Mobile ECG Monitoring System Prototype and Wavelet-Based Arrhythmia Detection

Andrey Kuzmin, Maxim Safronov, Oleg Bodin
Penza State University
Penza, Russia
{flickerlight, safronov.maxim, bodin_o}@inbox.ru,

Sergey Prokhorov, Anastasya Stolbova
Samara National Research University
Samara, Russia
sp.prokhorov@gmail.com, anastasiya.stolbova@bk.ru

***Abstract*—This paper describes a solution for mobile heart monitoring. In part of hardware the authors focused on engineering problems of increasing the number of ECG leads and increasing the sampling rate. It potentially allows to increase the effectiveness and accuracy of localization and to decrease the influence of pacemaker pulses on the ECG signal recording respectively. Implementation of hardware and software parts is described. The method and software tool for wavelet-based analysis of ECG signals are proposed for arrhythmia detection task. Experimental results show that proposed wavelet-based method of ECG analysis can detect signs of arrhythmia. Results of wireless channel speed test confirm that the chosen hardware meets the requirements of wireless protocol bandwidth. Proposed solutions are suitable for portable heart monitoring systems.**

I. INTRODUCTION

To a large extent standard methods of electrocardiogram (ECG) recording and analyzing have already run out of their resources. The authors are convinced that introduction of computerization and modern ways to process and visualize cardiographic information can help to improve heart diagnosis quality.

Two main groups of equipment for heart state assessment diagnosis could be distinguished – “clinical” and “screening”. The first one is intended for hospital application. This group includes high-precision diagnostic systems, such as a CAT scan, angiography, ultrasound scanning etc. The second one consists of portable devices for ECG recording and simple analysis of its parameters. These devices are applied for massive prevention medical examinations. More than 95 percent of modern heart diagnostic equipment might be attributed to the “screening” group. At the same time the existing methods of time and amplitude analysis of ECG characteristics have reached their limits. After electrocardiography connected to a personal computer functional and diagnostic capabilities of such systems have been increased substantially. It was caused by application of modern information processing methods realized through computer programs.

As international research companies report, the market of hand-held health monitoring devices has grown with 43.3 per cent per year since 2013. It is expected to reach $8 billion by 2019. The market growth is due to increased demand for informational technologies in medicine. It is also supported by public policies for citizens’ health promotion. Devices for cardiovascular disease diagnosis and control is sought-after medical equipment.

Unlike stationary ECG analyzing equipment, hand-held devices have greater diagnostic capacity [1]. Modern technologies allow to develop and produce small hand-held devices for registration of the parameters of human functional state. It is necessary to improve standard methods and technologies of ECG recording and processing for hand-held devices because such equipment relates to operation with patient’s free activity conditions. Distinctive features of these conditions are increased noise level and fewer leads. They also require more energy efficiency.

II. KNOWN ANALOGUES

QardioCore [2] is a hand-held heart monitor. It does not require any additional devices for its proper functioning. Attached to a patient’s chest by strap, a small device does not disturb human vital activity. QardioCore’s main functions are counting steps, travelled distances, calories, and breath and heart rate monitoring. The heart monitor sends all the indicators to Qardio or Apple Health applications, where the data is stored, via Bluetooth 4.0 technology. QardioCore is a single-channel heart monitor with continuous recording method. It has fixed A/D sampling rate 600 Sps, 16 bit resolution and splash and water resistant, rated IP65.

OMRON HCG801 [3] HeartScan is a portable ECG recorder which can be gripped in one hand due to its compact size. HeartScan uses the 30 second recordings of the heart waveforms to analyze various symptoms of any problems related to heart. Single channel HeartScan ECG Monitor feature of the device makes it a more flexible multipurpose tool which can be used by medical professionals. The operation without any cord and straight screen display provides fast scanning of the heart. The detailed information related to heart rhythm, heart rate and ECG wave form is provided by the ECG analysis of the device. Analyzed data can be stored on the SD card, and also be shown on the multi-stage display. One standard record consists of time and date, short cut analysis, heart rate and raw ECG signal up to 30 seconds.

The last reviewed analogue is the prototype of the mobile portable heart monitoring system [4] developed by the authors, which is a portable ECG recording device, fixed on the patient with wires with disposable electrodes, and a smartphone, using

ISSN 2305-7254

Android operating system with preinstalled software. Portable ECG recording device is a cardio amplifier with ECG recording function with a A/D sampling rate of 500 Sps and a resolution of 24 bits, as well as real-time data transmission using the Bluetooth Low Energy protocol.

Currently, most portable ECG devices, in contrast to their stationary counterparts, have the following problems:

- Low information content and low possibility of localization of myocardial infarction in three standard leads;
- Most devices for recording of ECG signal are liable to pacemaker pulses [5].

These tasks can be resolved by using up to 12 lead ECG systems, but it's hard to make them portable and easy-to-use for unprepared person.

III. IMPLEMENTATION

A. Hardware

The use of 3 leads is not enough to determine some types of myocardial infarction, so authors selected a scheme using 4 leads which provides more sensitivity to a specific types of myocardial infarction.

However, ADS1298R ECG front end [6] is sufficient for implementing a system of 4 or more (up to 8) leads, but the bottleneck in this system is System-On-Chip (SoC) CC2540 working in the Bluetooth 4.0 standard. Because of the spread of Bluetooth 5.0 technology, the authors consider it advisable to replace the outdated SoC 2540 with the more modern CC2640R2F solution, developed by Texas Instruments as well. The structure of the device is shown in Fig.1.

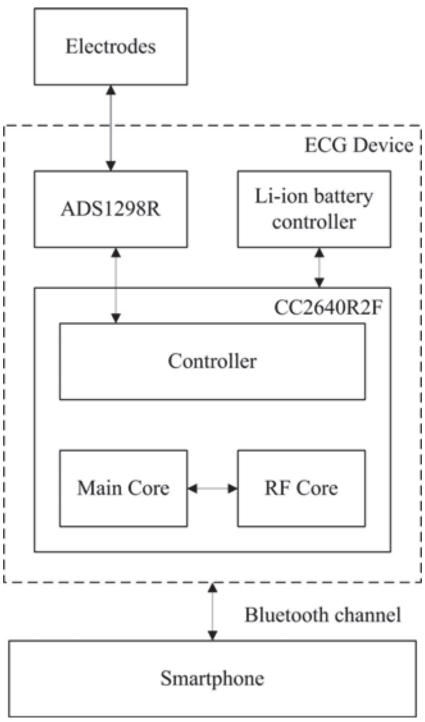

Fig. 1. ECG device structure

The CC2640R2F [7] device contains a 32-bit ARM Cortex-M3 core that runs at 48 MHz as the Main Core and ultra-low power Sensor Controller. This sensor controller is applied for interfacing external sensors and for collecting analogue and digital data autonomously while the rest of the system is in sleep mode. The interaction with the wireless protocol BLE is engaged in the RF core.

The RF Core contains an ARM Cortex-M0 processor that interfaces the analog RF and base-band circuitries, handles data to and from the system side, and assembles the information bits in a given packet structure. The RF Core offers a high level, command-based API to the Main Core. The RF Core is capable of autonomously handling the time-critical aspects of the radio protocols (Bluetooth low energy), i.e. can offload the main core of the device. The RF core has a dedicated 4-KB SRAM block and runs initially from separate ROM memory. Unfortunately, the ARM Cortex-M0 processor cannot be programmed.

Application of CC2640R2F allowed reorganizing the structure of the device, transferring work with wireless data transmission and ADC routine not just into separate threads, but into separate hardware modules specialized in these tasks. With the transition to the new architecture, it was possible to reduce the current consumption from 17 to 11 mA.

Due to increased data transmission speed, it is possible to solve the problem with a pacemaker pulses in ECG signal by simply increasing the A/D Sampling rate to 2000 Sps (0,5 ms interval) [8]. ECG device prototype is shown in Fig.2.

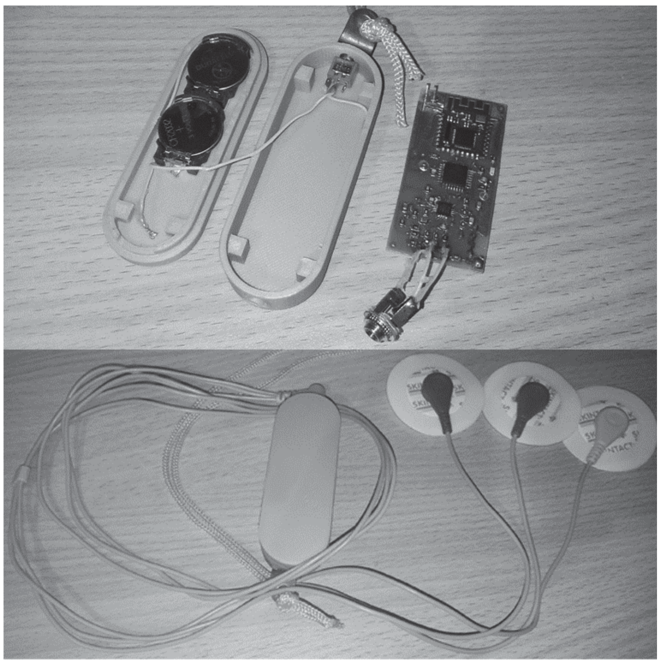

Fig. 2. ECG device prototype

In terms of energy efficiency, an important parameter is the transmitting power of the transceiver. The authors propose to control this power in order to reduce it depending on the distance to the receiver in which the smartphone acts. This functionality is provided by the built-in capabilities of the SoC

CC2640R2F and the control application on the smartphone, which can measure the data loss and adjust the transmitting power. Approximate parameters of the transceiver are shown in TABLE I

TABLE I. APPROXIMATE PARAMETERS OF THE TRANSCEIVER

Distance	**Less than 1 meter**	**From 1 up to 5 meters**	**From 5 up to 10 meters**	**Greater than 10 meters**
TX Power	-21 dBm	-6 dBm	0 dBm	+5 dBm

B. Software

The authors have improved the mobile application that was described in paper [4].

The user interface has been refined. The main functionality is divided into several related windows, which allows to simplify the application's main screen, previously full of information (see Fig.3).

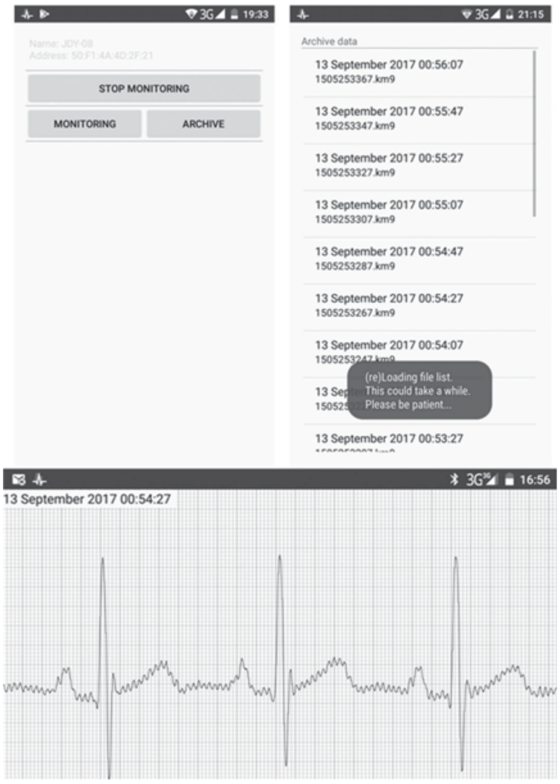

Fig. 3. Application visual forms

Authors have changed the format of data stored in the memory of the smartphone. Now at the beginning of each record, there are metadata, namely:

- Recording type: automatic or on-demand;
- Precise date and time of the recording;
- A/D sampling rate of the record;
- Minimum, average and maximum heart rates;
- Preliminary analysis data.

The structure of the transmitted packet has also been changed, since in the standard Bluetooth 5.0 the useful packet size is increased from 31 octets to 255 octet packets.

A/D sampling rate of the ECG device is now adjustable from the software. In addition to minimally necessary 500 Sps, ECG can be recorded with an A/D sampling rate of 1000 and 2000 Sps.

The duration time of each recording is increased to 30 seconds by recording a certain number of values at a specified sampling rate from the start time of the recording: the number of ECG readings will be 15000 for 500 Sps for 1 lead, for 1000 Sps - 30000, for 2000 Sps - 60000 samples, respectively.

The automatic power control function is added depending on the distance between the receiving and the transmitting devices.

IV. WAVELET-BASED ECG ANALYSIS

A. Analysis tool

In order to solve the task of signal analysis it's necessary to use spectral analysis methods. In the case when the signal is stationary it's possible to use Fourier transform. This transform allows to define the frequency spectrum of the signal which is useful for solving a range of problems. The disadvantage of frequency analysis is lack of possibility to localize in time the frequency component in the signal, which doesn't allow to analyse non-stationary signals. Thus time-frequency analysis has been developed. There exist various methods of time-frequency analysis: window Fourier transform, Gabor transform, Wigner-Ville transform and wavelet transform. In the theory of wavelet the works of I. Daubechies [9], S. Mallat [10], C.K. Chui [11] are fundamental. Wavelet transform is used in different fields: for medical signals analysis [12, 13] etc.

One of the applications of wavelet transform is ECG analysis. Wavelet transform in ECG analysis is especially useful for the analysis of R- and T-waves. It is applied to identify the changes following the coronary artery acute occlusion and can identify the components of ECG signal that are sensible to transitory ischemia [14]. A range of methods based on wavelet transform using Daubechies wavelets is proposed for identification, classification and analysis of arrhythmia according to ECG signals. In order to identify patients with ventricular tachycardia a transform with Morlet wavelet [15] is used. In paper [16] wavelet transform was used to evaluate the myocardium action potential which would allow to automatically diagnose heart diseases such as myocardium ischemia and cardiac insufficiency. At the Subdepartment of Information Systems and Technologies of Samara National Research University a software system is worked out for wavelet analysis of stochastic processes [17]. Its structure scheme is shown in Fig. 4.

The software system consists of the following modules.

Input signal module is meant to generate input sequences of the following types:

- Stochastic stationary ones with a chosen type of correlation function;
- Stochastic non-stationary ones with a chosen type of correlation function
- Determinate ones.

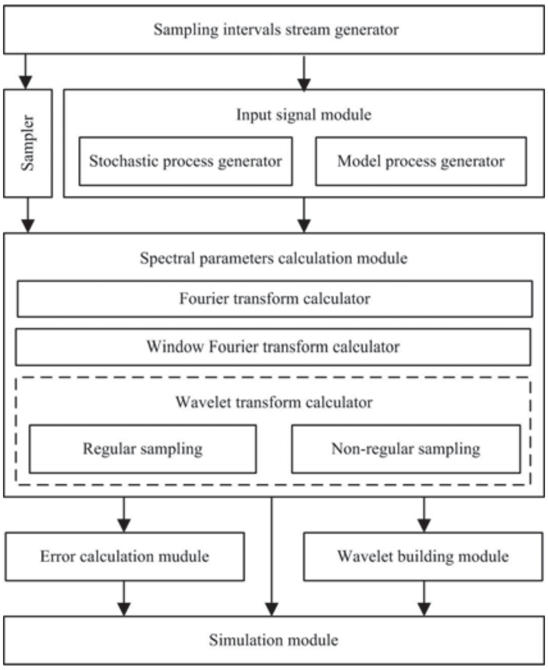

Fig. 4. Structure of wavelet-based software

The module allows to get either stochastic or model processes.

Spectral parameters calculation module uses the following methods:

- Fourier transform;
- Window Fourier transform;
- Wavelet transform with regular sampling;
- Wavelet transform with non-regular sampling;

Error calculation module calculated coefficients of wavelet transform.

Wavelet building module is meant to calculate wavelet functions. 10 main types of wavelets are used in the system. To build them it's necessary to indicate the number of wavelet samples *N*, sampling interval Δt, scale *a* and shift *b*.

Simulation module is meant to model wavelet transforms of processes with non-regular sampling, to evaluate the correctness of the developed algorithms.

B. Arrhythmia detection

With the use of this Wavelet-based software system there have been analysed ECG signals to detect an arrhythmia. Special long term ECG signals database is used for computational experiments. This database consists of two-channel ECG [18, 19] with sampling rate 128 Hz. It is available for free at physionet.org. This base was specially created for developing automated methods for detecting and predicting paroxysmal atrial fibrillation (PAF). The base includes signals recorded from people:

- Without arrhythmia;
- With arrhythmia;

and divided into two groups:

- Directly before the attack (30 min.);
- During the attack (5 min.).

«Clear» records that presented later in the paper are the ECG records got from people without signs of arrhythmia. Long (30 min.) records from healthy people are "clear" as well short (5 min.) records. They are used evaluate the false positive detections.

The sequence of operations while analyzing signals is given in Fig. 5.

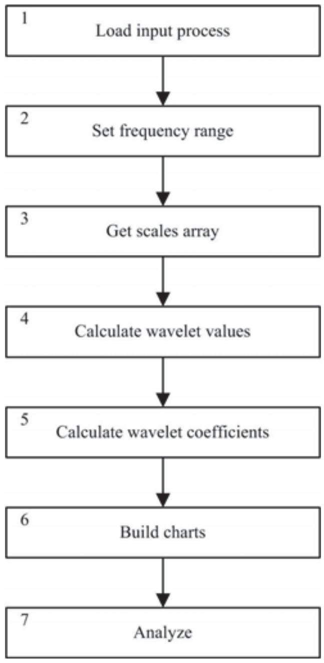

Fig. 5. Wavelet-based arrhythmia detection experiment scheme

Step 1. To load input process *y(t):* one of ECG-channels.

Step 2. To set frequency range ω: 0,01 Hz – 15 Hz.

Step 3. To get scales array *a* inversely proportional to frequency.

Step 4. To calculate Morlet wavelet values for all scales *a* by the following formula:

$$\psi(t) = \exp(-ikt)\exp\left(-\frac{t^2}{2\sigma^2}\right) \quad (1)$$

where *k* and σ are wavelet parameters.

Step 5. To calculate wavelet coefficients *W(a, b)* with wavelet (1), using expression (2):

$$W(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} y(t)\psi\left(\frac{t-b}{a}\right)dt \quad (2)$$

where *y(t)* is a stochastic process, *ψ(t)* is the chosen analyzing wavelet, $a \neq 0$ – scale parameter, $b \geq 0$ – shift parameter.

Step 6. To build scalograms and wavelet spectra.

Step 7. To analyze parameters in terms of significance as detection criterion.

V. EXPERIMENTAL RESULTS

A. Wavelet-based arrhythmia detection

The analysis of ECG wavelet transform results detected five frequency ranges present in ECG-signals (see TABLE II).

TABLE II. EXPERIMENTALLY DETECTED FREQUENCY RANGES

Number	Range, Hz
1	less 1
2	1 – 2
3	2 – 4
4	4 – 5
5	5 – 8

For healthy patients there are frequencies in 2-5 Hz range from 0,45 to 1 Hz in wavelet-spectrum of the first ECG-channel.

For patients with arrhythmia (15, 16) frequencies from range 2 and 3 predominate on the first channel, and the power of frequencies from range 4 and 5 decrease two to three times comparing to healthy patients.

Scalograms of “clrear” and arrhythmic ECG records are shown in Fig 6.

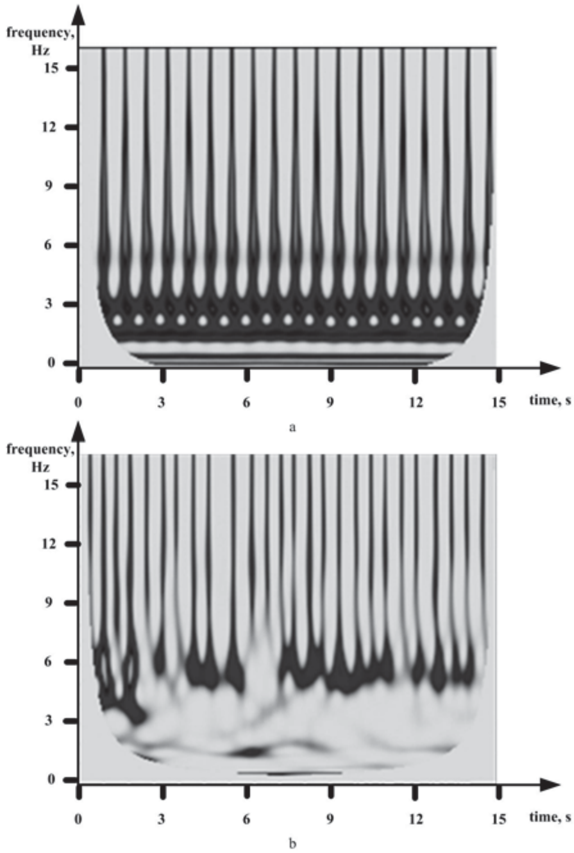

Fig. 6. Examples of scalograms of ECG signals fragments: (a) – record 1; (b) - record 15

For patients 15 and 16 on the second ECG-channel before and during the arrhythmia there can be seen the increase of frequency power from range 5 two to four times comparing to other analyzed records (see Fig. 7).

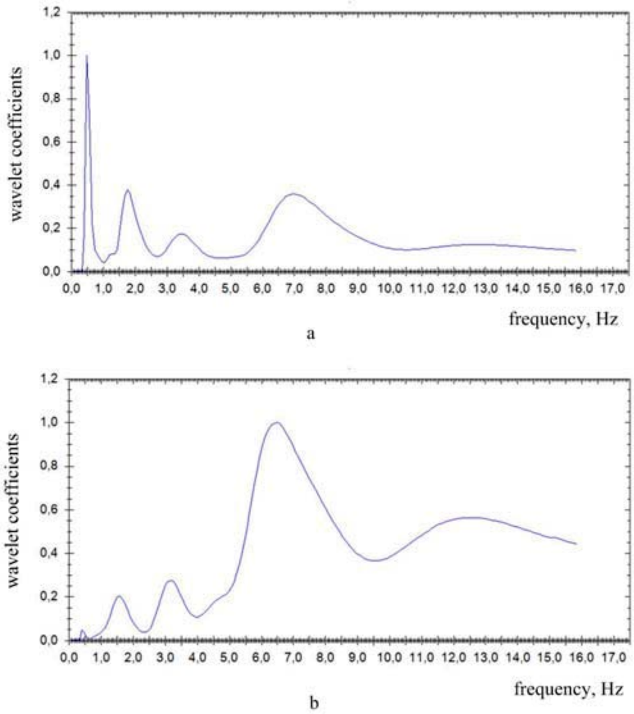

Fig. 7. Examples of wavelet spectra of second channel of ECG record 16 fragments: (a) – in relatively “clear” period; (b) – in arrhythmic period

In TABLE III there are particular frequencies detected in the signal and their power for “clear” records 1, 2 and “arrhythmic” records 15, 16.

TABLE III. ECG ANALYSIS RESULTS

Ch.	Record							
	1		2		15		16	
	ω, Hz	A	ω, Hz	A	ω, Hz	A	ω, Hz	A
1	1,2660	0,97	1,3451	0,83	1,6616	1	1,5825	1
	2,6902	1	2,7694	1	3,4024	0,48	3,1650	0,55
	4,0354	0,8	4,1145	0,65	5,0640	0,18	4,8266	0,2
	6,8839	0,5	6,9630	0,45	7,5169	0,19	7,5960	0,17
2	n/a	n/a	0,3956	1	0,3165	0,05	0,3956	0,4
	1,4242	1	1,5034	0,1	1,5034	0,2	1,5825	0,27
	3,0067	0,45	2,3737	0,05	3,0859	0,25	n/a	n/a
	4,5101	0,2	n/a	n/a	n/a	n/a	n/a	n/a

It is significant that during the arrhythmia ECG signal becomes non-stationary in its frequency both on the first ECG-channel and on the second one.

B. Wireless data transmission speed

In order to validate that proposed hardware solutions for implementation of ECG device meet the requirements of wireless data transmission channel bandwidth it is necessary to calculate and test wireless data transmission speed.

Data transmission speed (DTS) for this system is determined by the formula (in kbps):

$$DTS = \frac{Res_{ADC} * N * SR_{ADC}}{1000} \qquad (1)$$

where Res_{ADC} is ADC resolution in bits, N – number of leads and SR_{ADC} – A/D sampling rate.

For a system of four leads, the required data rate must be at least 48 kbps with a sampling frequency of 500 Hz and 96 kbps at a sampling frequency of 1000 Hz. Other values are shown in the TABLE IV.

TABLE IV. CALCULATED DATA TRANSMISSION SPEED

Number of leads	Data transmission speed for a specific A/D sampling rate, kbps	
	500 Sps	1000 Sps
3	36	72
4	48	96
5	60	120
6	72	144
7	84	168
8	96	172

The wireless channel bandwidth is tested by means of Matlab. The experimental scheme is shown in Fig. 8.

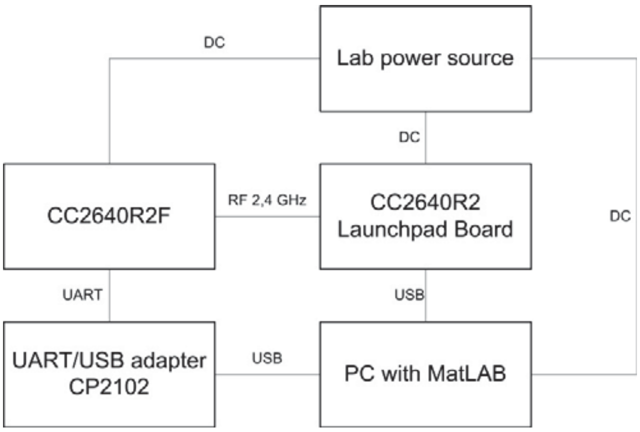

Fig. 8. Wireless channel speed test scheme

The obtained results are shown in Fig. 9.

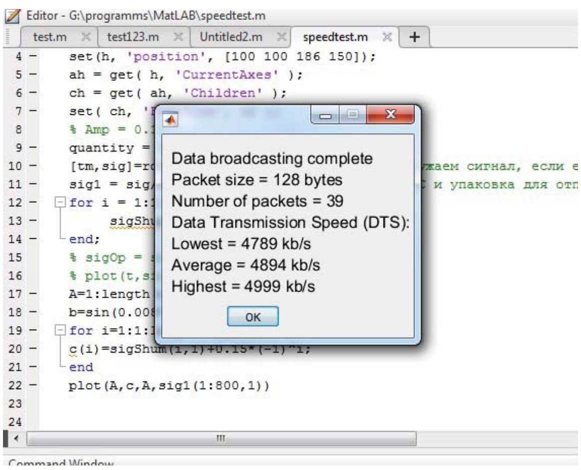

Fig. 9. Wireless protocol bandwidth test results

Fig. 9 shows that the lowest DTS estimated from the computational experiment (see Fig. 9) is 4789 kbps whereas the maximal required DTS is 172 kbps (see Table IV). Experimentally evaluated data transfer speed is fully consistent with the real-time transmission of test ECG data.

VI. FUTURE WORK

Because of the increased number of leads (and its even greater increase in the future), the authors will work out the possibility of placing electrodes on various kinds of surfaces, such as a belt or a T-shirt. It can partly solve one of the main problems of wearable ECG monitors - the user's inability to place electrodes correctly and durably.

VII. CONCLUSION

This work shows the approach and technical implementation of mobile heart monitoring system. The authors focused on solving two important engineering problems: increasing the number of ECG leads and increasing the sampling rate. Experimental results show that chosen hardware meets the requirements of wireless protocol bandwidth.

Experimental results show that proposed wavelet-based method of ECG analysis in terms of non-stationary process can detect signs of arrhythmia and can be an important tool for offline ECG analysis in portable heart monitoring solutions for wide range of applications from sports and fitness to monitoring for medical reasons.

REFERENCES

[1] S. Suresh, K. Kumar, V. Kamakoti, "Portable Low Cost 3 Lead Wireless Wearable ECG Device", in *World Congress on Medical Physics and Biomedical Engineering IFMBE Proceedings*, 39, 2013, pp 1331-1334

[2] Qardio Inc. official website, Qardiocore, Web: https://www.getqardio.com/qardiocore-wearable-ecg-ekg-monitor-iphone/.

[3] OMRON Healthcare Europe B.V. official website, HeartScan HCG-801 ECG Monitor. Web: https://www.omron-healthcare.com/en/products/electrocardiograph

[4] A Kuzmin, M. Safronov, O. Bodin, M. Petrovsky, A. Sergeenkov, "Mobile Heart Monitoring System Prototype Based on the Texas Instruments Hardware: Energy Efficiency and J-point Detection", *International Journal of Embedded and Real-Time Communication Systems*, vol. 7, issue 1, 2016, p. 64-84.

[5] J. Kruse, C. Redmond, "Detecting and Distinguishing Cardiac Pacing Artifacts", *Analog-Dialogue*, 46-11, 2012, p. 1-6.

[6] Texas Instruments official website, ADS129x Low-Power, 8-Channel, 24-Bit Analog Front-End for Biopotential Measurements, Web: http://www.ti.com/lit/ds/symlink/ads1298.pdf.

[7] Texas Instruments official website, CC2640R2F SimpleLink™ Bluetooth® low energy Wireless MCU, Web: http://www.ti.com/lit/ds/symlink/cc2640r2f.pdf.

[8] IEC 60601-2-27:2011 *Medical electrical equipment - Part 2-27*: Particular requirements for the basic safety and essential performance of electrocardiographic monitoring equipment.

[9] I. Daubechies, *Ten Lectures on Wavelets*, Philadelphia: SIAM, 1992.

[10] S. Mallat, *A wavelet tour of signal processing. The sparse way*, Burlington: Elsivier, 2009.

[11] C. K. Chui, *An Introduction to Wavelets*, San Diego: Academic Press, 1992.

[12] S. Mantri, P. Agrawal, D. Patil, V. Wadhai, "Non Invasive EEG Signal Processing Framework for Real Time Depression Analysis", *SAI Intelligent Systems Conference*. – London, 2015, p. 518-521.

[13] R. Stepanov, S. Podtaev, P. Frick and A. Dumler, "Beat-to-Beat Cardiovascular Hemodynamic Parameters Based on Wavelet Spectrogram of Impedance Data, *Biomedical Signal Processing and Control*, 36, 2017, p. 50-56.

[14] C. Saritha, V. Sukanya, Y. Narasimha Murthy. "ECG Signal Analysis Using Wavelet Transforms", *Bulgarian Journal of Physics*, 35*,* 2008, p. 68-77.

[15] P.S. Addison, "Wavelet transforms and the ECG: a review", *Physiological measurement,* 26, 2005, p. 155-199.

[16] Z. Peng, G. Wang, "A Novel ECG Eigenvalue Detection Algorithm Based on Wavelet Transform", *BioMed Research International*, 2017, 2017, p. 12

[17] A.I. Khaymovich, S.A. Prokhorov, A.A. Stolbova, A.I. Kondratyev "A model of milling process based on Morlet wavelets decomposition of vibroacoustic signals", *Proceedings of the Mathematical Modeling Session at the International Conference Information Technology and Nanotechnology*,1904, 2017.p. 135-140.

[18] G. Moody, A. Goldberger, S. McClennen and S. Swiryn, "Predicting the Onset of Paroxysmal Atrial Fibrillation: The Computers in Cardiology Challenge", *Computers in Cardiology,* 28, 2001, p. 113-116.

[19] A. Goldberger, L. Amaral, L. Glass, J. Hausdorff, P. Ivanov, R. Mark, J. Mietus, G. Moody, C.-K. Peng and H. Stanley. "PhysioBank, PhysioToolkit, and PhysioNet: Components of a New Research Resource for Complex Physiologic Signals", *Circulation*, 101(23), 2000, p. 215-220.