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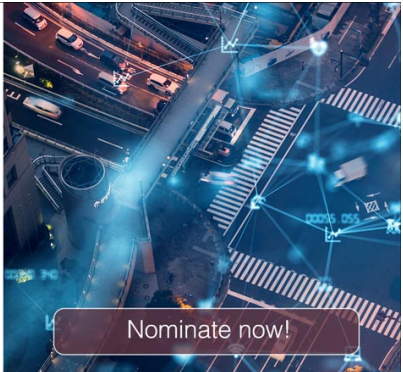


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Wireless Holter monitoring system with a dual-core processor

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Abstract. The article discusses the principles of building a wireless automated system for heart activity Holter monitoring using a WiFi module based on a dual-core processor. The system is focused on use in a medical cardiology center or at home. The article proposes the method of wireless transmission of an electro-cardio signal based on the paralleling of processing operations and Wi-Fi transmission of an electro-cardio signal. The paper presents algorithms for wavelet compression and filtering of the transmitted electro-cardio signal that ensure high reliability of the transmitted ECG information. A semi-realistic model of the Holter monitoring system has been developed, including real-time packages of the Matlab system, a PhysioBank ATM electro-cardio signal database, a hardware interface based on the PCI-1710HG Board and an external wireless ECG information transmission subsystem. The proposed methods and algorithms will provide high-quality and multi-day wireless transmission of ECG signals, characterized by low power consumption

1. Introduction

Holter Daily Monitoring is a diagnostic procedure of electrocardiography, where the electrical activity of the heart is recorded using a portable device for a day or more in the conditions of the free activity of the patient, followed by decryption in the offline mode using special decoders. This ECG monitoring is used for the diagnosis of cardiac arrhythmias and conduction disorders that cannot be detected by the standard ECG recording procedure [1].

As a rule, Holter monitoring (HM) involves recording an ECG for a long time on an autonomous medium, such as flash memory card. However, the recorded data, in this case, becomes known and can only be analyzed after the registration period is over. Therefore, recently, the method of wireless transmission of ECG from patients to a common server (in the conditions of a heart center) or to a separate minicomputer (at home) is becoming more widespread in order to continuously monitor the ECG of patients and further interpret (decrypt) the ECG in real-time [2]. This system allows quickly informing the patient and (or) the doctor about abnormalities in cardiac activity.

2. Problem statement

One of the main qualitative indicators of the wireless Holter ECG monitoring system is the continuity of ECG data collection, the speed of its transmission, and the system's noise immunity. Currently, there are wireless ECG signal transmission systems that work in Zigbee or Bluetooth standards [3,4]. The disadvantages of such systems include a low data transfer rate and a limited number of subscribers (for



Bluetooth) [5]. The Wi-Fi network lacks these disadvantages, but its use was limited to high power consumption. However, in recent years, the market for wireless devices has introduced quite interesting wireless transceivers, which, while maintaining all the necessary characteristics, have fairly low power consumption.

Prominent representatives of this class of devices are the receivers and transmitters of Chinese companies based on class chips [6,7]. The ESP8266 is a highly integrated on-chip (SoC) system developed by Espressif Systems specifically for low-power mobile systems. Many modern solutions in the field of wireless data transfer are built on the basis of Wi-Fi chipsets from Espressif Systems.

The most successful implementation of this series of transceivers is the NodeMcu v3 Wi-Fi module with an ESP8266 chip (ESP-12E) [7] characterized by controlled signal transmission power and ultra-low consumption. The operating current of the device is 80 mA. The current consumption at $U_p=3$ V and the maximum output power does not exceed 200 mW. The use of these modules in the construction of wireless Holter monitoring systems shall solve problems of increasing the rate of transmission of the electro-cardio signal (ECS) and increasing the continuous operation of the system for a day or more. A distinctive feature of this module is the high sensitivity of the Wi-Fi receiver that allows significantly expansion of the system operating range.

However, the main drawback of Holter monitoring systems built on the basis of Wi-Fi modules using ESP8266 chipsets is the presence of "dead" zones during the transmission of ECG information, which are caused by the lack of removal of the electrocardiogram signal during a Wi-Fi session with the ECS receiver. Although the Wi-Fi transmission process takes about 4 ms, there is a possibility of missing informative signs in the ECG.

The main task, in this case, is to develop the system structure and algorithms for its operation aimed at creating conditions for continuous measurement and transmission of ECG information throughout the entire cycle of the system. Independent operation for at least 24 hours is also a necessary condition.

3. Theory

In Holter monitoring, two deflections that intersect at a right angle or close to it are sufficient to diagnose rhythm disturbances. However, the diagnosis of myocardial ischemia should be based on data from at least three deflections [8], which could as fully as possible display the progress of repolarization processes in all the walls of the left ventricle myocardium. Therefore, it was decided to use ECG registration in three deflections in this system. Thus, when choosing Wi-Fi transmitter we focused on the simultaneous record and batch transmission of three ECG deflections, i.e. it was necessary to choose a module that includes Wi-Fi transmitter, at least three AD converters and a dual-core processor. These devices include the ESP32 chip system from Espressif Systems. Based on the requirements for Wi-Fi Holter monitoring systems, we made our decision on the DOIT ESP32 DEVKIT V1 module. The module is designed for mobile applications, personal electronics, and Internet-of-Things (IoT) tasks. The ESP32 is developed using TSMC 40 nm technology, which provides ultra-low power consumption and has a variety of power consumption modes with the ability to dynamically switch them. The radiation power of the Wi-F transmitter can also be flexibly configured, which makes it possible to achieve an optimal compromise between the communication range, transmission speed, and energy consumption within each individual task. The module includes an Xtensa Dual-Core 32-bit LX6 processor with a clock frequency of up to 240 MHz and a speed of up to 600 DMIPS, as well as eighteen 12-bit ADCs.

When choosing a Wi-Fi receiver, the main criterion is its sensitivity, i.e. the minimum level of the incoming signal that the device can receive. Since sensitivity (RX Power) is an important factor that affects the communication distance and transmission speed, choosing the NodeMcu v3 module as the Wi-Fi receiver is the right decision.

A fairly simple Arduino IDE development environment can be used to create projects using ESP32. However, in order to effectively apply certain energy-saving modes, it is required to use the official IOT (internet of things) application development environment ESP-IDF (Espressif's IoT Development framework), which was created specifically for the ESP32 system-on-a-chip (SOC). A distinctive

feature of this software is a menuconfig project configuration utility, which provides configuring of the serial port where the project will be loaded, the SDK (a set of project development tools), and set the processor clock frequency, which directly affects the power consumption of the module.

The next step for developing a program is to select the source code editor. The most convenient source code editor for ESP32 programming is the Visual Studio Code editor, on top of which the PlatformIO IDE cross-platform build system is installed as an integrated project development environment for IoT.

Figure 1 shows a functional diagram of a three-channel dual-processor HM ECG system designed for use both at home and in a medical cardiology center.

Main components of the system.

- Deflection cable for Holter monitoring, including seven disposable electrodes.
- A module containing three AD8232 chips. An AD8232 chip is an integrated signal processing unit for ECG and other biopotential tasks [9]. The chip is designed to receive, amplify, and filter weak biopotential signals under strong interference conditions. It is used in portable medical systems. The module, consisting of three AD8232 chips, provides the formation of three deflections necessary for Holter monitoring.
- DOIT ESP32 DEVKIT V1 Wi-Fi transmitter, the ADC inputs of which receive ECG information through three channels.
- The ESP8266 NodeMcu v3 Wi-Fi receiver receives ECG information from the Wi-Fi transmitter and transmits it over the I2C bus to a Raspberry class minicomputer.
- L-ion 18650 battery for power supply of elements of the autonomous part of the system.

The purpose of the Raspberry minicomputer is to receive and interpret DATA, as well as visualize the results of automated diagnostics and send them to the printer for printing the preliminary report.

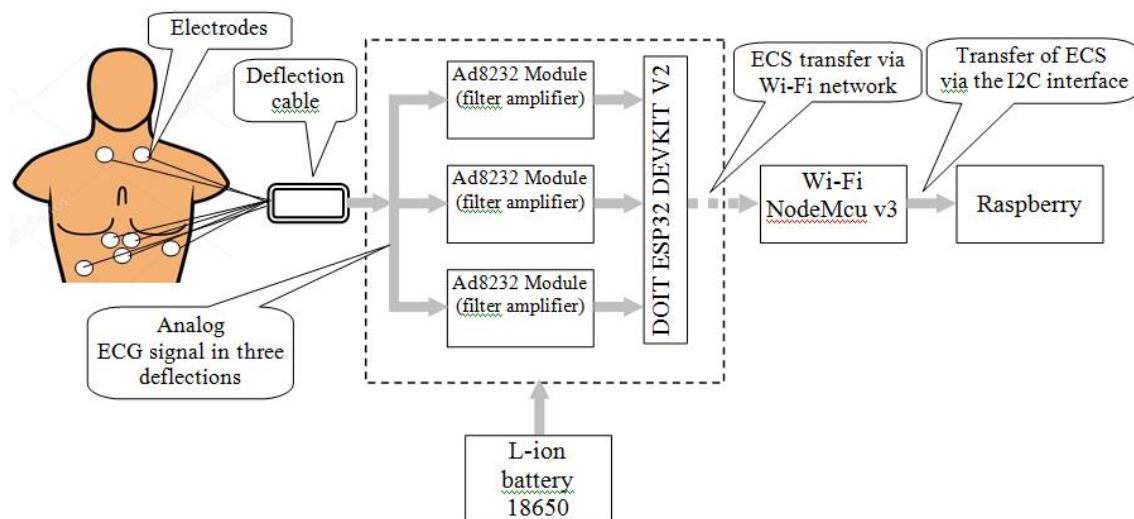


Figure 1. Functional Diagram of the Three-Channel Two-Processor Holter Monitoring System.

Note that the ADC of the ESP32 module is sensitive to noise, which leads to large discrepancies in ADC readings. To minimize noise, a 0.1 μF capacitor must be connected at the ADC input. In addition, Multisample anti-aliasing (MSAA) can be used.

Figure 2 shows the general structure of the program execution algorithm for the dual-core DOIT ESP32 DEVKIT V2 Wi-Fi transmitter.

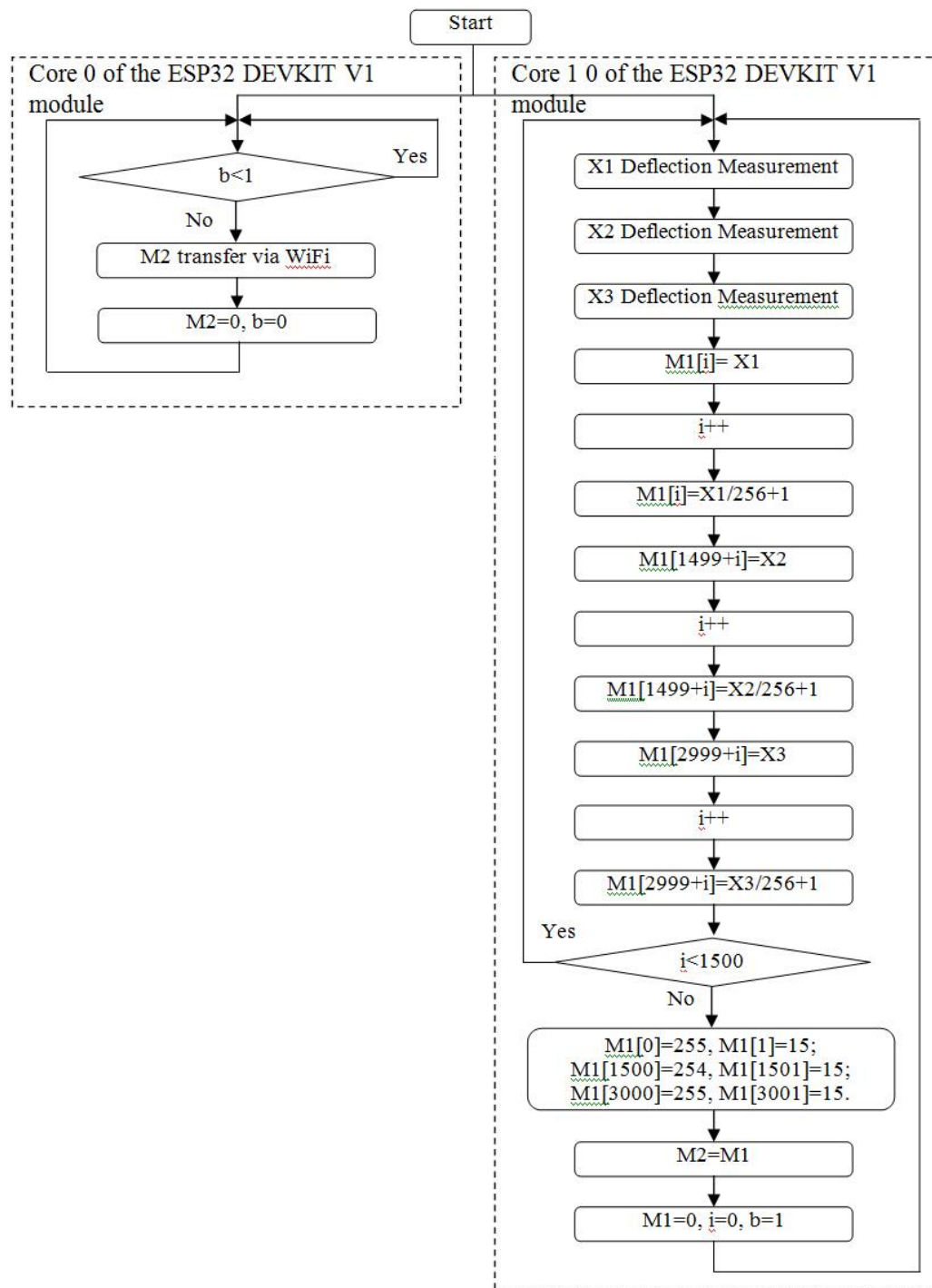


Figure 2. Program Execution Algorithm for a Dual-Core Wi-Fi Transmitter.

Preliminary, before writing a program in the ESP-IDF software environment, it is required to set the processor clock frequency to 80 MHz in the menuconfig menu. This will almost not affect the program execution speed, but will significantly reduce the power consumption of the battery pack.

Commands for measuring deflections or analog-to-digital conversion are executed on core 1 and take microseconds. Therefore, the process of measuring all three deflections takes place almost at the same

time. There are 750 measurements per deflection, with a period of 1 ms or 1 kHz between measurements. The process of Wi-Fi transmission of the receiving part of the system is assigned to core 0.

The algorithm of the transmitting part of the system begins with measuring the ECG signal in three deflections X1, X2 and X3 (Figure 2) using three ADCs. Besides, the measured values of X1, X2 and X3 have a two-byte size and, since arrays of information can be transmitted over the Wi-Fi interface only in the form of bytes, it is necessary to convert the received two-byte numbers into separate bytes. Each measurement cycle is sequentially recorded in the M1 array, which includes information from three ECG deflections and occupies a volume of 4500 units of information. Thus, the X1 deflection is recorded in the range $i=0\div1500$, the X2 deflection is recorded in the range $i=1501\div3000$, and the X3 deflection is recorded in the range $i=1501\div4500$, while vertical pulses with following amplitude are recorded between them to isolate and identify deflections: 4080, 4079, and 4078.

After the number of recorded values in each deflection reaches 1500, the already formed M1 array is transferred to the M2 array. After that, the M1 array is reset to zero, and the b flag is set to 1. The command to transfer data from one array to another is necessary in order to save the information of the recorded ECG data for the next measurement session and write it to the M1 array.

Since the M2 array is shared by the two Xtensa processor cores of the ESP32 module, a Wi-Fi ECG data transfer session occurs on core 0 after checking the b flag. The entire session takes 3-4 ms. Then the M2 array and the b flag are reset to zero. It should be noted that the processes of executing programs on two processor cores occur simultaneously, i.e. the measurement and transmission of ECG information occurs in a constant mode.

ECG data is received by the NodeMcu v3 Wi-Fi receiver (Figure 1), which transmits this data via the I2C interface to the Raspberry minicomputer. And the real time for the whole process of measurement output of all three deflections should be equal to the time spent for recording this information in a Wi-Fi transmitter as the recording was made in a parallel mode and the output - in a serial one. Thus, ECG data is scaled, i.e. it is compressed three times to preserve the reliability of the information. The task of the minicomputer, before starting the analysis and interpretation of ECG data, is to translate the recorded three ECG deflections into a real time scale.

The principle of semi-realistic modeling was used to debug and configure parameters of the wireless DATA transmission system, test ECG analysis algorithms, and various operating modes of the system. This principle assumes the use along with the components of the real system: Wi-Fi transceivers and a wireless router, the use of an archive database of PhysioBank ATM ECG signals, special software packages and hardware to implement the interface between real components and computer models of the Holter monitoring system.

The PhysioBank ATM archive database is a web resource containing well-described electrocardiographic signals and corresponding open source software for the biomedical scientific community [10, 11]. The annex to the ECS database presents the technology for transferring ECG copies to the Matlab environment. Using this technology, any copy of the ECG signal can be recorded in the Matlab Workspace. In this case, it is a variable named ECS.mat in the 21600x2 format the ECGreal_from2 file.

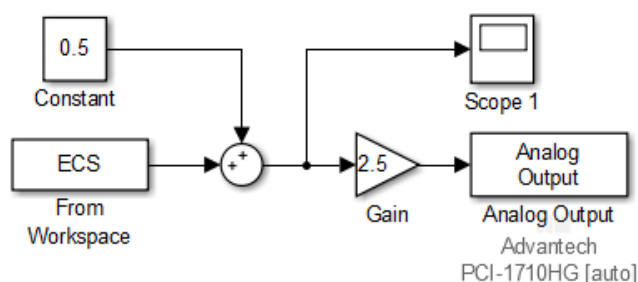


Figure 3. Simulink Model for the ECG Data Transmission.

Simulink, Simulink Desktop Real-Time packages, a multi-functional PCI-1710HG I / o card and an ADAM-3968 switch with a connecting cable are used for hardware implementation of the described process of transmitting and receiving ECG data using Wi-Fi technology. Figure 3 shows a Simulink model for transmitting an ECG signal recorded in the Workspace memory to the output pins of the PCI-1710HG (Analog Output) Board.

Since the output signal of the PCI-1710HG Board has a positive polarity, the constant component "0.5" is included in the circuit in order to eliminate the negative component. Also, an amplifier with a gain of 2.5 was added to the system for easy visual observation of the simulation process.

The general structure of the semi-realistic simulation of the Holter monitoring system is shown in Figure 4. A wireless communication subsystem has been moved from the real system (figure 1) to the real scheme, including Wi-Fi transceivers and an 18650 L-ion battery. Blocks indicating the Simulink model, a PCI-1710HG I/o Board, an ADAM-3968 switch, an ammeter, an Arduino DUE Board based on an Atmel SAM3X8E ARM Cortex-M3 processor, and an AKIP-4115 / 2A oscilloscope have been added (Figure 3). The Arduino DUE platform includes 12-bit DACs and is necessary for organizing the interface between the Wi-Fi receiver and the oscilloscope.

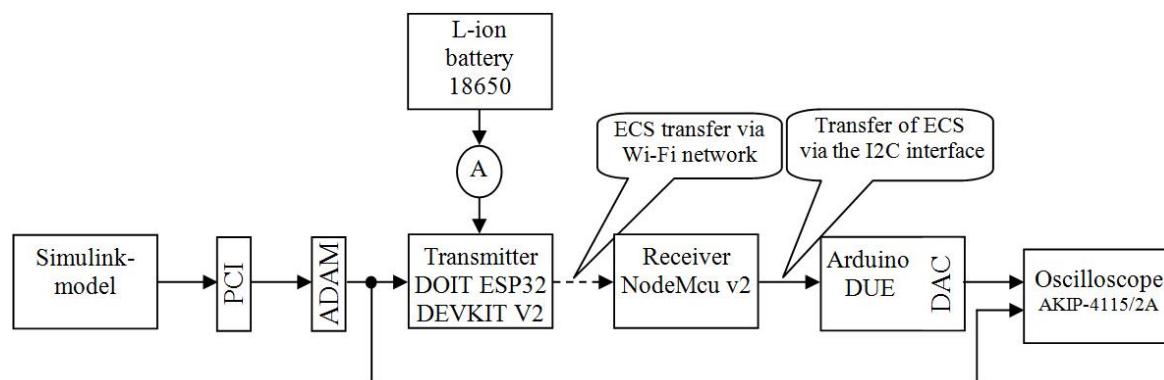


Figure 4. Semi-Realistic Model of the Holter Monitoring System.

The main purpose of the semi-realistic model of the Holter monitoring system is to develop a Wi-Fi technology for transmitting ECG data based on the principles of dividing the measured ECG deflections into separate blocks, compressing and restoring the transmitted information. To achieve this goal, it is enough to create one virtual electrocardiogram in the Matlab system and send it via the PCI interface to the DOIT ESP32 DEVKIT V2 transmitter. Here, the ECG signal must be connected to three ADCs, assuming that three ECG deflections are connected. As a result, a sequential recording of three identical compressed ECG signals shall be obtained on the receiving side. The time range of this recording will be equal to one measured ECG signal.

This conditional assumption simplifies the simulation, makes it quite clear and does not contradict the general principles of the entire Holter monitoring system.

4. Outcomes of the experiment

The proposed structure (Figure 4) is embodied in the experimental complex shown in Figure 5.

The following system components are numbered in Figure 5:

- 1 – Simulink-model for transmitting an ECG signal recorded in the Workspace working memory to the output pins of the PCI-1710HG Board (Analog Output);
- 2 – graph of the ECG signal recorded in the Workspace working memory;
- 3 – waveform of the ECS signal, which is obtained using the Matlab Simulink Desktop Real-Time package, the ADAM-3968 terminal connector connected via a cable to the PCI-1710HG multifunction I/o card installed in the PCI slot of the personal computer;

- 4 – ECS oscillogram at the DAC output of the Arduino DUE module;
- 5 – ADAM-3968 connector;
- 6 – Arduino DUE platform – a technological component of the circuit required for the Wi-Fi-receiver-oscilloscope interface;
- 7 – DOIT ESP32 DEVKIT V2 Wi-Fi transmitter;
- 8 – NodeMcu v2 Wi-Fi receiver;
- 9 – 18650 l-ion battery to power the Wi-Fi transmitter;
- 10 – ammeter.

Thus, following the algorithm (Figure 2) and the structural diagram (Figure 4), the ECG signal (2) from the Simulink model output (1) is transmitted via the ADAM-3968 connector (5) to the ADC of the DOIT ESP32 DEVKIT V2 (7) Wi-Fi transmitter and to the oscilloscope (3). Arrays of two-byte signals are formed from the digitized information and transmitted to the receiving side (8). The Wi-Fi receiver (8) sends each value of the received array via the I2C interface to the Arduino DUE (6). An analog ECG signal from the output of the Arduino DUE DAC (6) simulating a sequence of three ECG deflections is sent to the oscilloscope (4). Power consumption is controlled using an ammeter (10). Visual analysis shows that the output signal is compressed three times over the input signal and represents three copies of the input signal.

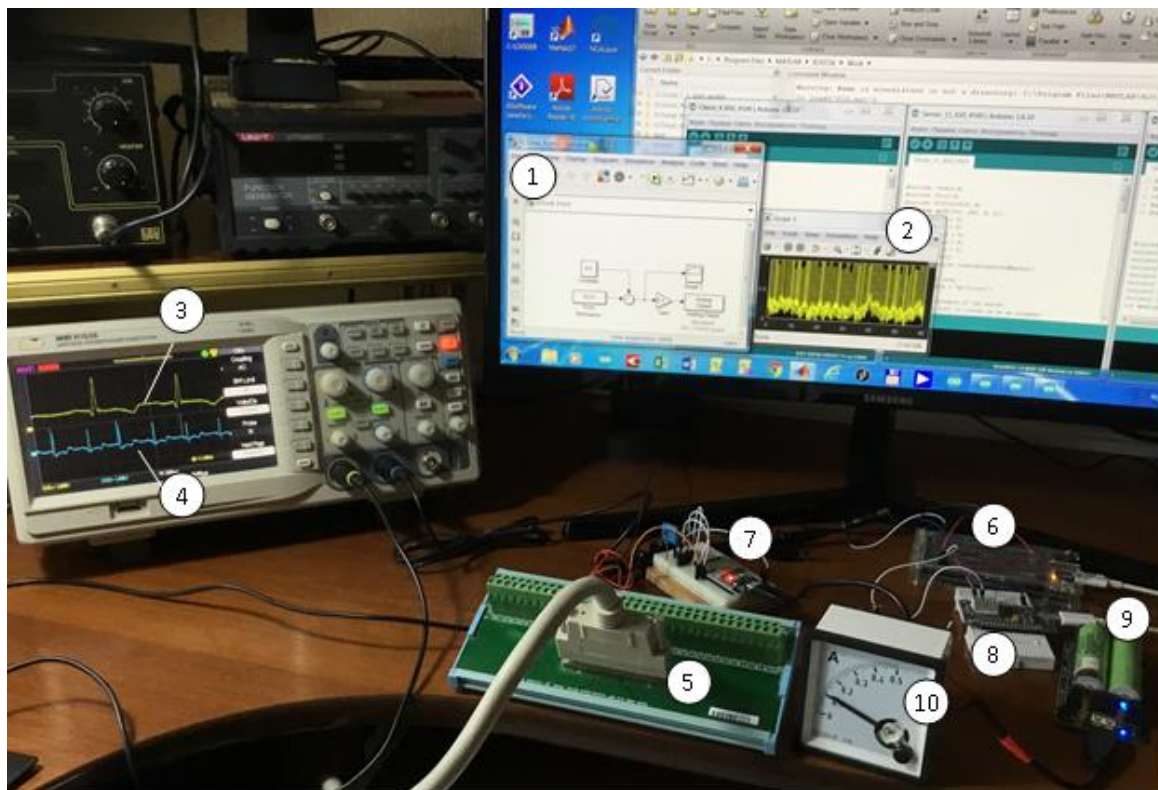


Figure 5. Experimental complex of the Holter monitoring System Model.

5. Results and discussion

There was developed a functional diagram of a wireless Holter ECG monitoring system that provides the measurement of three ECG deflections, as well as generation and transmission of ECG data packets to the receiving part of the system. An experimental complex for implementing a semi-realistic model

of the system being developed is presented. It contains a wide range of software and hardware tools, including specialized Matlab packages for configuring, debugging and optimizing the working algorithms of a real Holter monitoring system.

Schematic solutions for using a dual-core processor of a transmitting Wi-Fi device that provides parallel execution of the program were proposed: measurement and processing of information on one processor core and batch transmission of information on another. According to the ammeter, power consumption is an average of 100mA. This ensures the autonomous operation of the system for at least two days.

This work is a continuation of the project on the creation of a wireless high-speed and cost-effective hardware and software system for Holter ECG monitoring [12]. The next stage of work shall be focused on developing effective algorithms that increase the system's noise immunity, as well as creating software for analyzing and interpreting ECG for a Raspberry class minicomputer.

6. Conclusion

Analysis of the results of experiments and obtained graphs of real ECG shows that the use of a new generation Wi-Fi transmitter built on a dual-core processor, and the ESP-IDF software environment, as well as other original circuitry and software solutions aimed at improving the reliability of transmitted ECG information and minimizing the energy consumption of an Autonomous Wi-Fi transmitter, allows creating a practical and cost-effective system of Holter monitoring of ECS that will provide for better morphological analysis in cases of rhythm and conduction disorders, as well as diagnostics of myocardial ischemia.

In the future, it is planned to improve the algorithm and program for WiFi transmission of ECG data using the Modem Sleep software mode for the WiFi transmitter based on the own library developed for the PlatformIO IDE cross-platform build system.

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