detection, effectively demodulating the signal by using itself as the carrier wave. A low pass filter with a cut-off frequency of 6Hz is applied to each Bio-Z signal to pass only the pulse signal. A block diagram of the bio-impedance measuring system can be seen in Figure 2.

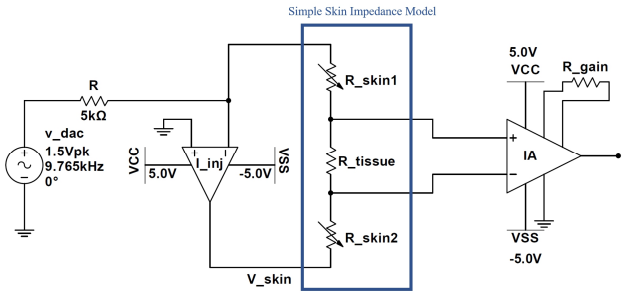

Figure 3. Calibration skin model connected with current injection model

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B. Simulating the Effects of High Skin-Electrode Impedance

Under normal operations for the cuffless blood pressure monitoring system, a simple skin model calibration board shown in Figure 3 is used to determine the relationship between the current injection amount and the programmed value within the firmware.

As mentioned earlier in the introduction, there is a possibility of saturating the current injection module in the presence of high skin-electrode impedance from the body. We can now simulate this using the calibration board, which is also a very simple skin-electrode impedance model, and the current injection module from our bio-impedance sensing hardware. With 0.3mA of constant current injection from the current injection module (I_{inj}), an arbitrarily small R_{tissue} of 50Ω, and a rail-to-rail supply of +/- 5V for the current injection operational amplifier, the current injection's output would saturate with a skin-electrode impedance of >16.67k Ω. Since bio-impedance signal recovery requires sensitive peak voltage changes at R_{tissue}, a saturated injected signal into the skin would degrade the differential voltage signal at R_{tissue}. This causes voltage changes at the input of the IA to be corrupted, causing noise and ultimately degrading the bio-impedance signal we are trying to recover.

The need for a method of detecting high skin-electrode impedance becomes apparent as a saturated current injection signal would cause problems in the detection of impedance changes in the tissue making it more difficult to detect peak voltage changes that represent physiological bio-impedance signals.

C. Automatic Gain Control (AGC) Circuit

The automatic gain control (AGC) circuit is a closed feedback loop method of detecting the possibility of a noisy Bio-Z signal due to voltage-to-current converter saturation. When injecting current into the body, the skin-electrode impedance must be considered such that the amplitude of current being injected does not saturate the operational amplifier (OpAmp) used in the voltage-to-current converter. The value of the skin-electrode impedance varies from person to person due to multiple factors. Some factors include skin wetness, age, skin-electrode contact quality, length of skin-electrode contact, and more. When using dry electrodes, the length of time the electrodes have been in contact with the skin is important since sweat and moisture can develop under the electrode and cause the skin-electrode impedance to decrease over time.

The AGC circuit will check and avoid saturation of the cuffless blood pressure monitoring device by measuring the RMS of the skin voltage and adjusting the signal amplitude accordingly based on thresholds set in the firmware of the device. The circuit consists of three major components: a voltage buffer, voltage rectifier, and voltage divider and subtractor with its input connected to the output terminal of the voltage-to-current converter. The final AGC circuit schematic can be seen in Figure 4(a) which also blocks the schematic into the three main components of AGC.

The AGC circuit is designed such that saturation on the voltage-to-current converter due to high skin-electrode impedance causes a high DC output voltage from the AGC circuit. A defined DC threshold within the firmware of the device determines whether the amplitude of the current injection signal needs to decrease to avoid saturation. The AGC system can also increase current injection amplitude if the system determines that the current injection signal has ample headroom before saturation and can be used to also help increase the SNR. Current injection amplitude is handled by the MCU after receiving feedback from AGC which can be seen in Figure 4(b).

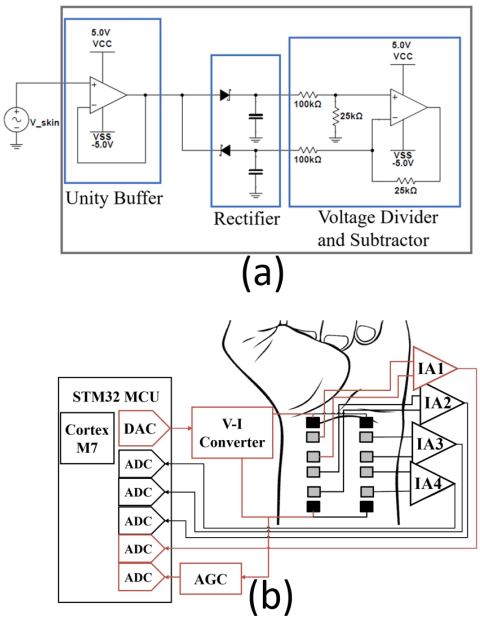

Figure 4. (a) Automatic gain control (AGC) Circuit Schematic connected to (b) the bio-impedance sensing hardware

III. Data Collection

Data collection is split into two categories: 1) calibration board testing and 2) human subject testing. Furthermore, since the quality of the Bio-Z signal is important, there is no need to calculate PTT since improvement of Bio-Z signals in every channel will propagate towards other channels. Therefore, only one channel of Bio-Z sensing is used. This allows us to capture the raw ADC signal of a single channel and simplify testing results. Additionally, since all Bio-Z channels are identical, replication of procedures from one channel can be easily transferred over to other channels.

A. Calibration Board Testing

Since the calibration board also models as a simple skin-electrode impedance model, the calibration board can also be utilized to test the accuracy and efficiency of the AGC circuit. As seen from Figure 3, there are variable resistors on the simple skin-electrode impedance model which help model different impedances found on the wrist. R_skin1 and R_skin2 are defined as the skin-electrode impedances from each skin-electrode contact. R_{tissue} is defined as the impedance found from blood volume changes due to arterial pulse waves. Normally this is variable during human testing, however, for this model, it is set to 50Ω. Once a starting amplitude for the current injection module has been set via the above method (normally 0.3mA), R_{skin1} and R_{skin2} are set to arbitrary resistive values, and the cuffless blood pressure monitoring device is turned on. This starts the current injection signal into the

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calibration board. If the voltage-to-current converter is saturated, and if AGC is installed and activated, the amplitude of the current injection signal should decrease to reduce potential noise being introduced into the bio-impedance signal due to saturated sinusoidal signals.

Six skin-electrode impedances were tested starting from 5kΩ and increasing by 5kΩ up to 30kΩ. The skin-electrode impedances were set on the calibration board by setting R_{skin1} and R_{skin2} so that they add up to the target skin-electrode impedance. For the purposes of this test, R_{skin1} is set equal to R_{skin2} to simplify testing.

The results collected for each skin-electrode impedance tested would include the SNR of the received ADC signal calculated based on the power spectral density from the ratio in dB between the power of the carrier fundamental frequency component to the power of the noise and the harmonics as:

$$SNR = 10\log_{10}\frac{P_{fundamental}}{P_{harmonics} + P_{noise}}$$

In addition, the RMS error of the demodulated signal was used to measure the accuracy of the bio-impedance signal expected at that skin-electrode impedance.

B. Human Subject Testing

The human subject testing was done under Texas A&M University IRB (IRB2017-0086D). One subject was asked to put on the array wristband and take one-minute trials over 15 minutes after application of wristband at intervals of 1.5 minutes. This test was repeated three times. The initial contact of the dry electrodes on the array wristband with the body creates high skin-electrode impedance which will naturally decrease over-time due to moisture developing between the skin and electrodes. Therefore, the test spans over 15 minutes so that a wide range of skin-electrode impedances can be measured as the impedance between the skin and electrode gradually decreases over time.

Similar to the calibration board testing, the SNR of the received signals from the ADC will be calculated. However, since RMS error of the demodulated signal would not have any represented meaning, since a physiological Bio-Z signal would be counted as an error as well, the average ΔBio-Z is calculated instead. ΔBio-Z of a Bio-Z signal is important since it helps determine the consistency of features extraction such as the peaks and troughs of an arterial pulse wave signal and will lead to more accurate PTT calculations. Since the test was repeated three times for one subject, the averages of the three tests were captured for each of the performance indicators.

IV. Experimental Results

The method of a closed feedback loop system to control the current injection amount into the body, in this study, the AGC system, to avoid signal saturation due to high skin-electrode impedance was evaluated through certain performance indicators, SNR, RMS error for calibration board testing, and average ΔBio-Z for the human subject testing.

A. Calibration Board Testing Data

Since skin-electrode impedance varies per person and varies over time as well, a calibration board, also known as the simple skin-electrode impedance model, was used to test the functionality and the expected outcomes of the AGC circuit and bio-impedance sensing through simulated skin-electrode impedances. Figure 5(a) shows the SNR of the received ADC signal through the calibration board over a wide range of skin-electrode impedances. Towards higher skin-electrode impedances, SNR decreases due to saturation of the current signal through the calibration board. However, it can be noted that at 30kΩ, the SNR of the bio-impedance sensing system with the AGC circuit is higher than the system without a feedback loop. This is evident since the maximum (amplitude) of the current injected into the calibration board is much lower than the constant current amplitude of 0.3mA present in the system without AGC. The trend of the current injected over the simulated skin-electrode impedance can be seen in Figure 6(a). The lower current amplitude disallows the current injection module to saturate, allowing for a clean sinusoid to be injected into the calibration board. Since the peaks of the signals are also present in the IAs which are then captured by the ADC, the signal has lower noise, allowing for a higher SNR than a bio-impedance sensing system without a varying current.

Current saturation is also indicated in RMSE since demodulating a saturated carrier signal degenerates the information-bearing signal, causing high errors from the

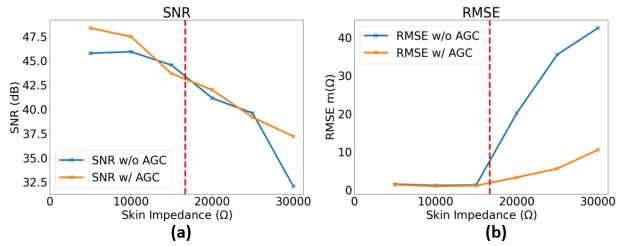

Figure 5. (a) The SNR and (b) the RMS error over simulated skin-electrode impedance

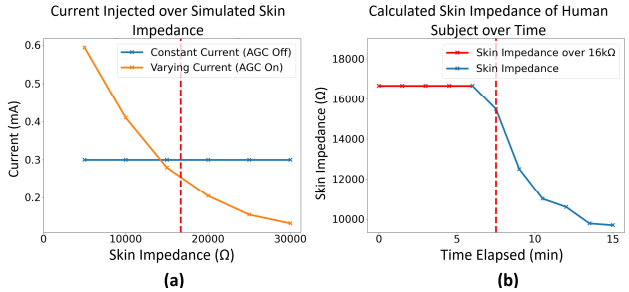

Figure 6. (a) The current injection over simulated skin-electrode impedance and (b) calculated skin-electrode impedance from human subject testing over the time elapsed since the application of the wristband

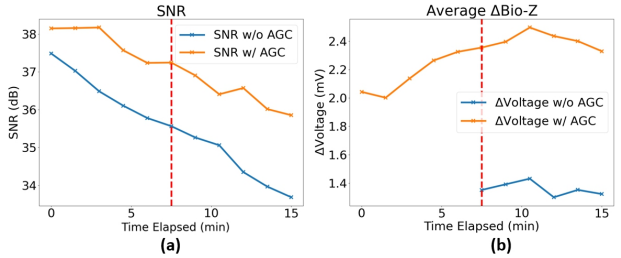

Figure 7. (a) The SNR and (b) average ΔBio-Z over time elapsed since the application of the electrode wristband

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filtered signal. Here, we see a drastic improvement in RMS error at higher impedances when the system contains an AGC system to tune the current injection based on varying skin-electrode impedances which can be seen in Figure 5(b).

B. Human Subject Testing

The data collected from the calibration testing helps define the expected accuracy of the bio-impedance signals, the raw signals before and after demodulation. After the application of the array wristband and dry electrodes on the body, skin-electrode impedance decreases continuously over time until settling to the final impedance value. Therefore, we test the AGC system after placing the wristband on the skin during the change of skin-electrode impedance by collecting data over a time interval of 15 minutes with 1.5 minute time step. The skin-electrode impedance was measured using an oscilloscope measuring the voltage signal of the current injection module. The maximum of the plot line is only 16kΩ and is shown as a red horizontal line in Figure 6(b) due to the limitations of the current injection OpAmp module supply rails which saturate the signal when skin-electrode impedance is over 16kΩ. Therefore, it can be assumed that the skin-electrode impedance before 7 minutes is higher than 16kΩ.

From Figure 7(a), the SNR of both bio-impedance sensing systems decrease over time, however, the system with AGC assistance has an overall average SNR of 1.59 dB higher than the system without AGC. The average ΔBio-Z signal was calculated by averaging the differences of voltage between the peaks and troughs of each Bio-Z pulse wave during an interval of time. These values were plotted over time for both the AGC-assisted bio-impedance sensing system and the constant current injection system as can be seen in Figure 7(b). The average ΔBio-Z signal is an important performance indicator for this test because it aids in consistent calculations of the features found in each arterial Bio-Z pulse signal. Larger ΔBio-Z allows for more consistent detection of the peaks and troughs of each arterial pulse wave in the Bio-Z signal. The accuracy of the peak detection in the Bio-Z signal is directly correlated with the accuracy of PTT calculations. Therefore, larger ΔBio-Z can increase the accuracy of BP estimations.

As reflected in Figure 8, the quality in the Bio-Z signal between a saturated carrier signal system versus an AGC-assisted system shows the necessity of limiting current saturation in carrier signals. In Figure 8(a), the demodulation program has trouble calculating the physiological features since a pulse is hardly detected when the current is saturated. On the other hand, Figure 8(b) shows a clean physiological system from the test subject.

V. Conclusion

In this research, a closed feedback loop system was introduced and developed for a bio-impedance sensing system that improved Bio-Z signals obtained from the wrist. This feedback system allowed for more consistent and high-quality Bio-Z pulse signals after post-processing. The bio-impedance sensing system with AGC also showed a higher overall SNR than the system without a feedback loop system with both high skin-electrode impedance (where the system without AGC would have saturated) and lower skin-electrode impedance. The proposed method can improve the quality of Bio-Z signals and blood pressure estimation of cuffless blood pressure measuring devices that utilize bio-impedance sensing hardware.

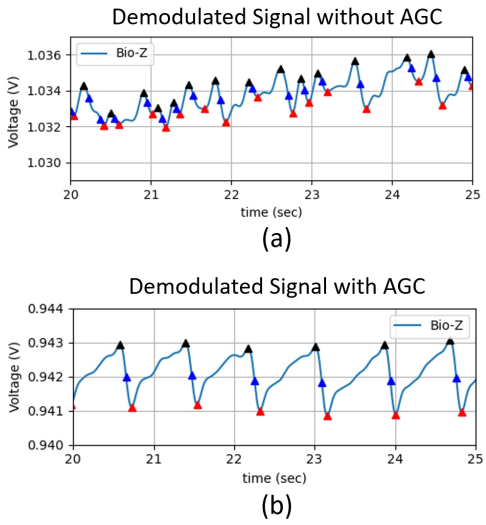

Figure 8. Comparison of demodulated Bio-Z signals after 3 minutes for the (a) non-AGC system and (b) the AGC assisted system

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