Reducing of Bioimpedance Influence on ECG by Correction Filter in Mobile Heart Monitoring System

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***Abstract*—The paper considers the problem of distortion of the ECG curve caused by bioimpedance of a patient's skin. The authors compare traditional analytical methods of bioimpedance estimation based on equivalent circuits (RLC and others) and "black box" method. Advantage of "black box" method is shown in the task of estimation of parameters of parasitic filter of the skin in comparison with traditional methods. The paper describes the theoretical base and the measurement experiment directed to estimation of real transition parameters of the correction filter. Obtained digital correction filter was experimentally investigated. The results of the computational experiment with ECG records from PhysioNET base shows the impact of bioimpedance changes to ECG signal form. The proposed solution is intended to implementation in portable heart monitoring systems.**

I. INTRODUCTION

At the present time, one of the major reasons of death in the world is cardiovascular disease (CVD) such as cardiac rhythm disorder and heartbeat abnormalities. To prevent this, disruptions of cardiac performance should be timely detected.

One of the most common methods of cardiac performance observation is daily electrocardiogram monitoring. Electrocardiogram (ECG) is a simple long-term recording of the heart electrical activity using surface electrodes [1]. Electrocardiography is an efficient non-invasive method that has different employment in biomedical sciences such as diagnosing rhythm disturbances, evaluating the heartbeat rate, checking the cardiac rhythm, biometric identification, emotion identification, etc. [2] Today, the ECG analysis is not limited to the diagnosis of CVD and is also used for emotion recognition and biometric identification. The main problem of cardiac performance monitoring by the electrocardiography is electrical interference. It distorts the waveform of ECG in conditions of patient's free movement. The noise immunity of an electrocardiograph is achieved by the use of special digital filters [3].

The methods of bioimpedance parameters assessment are used to minimize the noise, define the parameters of person's breath, asses the throughflow capacity of veins and arteries. In this way, impedance cardiography (ICG) is a method of great clinical interest related to the noninvasive monitoring of cardiac dynamics [4], [5]. The analysis of ICG signals is used in the diagnosis of patients with cardiovascular diseases too. ICG allows to obtain a series of parameters related to the mechanical function of the heart such as stroke volume, cardiac output, preejection period, lef-ventricular ejection time, or systolic time ratio. From bioimpedance measurements and more specifcally by the analysis of pulse wave velocity (PWV), arterial stifness can also be estimated, which is a parameter of interest in the diagnosis of hypertension situations or arrhythmia and stroke events. Moreover, it can be used to find blood pressure indirectly [6].

The main problem of cardiovascular system (CVS) monitoring by the ICG are individual differences in bioimpedance of patient's tissues and organs, which are located between the signal source and impedance cardiograph [7]. The same bioimpedance distorts the waveform of ECG. It reduces the reliability of assessing the state of CVS, the detectability and identification of abnormalities in cardiac performance. This study focuses on minimizing these distortions.

Methods and system for Simultaneous Recording of ICG are known [8], [9]. The additional bioimpedance channel is mostly used for respiration monitoring [10], [11]. Special medical diagnostic equipment based on rheography methods is known and available [12]. However, there is no available information related to known commercial ECG devices and specific methods for correcting ECG shape based on measured bioimpedance data.

The research begins with the theoretical part, where the authors describe the traditional approach to bioimpedance analysis and modeling. This approach is based on basic RLC elements and advanced elements (traditional Warburg, mass dissipative Warburg, etc.).An experimental "black box" method is proposed as a method for obtaining parameters of the bioimpedance distortion filter. The experimental part describes the instruments, algorithm, and results of the measurement experiment. A computational experiment demonstrates the application of a reduction filter with the obtained parameters to real ECG signals. The results and possible ways of further research are discussed.

II. PROBLEM STATEMENT

Bioimpedance measuring device is usually balanced or unbalanced measuring bridge, composed of an object of measurement and 3 two-pole elements [13]. Object of measurement is connected to the measuring device as an electrical two-pole element.

Devices bases on voltage divider composed of an object of measurement and reference two-pole element are also known

[14]. Reference two-pole element composed of active resistance measure (resistor), capacity measure (capacitor) or inductive measure (inductor) or their serial-parallel combination. In all these cases impedance measurement is based on comparison of reference two-pole element impedance and measurement object impedance.

Measurement object model is multi-element electrical circuit formed of serial-parallel connection of resistors, capacitors and/or inductors. Reference two-pole element has the same structure.

Nyquist diagram for this bioimpedance model has the half-round form in the first quadrant as the bioimpedance is resistive-capacitive. However bioimpedance diagrams obtained experimentally has the forms considerably different from the half-round form.

General impedance measurement conception described above cannot be mechanically applied to bioimpedance measurement correctly due to the fact that bioimpedance is formed by ionic conductivity in addition to electronic conductivity [15]. Therefore bioimpedance model requires multi-element circuit with expanded element basis including 3 classical elements (resistor, capasitor and inductor) and additional elements such as Warburg element, Gerischer element and constant phase element.

Bioimpedance models with expanded element basis allow obtaining Nyquist diagram that fits with the experimental data. However there is no way of measuring of these elements' parameters using traditional approach as there are no reference analogies of them.

The main technical task of the electrocardiography is recording the form of ECG. The form of the recorded ECG curve is the result of filtering (signal form distortion) of signal of electrical activity of the heart by bioimpedance of the tissues between a heart and electrodes of electrocardiographic device. Determination of parameters of filtering (or distortion) with help of adequate multi-element model of bioimpedance and measurement of the elements' parameters is a complex task.

III. SOLUTION VISION

Traditional analytical methods of investigation of external influences on the measurement object are brought to designing of electrical models based on the equivalent circuits consisting of discrete elements like resistor, capacitor and inductor. In the simplest case electrical models obtained with help of analytical methods provide more reliable information about simulated external influence on the signal.

Schematic view of this approach is shown in Fig. 1. The application of this method to bioimpedance problem allows the correction of ECG form that is demonstrated in work [16].

Therefore these methods are appropriate for simple tasks. However if the task is to estimate the influence of a complex system (like human tissues) on the measurement object (ECG in this case), traditional methods based on electrical models and equivalent circuits are not able to adequately describe the distortions in a complex systems.

Solution of these complex tasks by the methods of mathematical modeling require new elements in addition to traditional resistors, capacitors and inductors. Formal description of these elements is in the Table I.

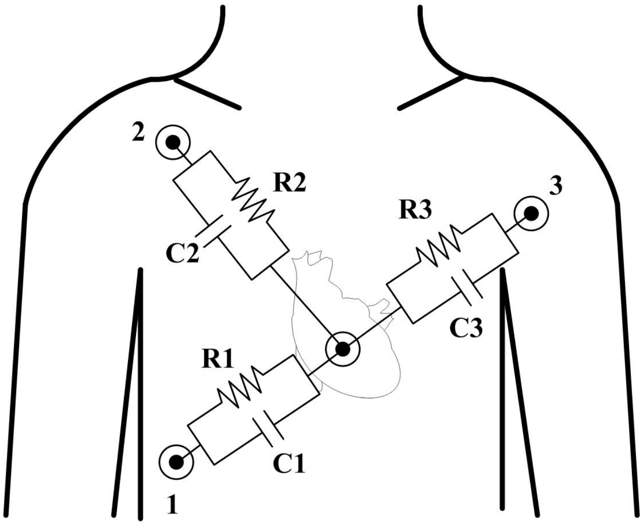

Fig 1. Schematic view of traditional approach

TABLE I. MATHEMATICAL DEFINITION OF THE EQUIVALENT ELEMENTS

Element	Equation
Debye-type	$\frac{R}{1+RC2\pi fj}$
Inductive Debye-type	$\frac{RL2\pi fj}{R+L2\pi fi}$
Cole-Cole-type	$\frac{R}{1+RT(2\pi fj)}$
Traditional Warburg	$\frac{1}{T(2\pi fj)}$
Mass dissipative Warburg	$R\tanh$
Non mass dissipative Warburg	$R\coth$
Gerischer type-I	$\frac{R}{\sqrt{1+(T2\pi fj)}}$
Gerischer type-II	$\frac{R}{1+(T2\pi fj)}$

Extension of the tools for analytical estimation of the external influences on the measurement object allows reaching the adequate accuracy for complex systems that distort the signal. However the resulting models cease to be electrical as the new elements have no physical implementation. Traditional Warburg element has infinite phase that is practically impossible but can be described mathematically (as transfer function). Consequently these models became mathematical rather than electrical.

Increasing of the accuracy of the new models including Warburg elements leads to the increasing of the complexity and resource consumption of the calculations hence. As a result it decreases the battery life of portable ECG monitoring systems.

Promising way of resolving this task is “black box” method instead of analytical method (analysis of multi-element electrical circuit). In this case bioimpedance of the tissues is considered as whole measurement object with unknown structure. One only measured value that reflects electrical parameters of the object is tension amplitude of the response bioimpedance of the object to applied harmonic tension with known amplitude and frequency. Evaluation of amplitude-frequency characteristic of the bioimpedance based on response amplitudes of discrete samples allows obtaining reliable information suitable for reconstruction the ECG form distorted by the bioimpedance. Fig.2 illustrates this approach.

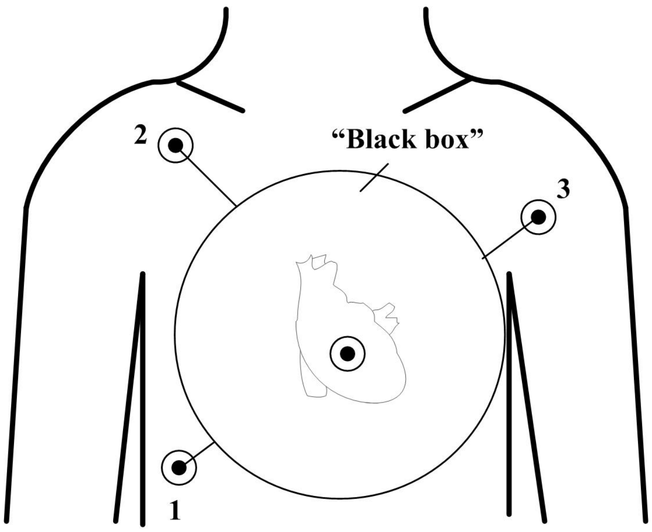

Fig 2. Schematic view of “black box” approach

Taking into consideration that the main goal of the estimation of the external influences on the measurement object is obtaining the amplitude-frequency characteristic of this distortion the authors propose usage of “black box” method instead of traditional and advanced methods. It consists in investigation of the influence of whole system (human tissues) on ECG and not every factor separately.

This approach allows focus on the complex influence of body tissues by direct measurement of bioimpedance at different frequencies and obtain reliable amplitude-frequency characteristic for every ECG record session during ECG record. It will allow obtaining accurate form of the ECG curve after corresponding reconstruction filtering without additional resource-demanding calculations on a low computing power portable devices. Fig. 3 illustrates the scheme of the investigation.

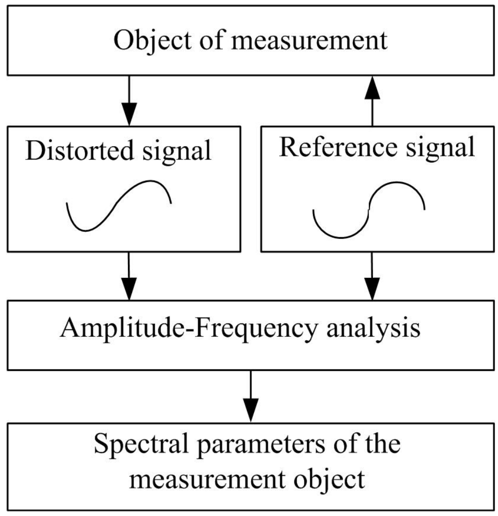

Fig 3. Scheme of the investigation

V. Experimental investigation

A. Laboratory measurement setup

The scheme of the measurement setup is shown in Fig. 4.

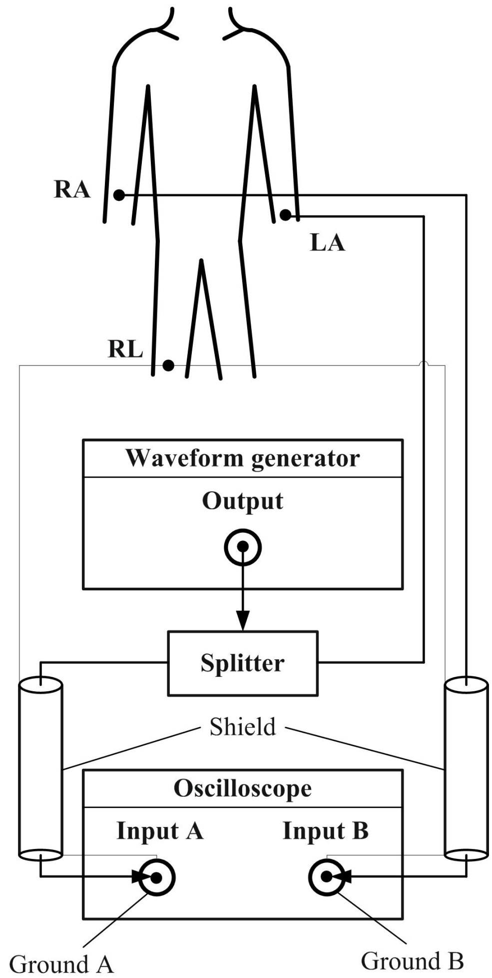

Fig 4. Measurement setup scheme

Laboratory measurement setup consists of:

- Functional dual channel waveform generator Aktakom AHP-1105 [17]
- Oscilloscope Tektronix TDS3012B [18]
- ECG electrodes [19]
- Shielded wires and connectors.

The output A of the waveform generator is connected via splitter in parallels to input A of the oscilloscope and to LA (Left Arm) point on the skin of the patient using shielded wire and ECG electrode. Input B of the oscilloscope is connected to RA (Right Arm) point on the skin of the patient using shielded wire and ECG electrode. Ground of both A and B input channels of the oscilloscope is connected to the RL (Right Leg) point on the skin of the patient using shielded wire and ECG electrode that is required for signal level matching. This connection is implemented using shielded wire with a thread connected to common ground of the signal wires.

Therefore input A of the oscilloscope receives the signal directly from the waveform generator and input B of the oscilloscope receives the signal that was distorted by the skin of the patient and other factors. The influence of these factors on the frequency components of the signal in all the frequency range could be additionally estimated. Waveform generator generates a signal with 1% error on amplitude that is approximately 20 mV in this case.

Special test bench is presented in fig.5.

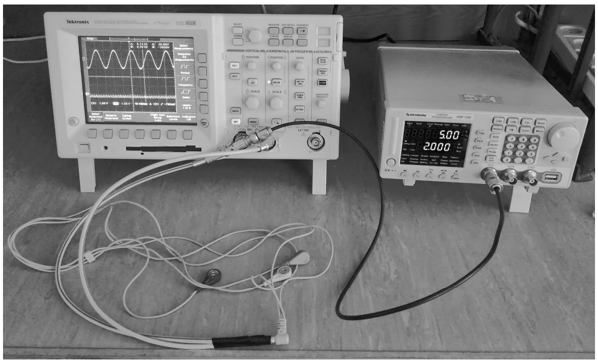

Fig 5. Laboratory measurement test bench

B. Process of measurement experiment

Measurement experiment was implemented as two series of measurements with two volunteers playing roles of patients. These volunteers have different age body mass index (BMI). It is organized to prove the systematic character of influence of bioimpedance on the form of the ECG curve.

Measurement of the amplitude of every frequency component of the signal in the determined frequency range is implemented as a series of 10 measurements:

- 5 measurements in the points with maximal amplitude;
- 5 measurements in the points with minimal amplitude.

The result is determined by the formula:

$$a = \sum_{i=1}^{N} \frac{|x_i|}{N} \qquad (1)$$

where N — number of measurements (10 in this particular experiment);
X_i — the result of the single measurement of the series of multiple measurements.

It allows to estimate the influence of the bioimpedance both in positive and negative areas of amplitude.

To minimize the distortion caused by electrical grid and lighting (50 Hz) and cell nets (GSM, 3G, LTE – from 900 to 2100 Hz) all measurement experiments were fulfilled in daytime (without electrical lighting) in grounded room.

C. Measurement results

The recorded ECG signal was decomposed into the spectrum with the help of fast Fourier transform (FFT). All calculations are made in GNU Octave [20] with Signal processing toolbox.

Raw ECG spectrum is shown in Fig.6 demonstrating that frequency spectrum of the ECG is located in the range from 0 to 180 Hz. Consequently, most measurements of the bioimpedance should be performed in this range.

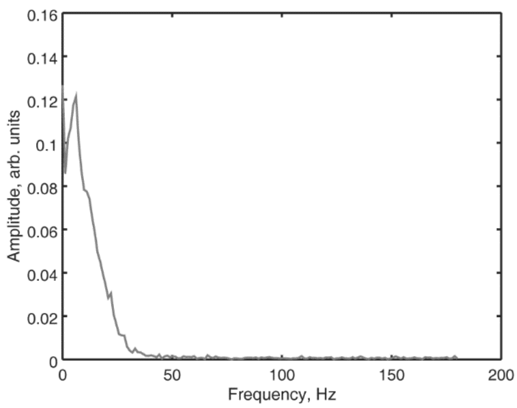

Fig 6. Raw ECG spectrum

The fact that the frequency spectrum is so wide is caused by the application of discrete algorithm of Fourier transform (FFT). This algorithm returns symmetric spectrum of discrete signal. Frequency range of the result is equal to half of sample rate of the input signal (360 Hz in this case). Therefore frequency range from 0 to 180 Hz is taken for further computations. However, the useful part of the signal is mostly located in the range from 0 to 50 Hz.

After this the amplitude – frequency parameters of influence of the bioimpedance of the tissues on the recorded signal. The results are in Table II.

The application of amplitude-frequency dependencies to the ECG signal processing requires more measurements (ideally for every frequency). The authors used 1-dimensional cubic interpolation to obtain the data. The result is shown in Fig. 7.

TABLE II. FREQUENCY RESPONSE OF A SKIN FILTER

Frequency, Hz	Attenuation coefficient
3.0×10^{-2}	5.0×10^{-1}
1.0×10^{-1}	2.2×10^{-1}
2.0×10^{-1}	4.5×10^{-1}
3.0×10^{-1}	4.5×10^{-1}
4.0×10^{-1}	3.9×10^{-1}
5.0×10^{-1}	4.0×10^{-1}
7.0×10^{-1}	4.3×10^{-1}
1.0	6.0×10^{-1}
2.0	4.2×10^{-1}
3.0	4.8×10^{-1}
5.0	4.5×10^{-1}
7.0	5.2×10^{-1}
10.0	6.1×10^{-1}
50.0	7.8×10^{-1}
100.0	$8.4\times10^{-}$
180.0	9.6×10^{-1}

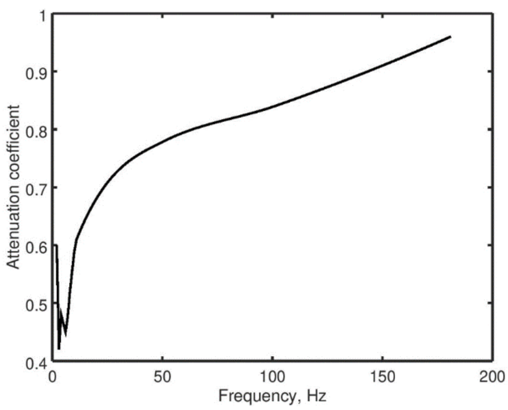

Fig 7. Plot of frequency response of a skin filter

Fig. 7 shows that decreasing of the amplitude of the useful signal under the influence of the bioimpedance of the body tissues is maximal in the area of 5 Hz and goes lower with the frequency. This effect is caused by the fact that human skin conducts alternating current better than direct one. For example, critical values for the current that lead to fails in the heart activity are [21]:

- 60 mA for alternating;
- 300-500 for direct.

As a result of the measurement part of the experimental investigation the amplitude – frequency dependencies of reconstruction filter are obtained using "black box" method.

D. Computational experiment

The authors conducted a series of computational experiments to estimate the influence of the tissues' bioimpedance on the ECG signal. All calculations are made in GNU Octave [20] with Signal processing toolbox.

Test data set is taken from PhysioNET free database [22]. This data set includes 1000 unique ECG records. Every ECG record has 10 sec. length and more (at least 10 cardiac cycles per record).

Computational experiment consists of the following steps:

- Obtaining the signal spectrum;
- Correction of the signal spectrum;
- Reconstruction of the signal.

On the first step the spectrum of the signals was obtained using FFT. After that this spectrum was corrected using a special filter.

The correction (reverse, reconstruction) filter was implemented using the parameters from Table II. This filter corrects an input signal changing the spectrum of the input signal with the following inverse Fourier transform (iFFT). The aim of this operation is to reconstruct the true form of the ECG curve reducing the influence of the bioimpedance that plays the role of a parasitic filter. The result of the correction of the spectrum is shown in Fig. 8 and Fig. 9.

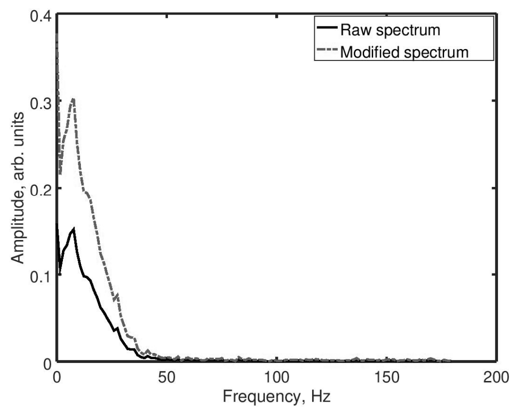

Fig 8. Comparison of raw and filtered signal spectrum

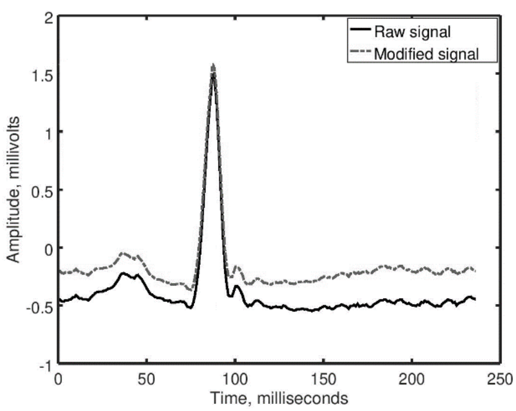

Fig 9. Comparison of raw and filtered signals

Fig. 9 shows that there is a shift of isoelectric line of the ECG up to 300 μV (positive direction) in addition to morphological changes of concrete areas of ECG (P wave, ST segment)

Evaluation of the full-scale accuracy requires absolute error that allows estimate the error in measurement units (in mV):

$$\Delta = x_{actual} - x_{meas} \quad (2)$$

$$\gamma = \frac{\Delta}{x_{range}} \cdot 10 \quad (3)$$

where the X_{range} of ±2,5 mV.

The result is shown in Fig. 10.

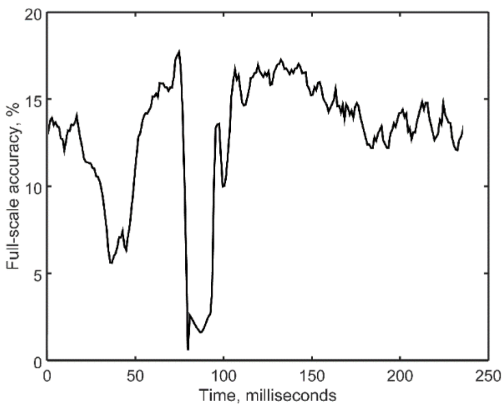

Fig 10. Full-scale accuracy of Raw vs Modified ECG signals

Fig. 10 shows that maximal full-scale accuracy is non-uniform during cardiac cycle. The mostly influenced areas of ECG are P, Q and S peaks and ST segment:

- increase in the P-wave amplitude was found, which can lead to a wrong diagnosis of such diseases as chronic obstructive pulmonary disease (COPD), congestive heart failure and coronary heart disease [23];
- increase in the ST segment is detected. The displacement of this segment and correspondingly J-point more than 2 mm relative to the isoelectric line can be considered as a sign of myocardial infarction [24].

So, the results of the computational experiment show that bioimpedance impacts ECG signal and its influence is non-linear and may lead to diagnostic errors. Spectrum correction filter is able to reconstruct the true form of ECG.

VII. Discussion and Future work

This work should be considered as an attempt to experimentally estimate the influence of complex impedance of body tissues on the form of the ECG curve. The results of the work allows to propose a reverse filter for reconstruction of the ECG form using spectrum correction. The parameters of this filter can be determined more precisely (for example, dynamically and individually), which is a promising direction for future research in the field of reducing bioimpedance influence on the ECG.

The proposed filter allows a quite simple practical implementation in mobile ECG monitoring systems.. The possible ways of its implementation are the following:

- Software (with pre-loaded parameters of the reconstruction filter, possibly individual) as a part of mobile application for ECG processing;
- Hardware-software (with special hardware component for real-time bioimpedance measurement on ECG recording device and the following software processing).

The ECG monitoring system that obtains an ECG signal cleared of the influence of bioimpedance changes can be used independently or as part of intelligent spaces [25], cyber-physical systems [26] , and IoT environments [27], [28].

VIII. Conclusion

The results show that the "black box" method is a suitable method for evaluating the parameters of a parasitic bioimpedance filter. The proposed method of ECG reconstruction was experimentally tested. A computational experiment demonstrates that a special digital filter based on obtained parameters reconstructs ECG signals. Its simplicity and efficiency allow it to be used in portable heart monitoring systems based on mobile devices.

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