Device and Software for Mobile Heart Monitoring

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***Abstract*—This paper describes a new solution for mobile heart monitoring. This approach is based on the experience of ECG processing algorithms development for diagnostic purposes. The described approach allows developing a new mobile heart monitoring system consisting of ECG recording device, mobile computer (smartphone or tablet) and server (medical database). It is based on specially developed software components (microcontroller program, mobile computer client software and server software). ECG processing algorithms could be used offline without any communication with server. It lets mobile monitoring system inform the user about any signs of dangerous heart condition in ECG. Paper also describes experimental results of J-point detection, energy efficiency of the ECG device, wireless protocol bandwidth and contact break detection. They confirm the efficiency of the proposed technical approaches to mobile heart monitoring for wide range of applications from sports and fitness to monitoring for medical reasons.**

I. Introduction

Currently, portable systems for disease diagnosis and monitoring of human functional state are becoming more common. The market is growing due to increasing demand for information technologies in medicine and the policy of many countries of strengthening the health of their population.

Devices of control and diagnostics of cardiovascular diseases are the leaders among popular medical devices. Wearable devices possess better diagnostic capabilities compared to stationary monitoring tools [1]. Modern technologies allow to design and develop a miniature wearable device for recording of functional state parameters of the person. For their work it is necessary to improve the classical tools and the algorithms for registration and processing of ECG, because work in free movement conditions is characterized by high noise level and smaller number of measurement channels, therefore it requires more energy efficiency.

One of the unsolved problems of modern health care is the risk of sudden cardiac death. This risk affects both the elderly people with known heart disease, and young people who have no idea about their health problems. To reduce the risk of sudden cardiac death it's necessary to improve portable systems recording and processing of ECG, both in hardware and software by improving the methods and means of processing, applying them in free movement conditions. Portable computing devices, such as smartphones or tablets, could increase the effectiveness of heart monitoring.

Thus, the improvement of portable ECG recording and processing in hardware and software, and applying them in free movement conditions are actual scientific and technical tasks.

II. State of the Art

There are a lot of modern solutions for mobile heart monitoring that could be used under free movement conditions. Some of them are described below.

AliveCor's Kardia Mobile – is a modern device used to measure the heart rate and cardiac rhythm [2]. It is used for recording, storing and transmitting data. The device connects to any portable computer with iOS or Android. It is automatically turned on and connected with AliveCor's application via wireless connection. It informs the user with valuable information of the heart rate that could be used for the early detection of arrhythmia.

With all the advantages – ease of use and accessibility for users, the device has significant drawbacks. First of all, this a short time of ECG records, which does not allow a full diagnosis of the heart condition. It checks only one standard allocation that imposes restrictions on the use of the device in free movement conditions.

Metria Wearable Sensor – is a wearable device for heart activity monitoring, sensor of some valuable parameters [3]. The device has a small thickness, making it suitable to be worn during normal daily activities: walking, showering, exercise, etc. The device collects a variety of information about the patient, ranging from heart rate and breathing and ending with the sleep time and the activity level.

As the device detects the parameters of the user, the data is wirelessly transmitted to a computer and analyzed. The program processes the information, identifies current trends, simplifying the work of medical professionals.

The user can view the result via smartphone or web browser. The interface allows the user to summarize the collected data, to identify trends in vital parameters. The medical staff after reviewing the information received about the patient can respond accordingly and, if necessary, provide medical assistance.

eMotion ECG Mobile is a remote ECG monitoring system. [4] The solution contains ECG sensor and eMotion ECG Mobile software for real-time ECG monitoring. Continuous monitoring in real time is possible at home and at work. This solution is mostly focused on remote ECG analysis by the specialist. Report can be obtained after the analysis is done. The alarming system for reporting problems with patients or device is also provided. Additional functionality is available with HRV Scanner software.

A review of the current state of the problem [5] allows us to conclude that recording and analyzing the ECG in terms of free movement conditions has a certain specificity, due to the increased level of noise and signal artifacts, instability of contacts, etc. And one of the main risk factors remains signs of dangerous heart condition suddenly appeared in ECG. Detection of these signs is particularly important and effective in terms of free movement conditions when the person may not feel the acute symptoms of the disease and maintain normal or even increased physical activity. However, most of existing portable systems allow to record heart activity parameters in terms of free movement conditions, but most of them do not provide the ability to detect dangerous heart conditions in offline mode (without connection to the server)[6].

III. Solution vision

Authors state following requirements to mobile heart monitoring system:

- Automated detection of signs of dangerous heart condition in ECG (offline mode without connection to medical data server);
- Usability for target users (minimum requirements for the qualification of the users in the field of medical knowledge and special skills);
- Creation of common information space that provides centralized maintenance, storage, adjustment and analysis of information;
- High performance;
- High reliability;
- Scalability.

There is the system scheme at Fig.1. It consists of: multiple ECG devices (with portable computers); medical data server (Internet available); terminals providing access to the medical data server.

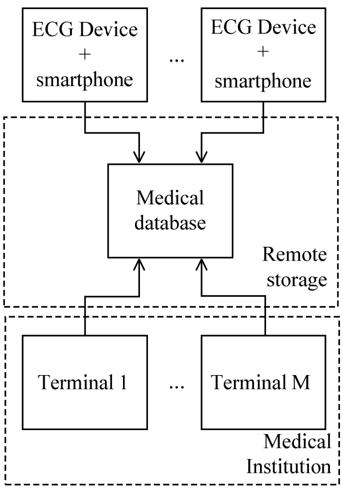

Fig. 1. Heart monitoring system scheme

Special requirements to the ECG device are small size and ergonomics, low current consumption, sufficient accuracy of ECG recording and safety.

Each mobile ECG device implements pre-processing, storage and transfer to the server for further storage and analysis. Pre-processing performs signal filtering with a digital low-pass filters. Each channel portable ECG device has its own low-pass filter, which has a positive effect on performance of the mobile ECG device. To implement the interaction of each individual portable device and medical data server secure connection protocol SOAP is used.

III. Implementation

A. Hardware

The main part of heart monitoring system is a mobile ECG device that implements functions of amplifying, data transmitting and self-diagnosis [6]. Another mobile part of the system is portable computer (smartphone or tablet) that implements functions of temporary data storage, ECS analysis and interaction with the user [7], [8].

As shown in Fig. 2, ECG device includes ECG recording unit (sensor, amplifier and ADC), control unit (detection of electrodes breaks and contact loss), preprocessing unit, wireless data transmission unit.

Android smartphone with installed software is used as mobile computer [9].

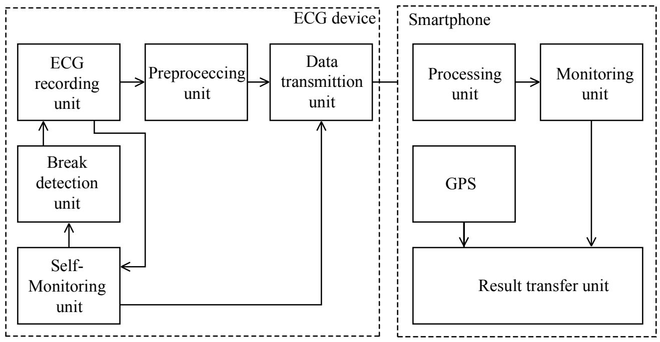

Fig. 2. ECG device scheme

Experimental prototype is shown in Fig 3.

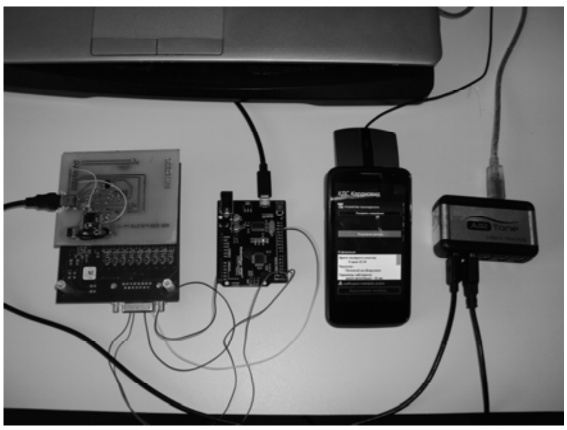

Fig. 3. Experimental prototype

ECG device is implemented on the base of ADS1298R ECG front end. Its main parameters are shown in Table I.

TABLE I. ADS1298R PARAMETERS

Parameter	Value
Number of channels	8
Wattage per channle	0,75 mW
Data Rate	250 SPS – 32 kSPS
Power Supply	Both Unipolar (below +3.6 V) and Bipolar (below ±1.5 V)
Output type	SPI

Choice of the ADS1298R ECG front end is motivated by a large number of channels and low power consumption. It allows recording a relatively large number of ECG leads for a long period of time.

ECG device and the smartphone are connected by widely used communication protocols (otherwise, the implementation of interaction of mobile devices becomes difficult). One of the main requirements for wireless devices is low power consumption for battery life improvement. It causes using data Bluethooth 4.0 wireless protocol (Bluethooth Low Energy). The latest version of Bluetooth 4.0 is officially presented by the group of developers SIG (Bluetooth Special Interest Group). The speed remained at the level of Bluetooth 3.0 with the value of 24 Mbps, but the range increased to 100 meters. It's exactly that which, with the simultaneous decrease of power consumption, allows to use the technology in autonomous devices.

To implement this Bluethooth Low Energy (BLE) protocol a turnkey solution from Texas Instruments – BLE112 on the chip CC2540 was chosen. Its parameters are given in Table II.

TABLE II. CC2540 PARAMETERS

Parameter	Value
Frequency range	2,4 GHz
Min Frequency	2402 MHz
Max Frequency	2480 MHz
Flash memory capacity	128; 256 kB
ROM capacity	8 kB
Data transmission speed	1000 kb/s
Min voltage	2.0 V
Max voltage	3,6 V
Current consumption (in transmission mode)	19,6 mA
Current consumption (in standby mode) (мкА)	0,4 µA
Standby-transmission modes transition	530 µs
Modulation type	GFSK
Sensitivity	-93 dBm

As follows from the table BLE112 meets the requirements for low power consumption, which positively affects the battery life.

B. Software

In the present embodiment, the recording device acts as Slave and the smartphone takes the role of Master. At the same Bluetooth module of the ECG device acts as a server that provides access to the attributes, and the client role is given to the smartphone.

Interaction between devices is performed as follows. Bluetooth module located in the ECG device goes into Advertisement mode. After that it becomes available for other devices to detect ECG device. The Bluetooth module of the smartphone detects the ECG device and stores information about it.

At the start of the analysis of ECG the user connects with the ECG device, if it has already been detected, or before connecting it searches for devices and connects after the detection. During the ECG recording application on the smartphone periodically polls the server and if it detects any new information that is available, it submits the request and reads the new data from the table of server attributes. These operations, as well as providing data security, are carried out through a set of special services, or services that underpin the implementation of the Protocol Bluetooth 4.0.

The software of the ECG device that controls wireless data transmission directly uses only the upper levels of protocol stack the Bluetooth 4.0. It is a SPI-bridge which allows to connect ECG device with smartphone directly, as if they were connected by wires.

Software is currently implemented as a standalone constantly running application using the Eclipse environment and Java programming language and is intended for use with Android version 4.4.2. A general view of this application is shown in Fig. 4. The next step is to run application as a service that periodically requests, gets and analyses data from ECG device.

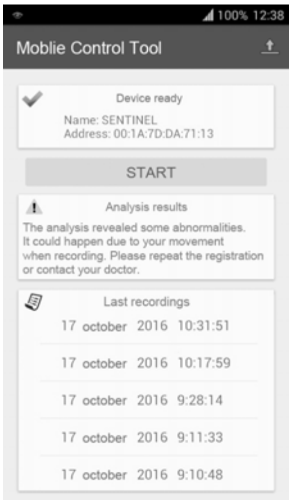

Fig. 4. Application main screen

ECG analysis software tools are included into Android application. If ECG contains the signs of dangerous heart condition it needs more in-depth analysis that may be performed by qualified medical personnel (e.g., cardiologist). This requires the transfer of the ECG to the medical data server (where the information is transmitted to the stationary terminal, which is a workplace of a cardiologist or other physician).These Stationary terminals are PCs with third-party software to work with a medical data server and to analyze ECG professionally.

EXPERIMENTAL RESULTS

A. J-point detection

The analysis of the method of allocating the beginning of ventricular repolarization (J-point). The algorithm that selects the beginning of ventricular repolarization was implemented in Matlab. The experimental investigation includes the following stages:

- Formation of database of ECG records;
- J-point allocation by means of developed program;
- Expert verification of the results.

Set of 200 30-seconds ECG records from different people was taken for this test. In addition, for a more complete test of the algorithm it was applied to all available standard leads and leads in Neb. The sample set includes ECG records from people of different age groups and with various conditions of cardiovascular system. To import the signals from the PhysioNet library extension was used wfdb-app-toolbox-0-9-9 that allows to import various signals and processes it. Both ECG record areas, as with high level of noise and artifacts, as with relatively low, are taken into test set. Test ECG signals were previously smoothed.

Result of the ECG record processing is a set of J-points detected for every heart beat. The appropriate algorithm scheme is given in Fig. 5.

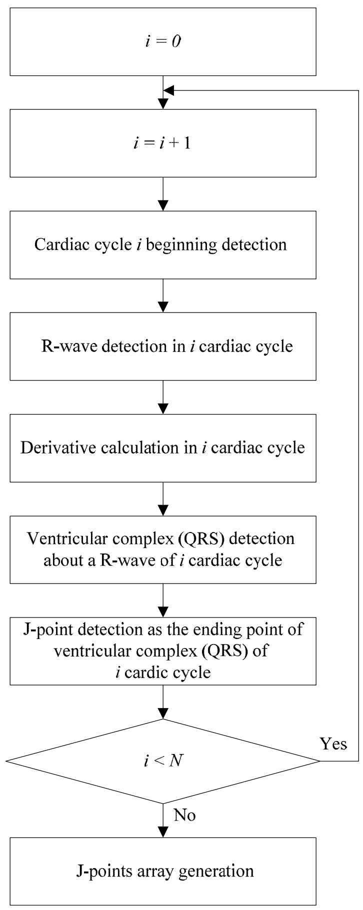

Fig 5. J-point detection algorithm scheme

Example of the result is given in Fig. 6.

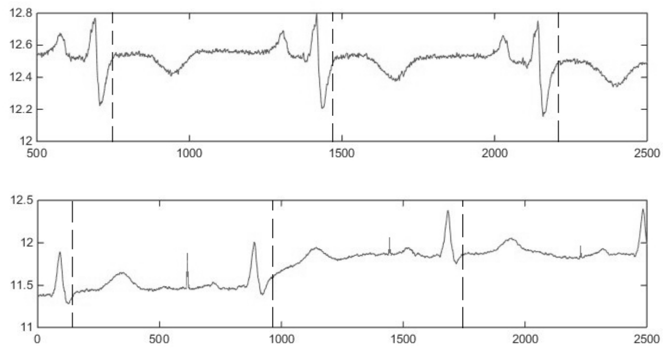

Fig. 6. J-point detection results: upper - normal ECG record; lower - ECG record with artifacts

The obtained results of the experiment are given in Table III.

TABLE III. J-POINT DETECTION RESULTS

Lead	Beats number	Right J-point detection	Missed J-points	Number of false J-points	False J-points
ECG areas with low noise level					
I	1026	954	7 %	0	0 %
D	1536	1398	9 %	0	0 %
A	1536	1390	9,5 %	0	0 %
In	1536	1391	9,4 %	2	0,001 %
ECG areas with abnormalities and artifacts					
I	1009	898	11 %	6	0,006 %
D	1067	949	11,1 %	8	0,007 %
A	1066	938	12 %	12	0,011 %
In	1066	939	12 %	11	0,01 %

Average difference between J-points detected by expert and by the program was 0.1 – 0.15 mV for ECG areas with low noise level and from 0.13 mV to 0.16 mV for ECG areas with abnormalities and artifacts.

Experimental results allow making a conclusion on the practical applicability of this automated method to select the beginning of ventricular repolarization in free movement conditions. The application of this method allows determining some valuable parameters of electrical heart activity which allows diagnosing dangerous heart condition in real time: for example the deviation of the ST segment.

B. Electrode contact break detection

To determine whether the electrodes of ECG device are in contact with the skin the resistance of the contact the amplitude of high frequency signal supplied to the body via these electrodes is measured. If the contact is broken the resistance increases, the amplitude of the excitation signal is respectively increased.

In order that the excitation signal has no influence on the useful ECG, 100 Hz frequency is usually chosen. For signals separation it is convenient to use digital filters. Fig. 7 shows the incoming signal using this method for determining the break of contact before and after filtering (curves are shown with offset for better clarity).

This method is easy to implement by built-in features of the ADS1298R chip. The magnitude of the excitation current and the threshold can be adjusted by programming the appropriate registers.

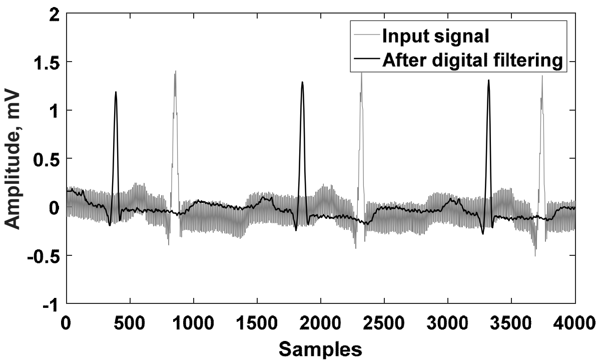

Fig. 7 – ECG in the frequency method of Electrode contact break detection

Electrode contact break detection is experimentally investigated as follows. The used type of electrodes has diameter of 50 mm, particularly strong adhesion for stress test, in terms of sweating [10]. It allows using them for a long time in conditions of free movement. Electrodes fixed on the body of a real person are connected by the shielded cable to the development board. Electrode contact break data is recorded through a computer interface included in a debug kit. The total power consumption of the system is controlled by a measuring device connected to the debug set. Experiment scheme is shown in Fig. 8.

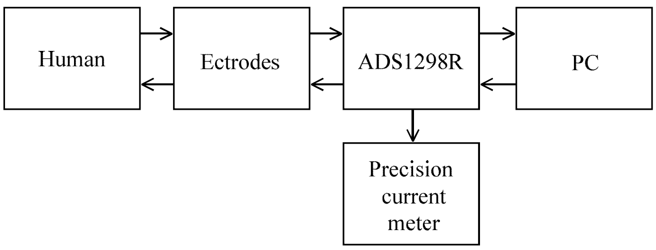

Fig. 8 –Electrode contact break detection experiment scheme

Eight volunteers have taken part in the experimental investigation. For each person the experiment presumes 1 minute ECG recording and from 1 to 5 premeditated electrode connection breaks within a minute in random order (one or more leads simultaneously). Two series of experiments are completed: stationary and free movement.

First of all, it was examined how the excitation signal current magnitude influences the total percentage of correct electrode contact break detections. The used hardware lets us select the value of the amplitude of the current from four discrete values 6, 12, 18 and 24 nA. Threshold 97% of correct detections is chosen. This percentage is comparable to other factors that make ECG recording difficult or impossible. The total results of the study are displayed in table IV.

These results are important for increasing the overall energy efficiency of the device.

TABLE IV. CONTACT BREAK DETECTION EXPERIMENT RESULTS

Current	Total consumption	Contact breaks	Contact break detections	Detections percent
6 nA	15,9 mA	200	186	93 %
12 nA	16 mA	200	190	95 %
18 nA	16,15 mA	200	195	97,5 %
24 nA	17,0 mA	200	198	99 %

C. Energy efficiency

One of the most serious challenges for autonomous device designing is energy efficiency. Time of battery life is one of critical parameters for mobile medical devices. The authors propose measures to improve the efficiency of the developed device by controlling two parameters: amplitude of the excitation signal and gain coefficient. Experimental results are given below.

In terms of energy consumption, the gain coefficient should be as small as possible (the optimal value is 1), on the other hand, to exclude complex filters and amplifiers from the construction of the device it is necessary to provide the maximal gain using the existing hardware. The gain coefficient changing can be done by program using the built-in chip amplifier. The efficiency of the system can by estimated as a number of correctly detected cardiac cycles in the ECG record. The correct detection of the cardiac cycle under free movement conditions is required for noise and artifacts removal, as well as the possibility of detection of the QRS complex key points and analysis of heart electrical activity.

The current consumption is increased significantly with the increasing gain. The choice of operating mode will depend on the value of the threshold criterion of the overall efficiency. If this value (the percentage of correctly selected cardiac cycles) is equal to 97%, the minimum required gain is 4. The current consumption of the chip is 21 mA. With further increase of the gain the percentage of correctly selected cardiac cycles is slightly changed, but the energy consumption is increased by 14%.

For mobile ECG devices the default gain coefficient should be chosen in terms of energy efficiency. If the noise or skin-electrode resistance increases, the gain coefficient should be increased to maintain the required level of reliable cardiac cycle detection. If the user or specialist selects the energy saving mode of operation gain level can be reduced.

The auto-setup algorithm is shown in Fig. 9. It adjusts the gain coefficient and the amplitude of excitation current as minimal as possible at this moment. It improves the energy efficiency of mobile ECG device and allows to increase its operating time by 19% when using ADS1298 hardware.

One of the work directions for the future is increasing energy efficiency by using Bluetooth 4.2 that allows wider possibilities to control energy consumption of the radio module.

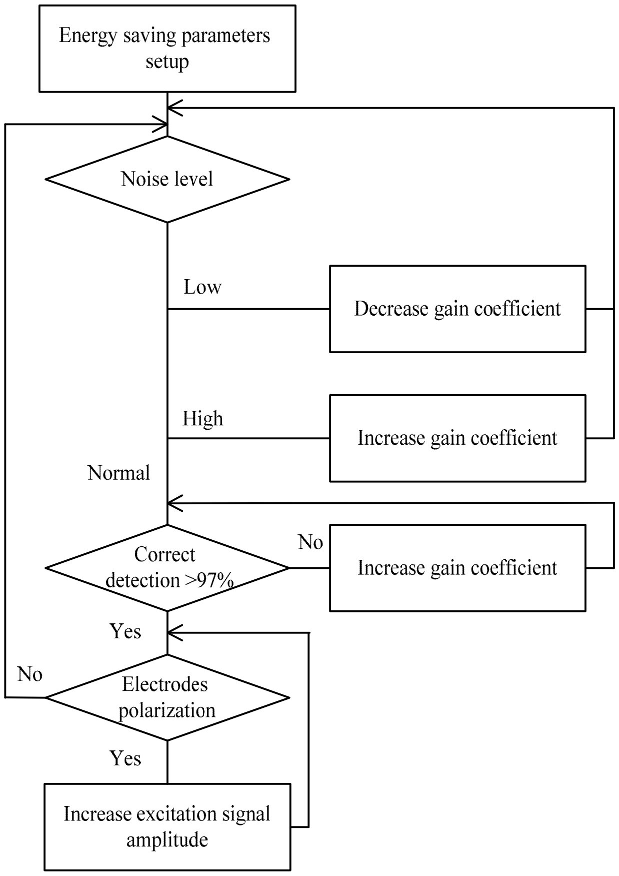

Fig. 9 – Energy saving setup algorithm scheme

D. Wireless protocols tests

ECG device is used for a long-time autonomous work, therefore, energy-saving protocols are considered. Among them: ANT/ANT+; ZigBee; Bluetooth 4.0-4.2.

All existing data transfer protocols with low power consumption are suitable for the transmission of medical information. For a more detailed verification of the feasibility of ECG transmission of information through energy-saving wireless protocols experiment was planned. It consists of measuring real bandwidth of the wireless channel by transferring the data that simulate real ECG data. Chip CC2540 from Texas Instruments is used as wireless module. This module is a microcontroller with integrated Bluetooth 4.0 stack. The experimental setup is as follows.

The module with program simulating the transmission of data from three ECG channels in 24-bit resolution and a sampling rate of 500 Hz is used as a data source. This configuration was selected as the most frequently used in modern portable devices.

The same module is used as a receiver with connection to a PC. The data is transmitted by packets of 5 bytes size. The bandwidth is tested by means of Matlab and Adafruit Bluefruit LE SPI Friend – BLE [11]. The experimental scheme is shown in Fig. 10.

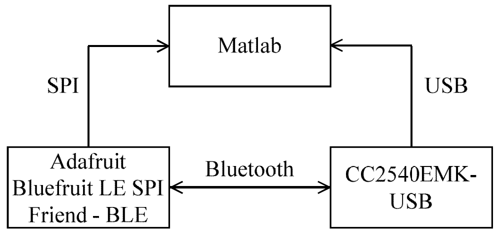

Fig. 10. Wireless protocol test scheme

The obtained results are shown in Fig. 11.

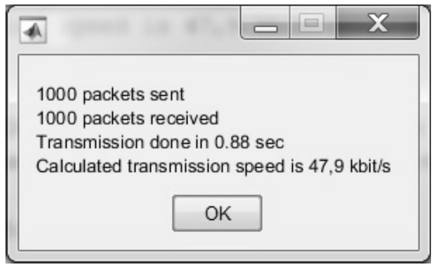

Fig. 11. Wireless protocol bandwidth test results

The measured data transfer rate is about 48 kbit/s, which is fully consistent with the real-time transmission of test ECG data

The obtained results allow concluding that the chosen wireless protocol with low energy consumption fully corresponds to the development of mobile heart monitoring system.

VII. Conclusion

This work shows the approach and a technical implementation of mobile heart monitoring system. The authors show a particular way of solving two main problems of mobile heart monitoring: stability and effectiveness in a free movement conditions and offline analysis of ECG. It allows to inform the user about signs of dangerous heart condition in ECG. The proposed system could be a base for a set of application for ECG analysis, electrical activity of the heart analysis and applications for mobile heart monitoring for wide range of applications from sports and fitness to monitoring for medical reasons.

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