A Low-power and Compact-sized Wearable Bio-impedance Monitor with Wireless Connectivity

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Abstract. In this paper, we present a new bio-impedance monitor for wearable and continuous monitoring applications. The system consumes less than 14.4mW when measuring impedance, and 0.9mW when idling. Its compact size (4.8cm × 3cm × 2cm) makes it suitable for portable and wearable use. The proposed system has an accuracy of 0.5Ω and resolution of 0.2Ω on both resistance (R) and reactance (X) measurements, for impedance ranging between (j0.7)Ω to (54+j5)Ω with 2.9<φ<5.7. We also report the results of the system validation using passive loads as human tissue model, and show our wireless and miniaturized bio-impedance monitoring system has comparable performances with a reference system.

1. Introduction
Bio-impedance has been considered as one of the promising parameters for several healthcare applications [1], such as body composition, cardiac output, respiration, and body fluid monitoring applications. Several bio-impedance monitors have been developed and used in preliminary tests [2]-[4]. Most of them focus on small size and wireless connectivity for convenience. However, none of them also considers low power consumption for portable usage. As a result, there is no wearable system currently available for continuous bio-impedance monitoring in daily life. In this paper, a new bio-impedance monitor is introduced which enables low power, small size, and wireless connectivity at once. Its initial validation with passive loads shows that it can successfully replace the existing bulkier bio-impedance monitors.

2. Low-power Wireless Bio-impedance Monitor

2.1. System Architecture
The proposed bio-impedance monitor consists of a sensor and a controller module. The sensor module is based on a low-power analog-front end ASIC with square-wave current generator designed by imec. Using square-wave for both stimulating current and the demodulator clock allows to reduce ASIC power dissipation below 25μW. A microcontroller (TI MSP430F1611) is used for multi-frequency control, A-to-D conversion, and interface to the controller module via SPI. The controller module provides embedded processing, wireless connectivity, and data storage functionality. It includes a microcontroller (TI MSP430F1611), 2.4GHz Radio (Nordic nRF24L01), and micro SD card so that it can stream or store data according to the application. Figure 1 shows the overall architecture of the
proposed bio-impedance monitor and its photograph. Two modules are stacked and connected to each other via a 10-pin connector. One battery (3.7V, 150mAh) is physically placed between them and electrically connected to the power management unit of the controller module so that operating power is distributed by it. The load is biased at half supply voltage, i.e. 0.6V in this case, during whole measurements in order to hang the input common mode voltage to a value within the dynamic range of the analog-front end.

![System architecture and its photograph](image)

**Figure 1** System architecture and its photograph

### 2.2. System Implementation Results

As shown in Figure 1, the overall size of the system is 4.8cm (W) × 3cm (L) × 2cm (H), which is, to our knowledge, the most compact bio-impedance monitor ever reported [2]-[4]. The system dissipates 7.5mW for sensing and 6.9mW for controlling, streaming and storing so that it can be continuously used for over 30 hours on a 150mAh battery with 3.7V. In order to improve measurement accuracy (less than 0.5Ω error) and resolution (less than 0.5Ω step) which are important specifications of a bio-impedance monitor, the sensor module of the proposed bio-impedance monitor includes on-board calibration performed before every measurement. It consists of 3 phases measured with shorted, small ($R_{CL} + jX_{CL}$), and large ($R_{CH} + jX_{CH}$) loads, while the resistance ($R$) and reactance ($X$) are calculated from extra/intra-cellular resistance ($R_e$ and $R_i$) and membrane capacitance ($C_m$) [5].

![R and X error](image)

**Figure 2** Bio-impedance measurement error ($\Delta R$ and $\Delta X$) map according to load values

Figure 2 shows the R and X error ($\Delta R$ and $\Delta X$) from measurements according to load values. $\Delta R$ and $\Delta X$ are calculated based on the difference between known R and X of loads and measured values.
Using these graphs, the range for \( R \) where \( \Delta R \) is smaller than 0.5\( \Omega \) is found (blue box numbered as \( \textcircled{1} \) in Figure 2). Then, \( \Delta X \) in the same range is investigated whether it is smaller than 0.5\( \Omega \) or not (blue dotted box numbered as \( \textcircled{2} \) in Figure 2), showing that \( \Delta X \) is slightly larger than \( \Delta R \) but the values are still below 0.5\( \Omega \). It is also derived from measurements that the target load range of the system with less than 0.5\( \Omega \) error is directly related to \( R_{\text{CL}}, R_{\text{CH}}, X_{\text{CL}} \), and \( X_{\text{CH}} \) values as presented in Table 1. By setting their values to 22, 32, 0.7, and 3.2, respectively, the proposed monitor achieves 0.5\( \Omega \) accuracy and 0.2\( \Omega \) resolution at 10kHz for impedance ranging between \((j0.7)\Omega \) to \((54+j5)\Omega \) with 2.9<\( \phi \)<5.7.

### Table 1 Relations between measurable bio-impedance range and calibration values

| Parameter | General condition | Bio-impedance range in this work (at 10kHz) |
|-----------|-------------------|--------------------------------------------|
| R \( [\Omega] \) | \( R \leq R_{\text{CL}} + R_{\text{CH}} \) | \( R \leq 54 \) |
| X \( [\Omega] \) | \( X_{\text{CL}} \leq X \leq (1 + \frac{R_{\text{CL}}}{R_{\text{CH}}}) \cdot X_{\text{CH}} \) | \( 0.7 \leq X \leq 5 \) |
| \( \frac{R}{X} \) | \( \frac{R_{\text{CH}}}{X_{\text{CH}}} \leq \frac{R}{X} \leq \frac{1}{2} \left( \frac{R_{\text{CL}}}{X_{\text{CL}}} + \frac{R_{\text{CH}}}{X_{\text{CH}}} \right) \) | \( 10 \leq \frac{R}{X} \leq 20 \) |

### 3. Validation with Passive Loads

#### 3.1. Experimental Set-up

The system performance is verified using passive loads as a model for human tissue consisting of \( R_e, R_i, \) and \( C_m \) [5]. The Philips Bio-impedance Monitor [6] is used as a reference system, and the readings from the two systems are compared. Since single tone measurement can be seen as the subset of multi-frequency measurement, its validation is performed with 27 different frequencies between 10kHz and 211kHz for potential usage to the wider bio-impedance monitoring applications. After impedance measurement and calibration, the results are fitted to a Cole-Cole plot using the Least Squares Method over the target frequencies. Extracted parameters \( R_e, R_i, \) and \( C_m \) are compared with those from the reference system.

#### 3.2. Validation Results

In this validation test, 49 different combinations of load values in the range of 22 to 43\( \Omega \) for \( R_e \) and \( R_i \) and 22 to 49nF for \( C_m \) were chosen. Although some of them are somewhat out of range with respect to Table 1, their results are still considered as valid input to the analysis since multi-frequency measurement is less susceptible to the individual \( \Delta R \) and \( \Delta X \) from each single frequency measurement thanks to its reduced weight divided by the total number of frequencies. All pairs of \( (R, X) \) from whole frequency measurements are plotted together in one R-X plane, followed by fitting to the Cole-Cole plot to extract the \( R_e, R_i, \) and \( C_m \) value from it. Figure 3 shows two examples of multi-frequency measurement results. Each dot and line in the plot indicates theoretically calculated \( R \) and \( X \) from known values of \( R_e, R_i, \) and \( C_m \) (Theoretical in the legend, dot in blue color), measured and calibrated \( R \) and \( X \) using the proposed bio-impedance monitor (Measured, dot in red color), and fitted result to the Cole-Cole plot (C-C Fitted, line in red color). Even though few measured points are still included for analysis which are out of line and have larger error from the theoretical values than the average as found in Figure 3 (a), it does not significantly affect the fitting to Cole-Cole plot and extraction of \( R_e, R_i, \) and \( C_m \). These erratic points are occasionally observed in high frequency measurements above 120kHz, where an initial phase of the summation vector of \( R \) and \( X \) becomes equal to or slightly larger than 90°. Since they are varied according to the load impedance \( R \) and \( X \), it is not easy to exclude them from the every automatic analysis. Therefore, when the proposed bio-impedance monitor is
adopted for single frequency measurement applications, the upper limit of available frequency should be set below 120kHz, which is low enough for the bio-impedance range in Table 1.

![Figure 3 Multi-frequency measurement result examples with Cole-Cole plot fitting](image)

When compared with the reference system, the average error computed from the 49 different load values is 0.18%, 7.2%, and 7.2% for \( R_e \), \( R_i \), and \( C_m \), respectively. An accurate estimation of \( R_e \) is a quite promising result for many bio-impedance applications more related to \( R_e \) or \( Z \), which is equal to \( \sqrt{R^2 + X^2} \) and mostly determined by \( R_e \), than \( R_i \) and \( C_m \), such as shown in [7]-[8]. The relatively large errors in \( R_i \) and \( C_m \) is mostly caused by the lower maximum frequency used in the proposed monitor than the reference system, and could be improved by adopting a higher bandwidth analog front end or a stimulating current with reduced high frequency harmonics, e.g. sine current, while this would increase power consumption of the system.

### 4. Conclusions and Further Works

We reported a new bio-impedance monitor with compact form factor and wireless connectivity, validated against a reference system. Thanks to its low power consumption, convenience, and accuracy, the proposed system can be a good candidate to replace bulkier existing bio-impedance monitoring devices for wearable and continuous bio-impedance monitoring applications. The remaining work includes human body test for several applications, and investigation of the correlation factors between bio-impedance and biophysical phenomena.

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