UDC 004.772-621.396.99
DOI: 10.15587/1729-4061.2024.309387

HARDWARE-SOFTWARE IMPLEMENTATION OF A LOCAL WI-FI NETWORK FOR THE TRANSMISSION OF BIOMEDICAL SIGNALS

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The object of this study is a wireless local Wi-Fi network for broadcasting biomedical signals, its structure, and principles of construction. The task of minimizing the power consumption of a Wi-Fi transmitter has been addressed, which provides the possibility of building a wireless system for long-term monitoring of biomedical signals. As a result, a functional diagram of a wireless Holter monitoring system based on an ESP32 microcontroller was constructed, which includes a subsystem for setting up and diagnosing system units using MATLAB software packages, an ECG signal generator, and a multifunctional PCIe board from National Instruments. Evaluation criteria and methods for minimizing power consumption by an autonomous Wi-Fi transmitter have been proposed. Methods for synchronizing the working cycles of the transmitter and receiver of the Holter monitoring system were determined. A procedure for determining the optimal biosignal measurement frequency is presented, at which the distortion of ECG signals would be minimal, which means that the signal could be transmitted without losses. The concept of constructing an algorithm for implementing a program for a Wi-Fi transmitter has been developed, ensuring parallel execution of ECG signal measurement operations and their transmission over a local network. The data from semi-naturalistic tests with an experimental Holter monitoring system with a pre-setup subsystem and using external measuring devices, a computer, and the MATLAB software environment are presented. A comparative analysis of the experimental data with primary ECG signals and ECG signals at the receiver output showed a fairly stable correspondence between the input and output ECG signals. The proposed algorithms make it possible to reduce the average current consumption of the ESP32 microcontroller to 50.5 mA. The results of the study demonstrate the possibility of constructing an energy-efficient wireless system for long-term monitoring of biomedical signals based on the Wi-Fi interface

***Keywords:** biomedical signal, Holter monitoring, computer simulation, MATLAB system, Wi-Fi transmission, algorithm, ESP32 module*

Received date 24.05.2024
Accepted date 29.07.2024
Published date 30.08.2024

***How to Cite:** Gerassimova, Y., Ivel, V., Moldakhmetov, S., Petrov, P. (2024). Hardware-software implementation of a local Wi-Fi network for the transmission of biomedical signals. Eastern-European Journal of Enterprise Technologies, 4 (9 (130)), 34–43. https://doi.org/10.15587/1729-4061.2024.309387*

1. Introduction

Healthcare organizations in many countries need to improve the quality of medical services to people. This is explained by the emergence of new types of diseases and new approaches to treating long-known ones, the growth of people with complex diseases, changes in the general rate of population aging, and social changes occurring in society as a whole. All these facts lead to an increase in demand for additional services, which include regular monitoring of the body's condition [1, 2].

One of the main issues related to patient monitoring is the problem of mobility, since in most cases it is necessary to remain connected to devices within one ward. New generation systems increasingly use wireless technologies, which makes it possible not only to increase patient mobility but also to increase information content. The use of wireless technologies involves the use of computer systems for the transmission of biomedical data, as well as remote control of medical devices.

The duration of monitoring is of great importance for diagnosing various diseases since accurate diagnoses require an unambiguous assessment of the physiological state and how this state has changed over time. Annual screenings do not have sufficient time accuracy to predict the likelihood of many diseases, such as stroke, heart attack, or diabetes. Even regular monitoring of known health problems can be inaccurate and ineffective, requiring frequent visits to the doctor [3]. It is during the period of long-term continuous monitoring that the doctor can identify all existing pathological deviations in the patient and make an accurate diagnosis [4, 5].

One of such monitoring is Holter monitoring. It is the most commonly used method of outpatient examination of patients with suspected arrhythmia. Since many clinically significant arrhythmias are often asymptomatic, their proper detection and treatment are critical to reducing mortality and morbidity [6, 7]. Holter monitoring records an electrocardiogram on a special portable device located on the human body. Although portable Holter monitoring solutions involve recording an ECG for 24–48 hours, they lack the ability to provide real-time feedback with the ability to automatically detect pathological conditions [8]. The use of wireless communication for the transmission of biomedical information could improve the comfort of the electrocardiogram (ECG) registration procedure and would also provide the doctor with the opportunity to monitor the patient's condition in real time, predict and make a decision. Wireless monitoring involves the transmission of measured physiological data (e.g., ECG, blood pressure, muscle electrical activity, etc.) from peripheral sensors to a centralized platform. The platform may include both hardware and software units for signal acquisition, processing, and decision support. When designing monitoring systems, developers face various challenges. These include technological capabilities and efficiency of the system, reliability and validity, interoperability, data integrity, and quality, which is often accompanied by a lack of reliable verification of results and the lack of generalization [9].

The type of wireless technology used largely determines the capabilities of the monitoring system since the system performance, range, and signal transmission speed, noise immunity of the system, as well as ease of setup depend on this [10]. The most commonly used technologies in wireless transmission systems are Bluetooth, ZigBee, and Wi-Fi. The analysis of these protocols is given in detail in works [11–13].

If the registration procedure does not imply restrictions on the patient's movement, then the transmitting part of the system located on the patient's body must be provided with an autonomous power source. In this case, the duration of continuous registration becomes an important parameter, which depends on the power consumption of the transmitting part. With relatively high power consumption, the capacity and, accordingly, the weight of the power source increase. This creates inconvenience in wearing such devices, restricting the patient in activities. The problem arises to find algorithms and methods for reducing the power consumption of such an autonomous device. Thus, it is a relevant task to implement multichannel transmission of biomedical signals with minimal power consumption of the transmitter while maintaining the specified qualitative and quantitative indicators of the process of transmission and reception of biomedical information.

2. Literature review and problem statement

The main disadvantages of Bluetooth technology are its short range and limited number of connecting devices. Its advantage is low power consumption. This is confirmed in work [14], which reports the development of a wearable multi-frequency impedance cardiography device. This system provides long-term monitoring of ECG and multi-frequency impedance cardiogram (ICG). Due to the use of energy-efficient equipment, the system can operate for up to 18 hours on a 3 V battery, continuously sending data via the Bluetooth module.

Another example of a long-term monitoring system using Bluetooth technology is described in work [15]. The system under consideration can monitor physiological parameters important for patients with heart failure. These parameters include chest impedance, ECG, heart rate, and motor activity detection. But in this case, the system can no longer be classified as energy efficient since the Arduino Uno platform is used as a control unit. As a result, the battery lasts for about 5 hours.

ZigBee technology has a longer range than Bluetooth technology. It is also designed for long-term autonomous operation, is safe, and can be used to solve telemedicine problems [16]. In addition, ZigBee has a fast transition (less than 15 ms) from sleep to active mode, which is an advantage compared to Bluetooth technology (about 3 s) [17].

In [18], some disadvantages of ZigBee technology are noted. In this case, the wireless protocol was used to transmit bioelectric signals such as blood oxygen saturation, heart rate, and body temperature. The issue of some limitations regarding sending and receiving messages remained as unresolved issues. These limitations are due to the lack of memory to store all the nodes of the network addresses for sending and receiving messages, as well as the narrow bandwidth of the ZigBee network.

Another significant disadvantage characteristic of ZigBee technology used to monitor physiological states, described in [19], is a temporary interruption of the data flow. Such an interruption leads to a loss of communication between the end device and the parent. Searching for the latter takes a certain amount of time, which can generally lead to a conflict of nodes and negatively affect system performance and lead to data loss.

The problems associated with the speed and continuity of data transfer, their volume, communication range, structural complication of systems due to the use of additional modules can be solved by using Wi-Fi technology. Work [20] provides a comparative analysis of network technologies used in transmitting ECG signals, which confirms the advantages of this technology. It is indicated that the range of Bluetooth is 2–20 m, ZigBee – 20–30 m, Wi-Fi – 20–200 m. The data transfer rate of Bluetooth is 3–24 Mbit/s, ZigBee – 10–250 kbit/s, Wi-Fi – 11–54 Mbit/s. The power consumption of Bluetooth is low, ZigBee – low, Wi-Fi – average. Data collection when using Wi-Fi is carried out independently of intelligent terminals, unlike Bluetooth and ZigBee. In addition, when using Wi-Fi technology, data transfer is carried out without interruptions [21].

Power consumption can be reduced by using inexpensive, low-power Wi-Fi transceivers from Espressif Systems (ESP8266, ESP32). In [22], the authors use ESP32 to design an energy-efficient three-lead ECG monitor. The system consumes 165 mW, which allows the device to operate for up to 67 hours on a 3000 mAh battery. However, this system only records data to a microSD memory card and does not provide for wireless transmission.

In [23], a system for collecting, processing, and wirelessly transmitting ECG in real time is implemented based on ESP32. The experimental results show that the system meets the requirements of remote monitoring and auxiliary diagnostics, but the energy efficiency of the transmit/receive process was not addressed.

ESP32 transceivers can operate under four modes: transmit, receive, sleep, and standby. Sleep mode is considered the most energy-efficient mode of operation since it consumes significantly less energy than all other modes of operation. However, nodes cannot transmit or receive data under the energy-saving sleep mode. Therefore, it is necessary to use a method for synchronizing the operation of nodes that guarantees the coincidence of transmission and reception operations.

Our review of the literature demonstrates that issues on the development of energy-efficient methods for hardware and software implementation of a wireless Wi-Fi system for monitoring human biomedical parameters remain unresolved. The above arguments allow us to assert that it is advisable to conduct a study on the development of a local Wi-Fi network for transmitting biomedical signals that provides an optimal ratio of transmitter power consumption, transmission speed, and quality of transmitted signals.

3. The aim and objectives of the study

The objective of our study is to design a local Wi-Fi network for multichannel transmission of biomedical signals based on the ESP32 module, which ensures minimal power consumption of an autonomous transmitter while maintaining the specified qualitative and quantitative indicators of the process of transmitting and receiving biomedical signals.

To achieve this goal, it is necessary to solve the following problems:

– to develop an algorithm for implementing a program that makes it possible to reduce power consumption by the transmitter and synchronize the cycles of measuring and transmitting biosignals in the transmitter and receiver of the system;

– to organize parallel execution of two cycles of the transmitter program: a cycle of measuring biosignals and a cycle of wireless transmission of digitized biosignals to the receiving part of the local network;

– to determine the value of the biosignal measurement frequency at which the distortion of the biosignal will be minimal, which will avoid the loss of diagnostic features;

– to study the energy efficiency of the receiving-transmitting system for electrocardiosignals (ECS) using the proposed algorithms.

4. The study materials and methods

The object of our study is the processes of measuring and wireless transmission of biomedical signals over a local wireless network built on the basis of a Wi-Fi interface.

It is assumed that the development of an algorithm for generating a data packet, dividing the process of executing the algorithm between two cores of the ESP32 module could make it possible to synchronize the process of transmitting a packet over the Wi-Fi interface and switch the transmitter to a power-saving mode, which would reduce the energy consumption of the transmitter while maintaining the quality of the transmitted biosignals.

A set of measures was used, including the search for an optimal algorithm for implementing a biomedical signal broadcasting program, the selection of a Wi-Fi transmitter that ensures parallel execution of operations, and circuitry and software solutions aimed at minimizing the energy consumption of the biosignal transmission channel.

As a specific type of biomedical signal, it is advisable to choose an electrocardiological signal as the most common in medical practice, and as a diagnostic procedure – Holter monitoring, which involves recording ECS over a long period of time.

The basic components of the hardware in the local wireless network are shown in Fig. 1.

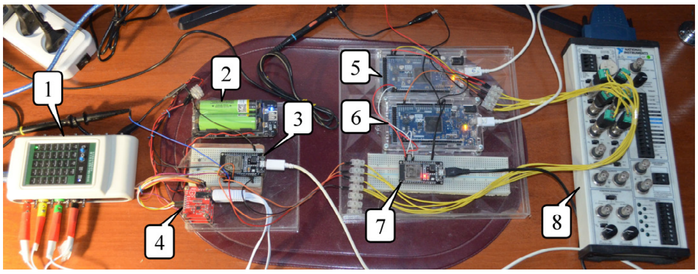


Fig. 1. Hardware of the ECS signal transmission system

The following designations are used in Fig. 1:

1 – ECG signal generator ECGS-12A;
2 – Li-ion 18650 batteries;
3 – ESP32 family transmitter module;
4 – ECG signal amplifiers;
5, 6 – Arduino Due boards;
7 – ESP32 family receiver module;
8 – auxiliary BNC-2120 module for data collection.

A module with a dual-core ESP32-D0WDQ6-V3 microcontroller from Espressif Systems is used as a Wi-Fi transmitter. ESP32 is built on an Xtensa LX6 processor (32 bit), has a Wi-Fi wireless interface controller, eighteen analog-to-digital converters (ADC) with a bit depth of 12 bits, an I2C interface, and 4 general-purpose timers. The programming environment is ESP-IDF and Arduino IDE. All of the listed technical features of the ESP32 are a necessary set for building a wireless local area network.

5. Results of investigating a local Wi-Fi network for transmitting biomedical signals

5. 1. Algorithm for minimizing energy consumption by the transmitter and synchronizing measurements in the transmitter and receiver of the system

There are two main technological methods for minimizing energy consumption. The first is to increase the duty cycle of the Wi-Fi biosignal transmission process, i.e., the ratio of the period of one cycle of measurement and transmission of the biosignal to the duration of the direct Wi-Fi transmission of the biosignal. The second is to use a special low-power mode of ESP32. The first method can be classified as algorithmic.

A characteristic feature of the algorithm, including measuring ECS, generating a data packet, and transmitting the packet via the Wi-Fi interface, is the serial-parallel principle of dividing the algorithm execution process between two cores of the ESP32 module. This principle ensures the continuity of the ECS measurement and transmission and eliminates the loss of electrocardiological information. Initially, an algorithm for measuring biopotentials and generating a data packet P is developed (Fig. 2).

The program fragment (Fig. 2) is a data array for three ECG leads and includes n bytes or $n/2$ measurements, since an array in the Arduino Ide programming environment can only be formed from bytes, and each measurement of one lead contains two bytes.

The degree of energy saving by the Wi-Fi transmitter is determined not only by the optimization of the program implementation algorithm for the transmitter but also by the hardware and software capabilities of the ESP32 module itself, which has six energy-saving modes. Among them, the Modem-sleep mode can be distinguished. Under this mode, a significant reduction in consumption is achieved by turning off the RF path of the microcontroller, as well as the Wi-Fi frequency generator. The remaining nodes of the module operate under a normal mode, taking into account the user settings of the clock frequency of the main processor.

The Modem-sleep mode is applicable only to the ESP32 module operating under the active Wi-Fi Station mode. In this case, the transmitter does not have the ability to create its own local Wi-Fi network, it connects to an existing one, in this case, to the network organized by the receiver. The mode comes into effect after connecting to the access point (Wi-Fi receiver).

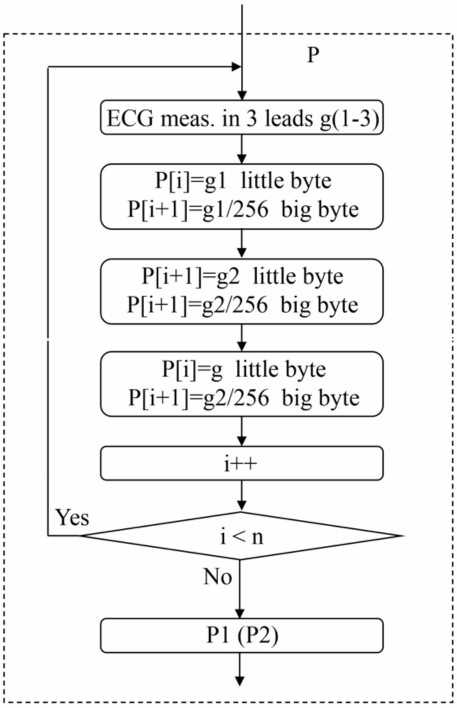


Fig. 2. Fragment of the algorithm for forming a data packet P1 (P2)

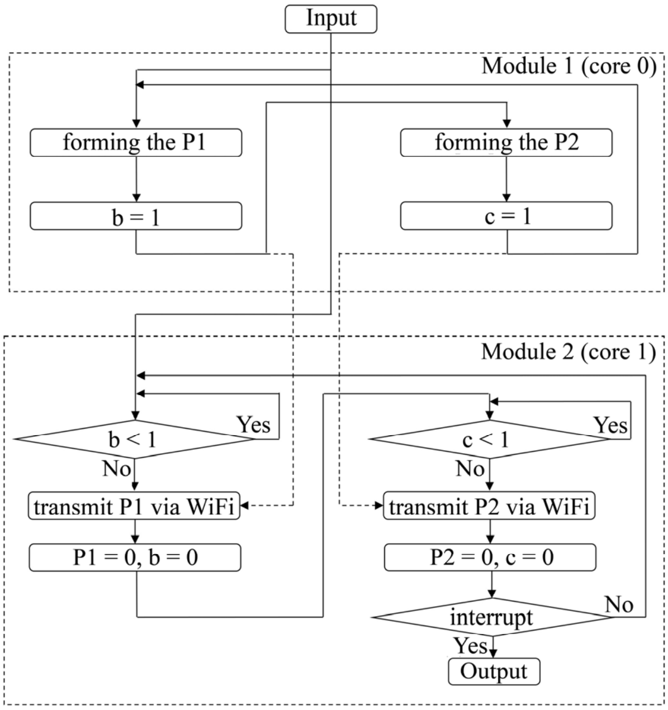


Fig. 3. Algorithm for two cores

The ESP32 module uses the Wi-Fi delivery traffic indication message beacon mechanism to maintain a connection with the Wi-Fi receiver. Under the sleep mode of the modem, the ESP32 switches off the radio frequency block between two beacons (messages). In the classic version, these messages are transmitted at predetermined time intervals (Delivery Traffic Indication Message). A distinctive feature of the proposed technique for generating permission signals for message transmission is that the discreteness of these signals is not strictly specified but is determined by the hardware timers of the receiver, which form the interval for processing information by the receiver. The resolution of the beacon signals is equal to 1 ms. Thus, the time interval of the active mode of the transmitter is reduced, due to which additional energy consumption is saved.

5. 2. Parallel execution of biosignal measurement and wireless transmission of digitized biosignals by the transmitter

The program algorithm for two ESP-32 module cores is shown in Fig. 3. Module 1 (core 0) is designed to implement the following command execution order: measuring the ECG signal in three leads, forming the $P1=P$ array and setting the $b=1$ flag. As a result, module 2 (core 1) is granted permission to transmit data from the $P1$ array to the receiving side. At the end of the $P1$ array transmission session, the b flag and the $P1$ array are reset. In parallel with the process of transmitting the $P1$ array, a repeated data array is created in module 1, but this time under the $P2$ symbol. After this, the $c=1$ flag is set, allowing module 2 to send data from the $P2$ array to the Wi-Fi receiver.

The receiver of the ECS broadcast system is also implemented on the ESP32 module, but in a single-core version. The reception algorithm is shown in Fig. 4.

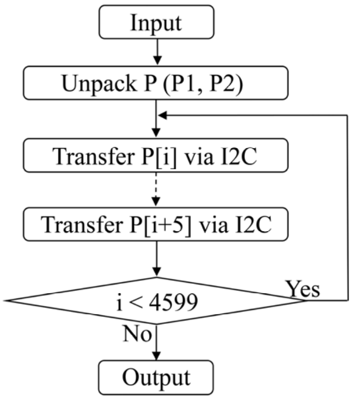


Fig. 4. Algorithm for receiving electrocardiological signals

The method of packet transmission of biosignals is characterized by an inversely proportional relationship between the power consumption of the transmitter and the volume of the packet of transmitted information. The volume of the packet of transmitted information is directly proportional to the duration of the cycle (period) of information transmission, i.e., the larger the volume, the longer the period. The maximum packet size is determined by the amount of RAM of the ESP32 module. However, there is another relationship – the larger the volume of transmitted information, the greater the probability of an error, distortion, or failure in the transmission process. It was determined empirically that the most optimal packet size should not exceed 6000 bytes. In this case, the array of measured ECS includes 3450 bytes of information. This volume of the data array was selected based on the possibility of increasing the number of measured leads to 5. The measured data is written to the memory of the ESP32 signal receiver module as a sequence of packets $P1$ and $P2$ (Fig. 4). Here, the packet is unpacked, and the data is sequentially transmitted via the I2C interface to the Arduino DUE boards for preliminary processing. After this, the receiver enters a standby mode to receive the next information packet.

5. 3. Determining the minimum sampling frequency of a biosignal

One of the most important characteristics of the procedure for measuring and transmitting biosignals is the duty cycle of the packet transmission process of biosignals. The duty cycle S is determined from the formula:

$$S=T/t_{tr}, \tag{1}$$

where T is the duration of one measurement cycle and Wi-Fi data transmission, and t_{tr} is the duration of the Wi-Fi transmission session of one measurement of all leads. Thus, the greater the duty cycle, the less energy is consumed.

The energy consumption (W) of the Wi-Fi transmitter is determined from the following formula:

$$W=M_{meas}(T-t_{tr})+M_{tr}t_{tr}, \tag{2}$$

where M_{meas} is the power consumed during the measurement of ECG leads, M_{tr} is the power consumed during a Wi-Fi transmission session of one measurement of all leads.

The functional components of the ESP32 include hardware 64-bit general-purpose timers. In the Arduino Ide software environment using the built-in libraries from ESP-IDF, one can set up certain identical time intervals for the transmitter and receiver of Wi-Fi information. These time intervals correspond to one cycle of measuring three ECG leads (for the transmitter) and one cycle of receiving the measured leads and transmitting the result via the I2C interface (for the receiver).

In this case, the duration of one cycle is set to 3000 μs (3 ms). This value was chosen taking into account that the duration of the shortest ECG fragment – the Q wave is on average 30 ms, there are 10 samples per wave digitization, which corresponds to a frequency of 333.3 Hz. This is quite sufficient for the correct interpretation of the ECG. Based on this, the time of one measurement cycle and Wi-Fi data transmission is T=30/10=3 ms.

Thus, by setting the required time intervals, the synchronization of the processes of executing the working programs of the receiver and transmitter is carried out.

5. 4. Results of the experimental study of energy consumption by the receiving-transmitting system of electrocardiographic signals

To implement the developed algorithms, a functional diagram of the ECG broadcasting system for three leads is proposed, shown in Fig. 5. The system also includes all the elements shown in Fig. 1.

The ECG generator is an imitator of a set of cardiograms, both normal and with various pathologies and interference. The bioamplifier unit includes three AD8232 boards. The AD8232 board from Analog Devices is used to extract, amplify, and filter the ECG under noise conditions [24]. Hardware correction of the signal pass frequency is also provided.

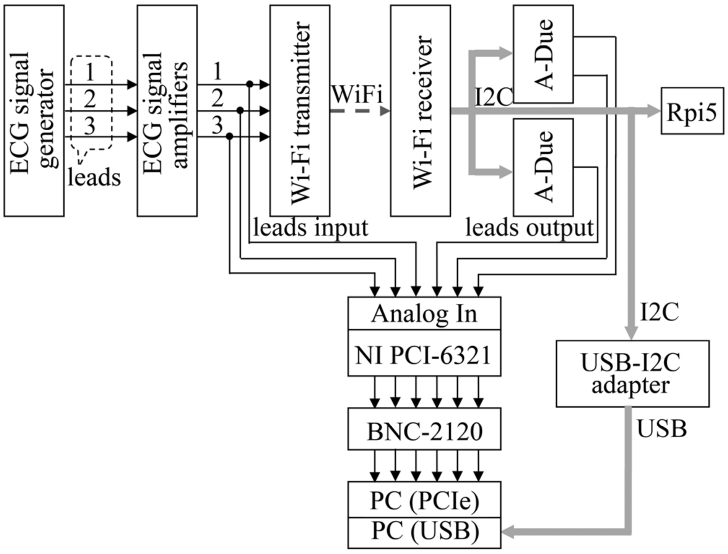


Fig. 5. Functional diagram of Holter monitoring

Three ECG leads (signals) are fed to the ADC inputs of the ESP32 module. Under Wi-Fi mode, the number of active ADCs is 6. The Wi-Fi receiver output is connected via the I2C interface to Arduino Due boards built on 32-bit AT91SAM3X8E microcontrollers from Atmel of the ARM Cortex-M3 family, with a frequency of 84 MHz. The module includes two 12-bit DACs and an I2C interface. The purpose of the Arduino Due is to pre-process the ECG signals and to be able to connect via an I2C-USB adapter to a personal computer or directly to a Raspberry Pi5 mini-computer for final automated processing and analysis of the information received.

The NI PCIe-6321 I/O board and the BNC-2120 module are used to configure the entire Wi-Fi complex. The BNC-2120 module serves as a switch between the NI PCIe-6321 board and the outputs of the bioamplifiers and the Wi-Fi receiver. The software environment for processing and studying signals coming through the NI PCIe-6321 I/O board is the MATLAB program with the Data Acquisition Toolbox (DAT) package installed.

The option of using the Simulink Desktop Real-Time (DRT) package as a software environment was considered. It is a real-time kernel for running Simulink models and simulating hardware on a computer. However, a comparative analysis of the two packages revealed that the DAT package supports much more time, frequency, and spectral analysis tools for Simulink models. Therefore, priority was given to using the DAT package.

Fig. 6 shows the entire complex assembled, including an oscilloscope and a computer. The two-channel oscilloscope allows monitoring the input and output signals of one lead. The computer makes it possible to monitor the signals at the input and output of the Holter monitoring system in three leads in the MATLAB software environment. The hardware units were shown in detail in Fig. 1.

The process of transmitting and measuring ECG includes several main stages. The first stage is amplification, measurement, and wireless transmission of signals from three leads generated by the ECG signal generator. At the same time, the amplified signals are sent to the BNC-2120 module.

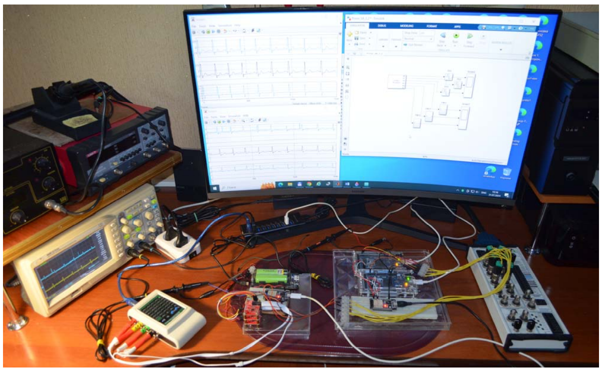


Fig. 6. Measuring-debugging system

The second stage is receiving and transmitting signals via the I2C interface to the inputs of the Arduino Due boards and in parallel via the adapter to the USB port of the PC for the final interpretation of the information received, i. e., the diagnostic conclusion.

The third stage includes preliminary processing and transmission of signals from the output of the Arduino Due boards to the BNC-2120 module, then to the PCIe-6321 board for further processing in the DAT package of the MATLAB system.

Fig. 7 shows a virtual model assembled in the MATLAB environment using the tools of the Data Acquisition Toolbox software package.

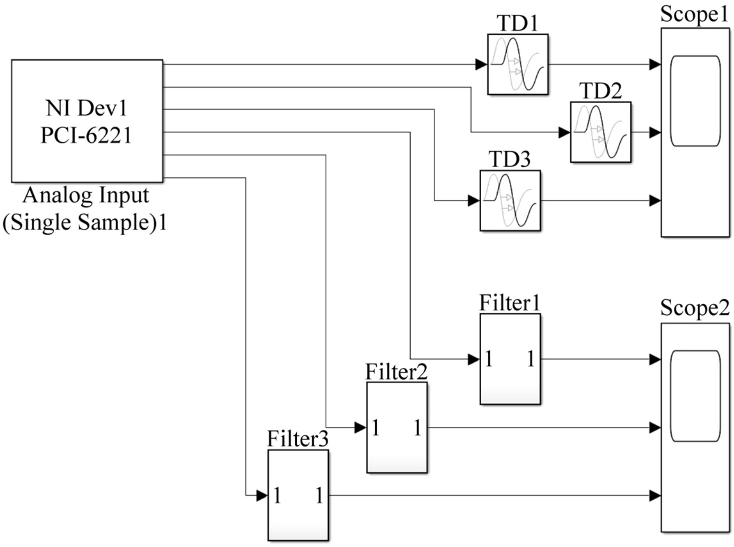


Fig. 7. Model for displaying input and output biosignals in the MATLAB software environment

The model includes the following modules: Analog Input (single Sample), Filtr1–Filtr3, TD1–TD3, Scope1, Scope2. The Analog Input (single Sample) module is designed to transmit signals from the external hardware interface module NI BNC-2120. Since the study was conducted for three leads, three inputs are used, designated as ai0–ai2, and three outputs are used, designated as ai3–ai5.

The Filtr1–Filtr3 modules are designed for preliminary processing and filtering. The TD1–TD3 modules implement a time delay of the input signals by one cycle since the processes in the Filtr1–Filtr3 modules occur with a delay of one measurement cycle. Thus, the modeling results are displayed on the screens of the Scope1 and Scope2 oscilloscopes at the same points in time (Fig. 8).

Fig. 8, *a* shows the signals from the bioamplifier output, and Fig. 8, *b* – output signals from the receiver. Comparative visual analysis of the obtained plots shows that the plots of the input and output signals have no visible discrepancies.

In Fig. 8, *b*, on the upper plot, there are two vertical marks between the ECG cycles. They are created by software so that the beginning and end of one data transmission packet can be observed (one transmission packet includes three measurement cycles corresponding to three leads). Observing this process helps analyze how much information has been transmitted in a certain time.

The signals under study can also be observed on the oscilloscope screen (Fig. 9). The upper plot (channel 2) is the output signal, the lower plot (channel 1) is the input signal.

The duration of one measurement cycle can be determined as follows. The total number of measurements is 3450, there are 1150 readings or 575 two-byte numbers per lead. The exact duration of one measurement set using the hardware timer is 3 ms. Thus, one measurement cycle takes 3*575=1750 ms, which is confirmed by the oscilloscope screen image in Fig. 9: one cycle lasts 7 divisions, the value of one division is 250 ms, thus 7*250=1750 ms.

A fragment of the output signal is shown in an enlarged scale in Fig. 10, which confirms that the duration of one measurement (step) is indeed 3 ms. The duty cycle of the packet transmission of biosignals is $S=T/t_{tr}=1750/3\approx575$.

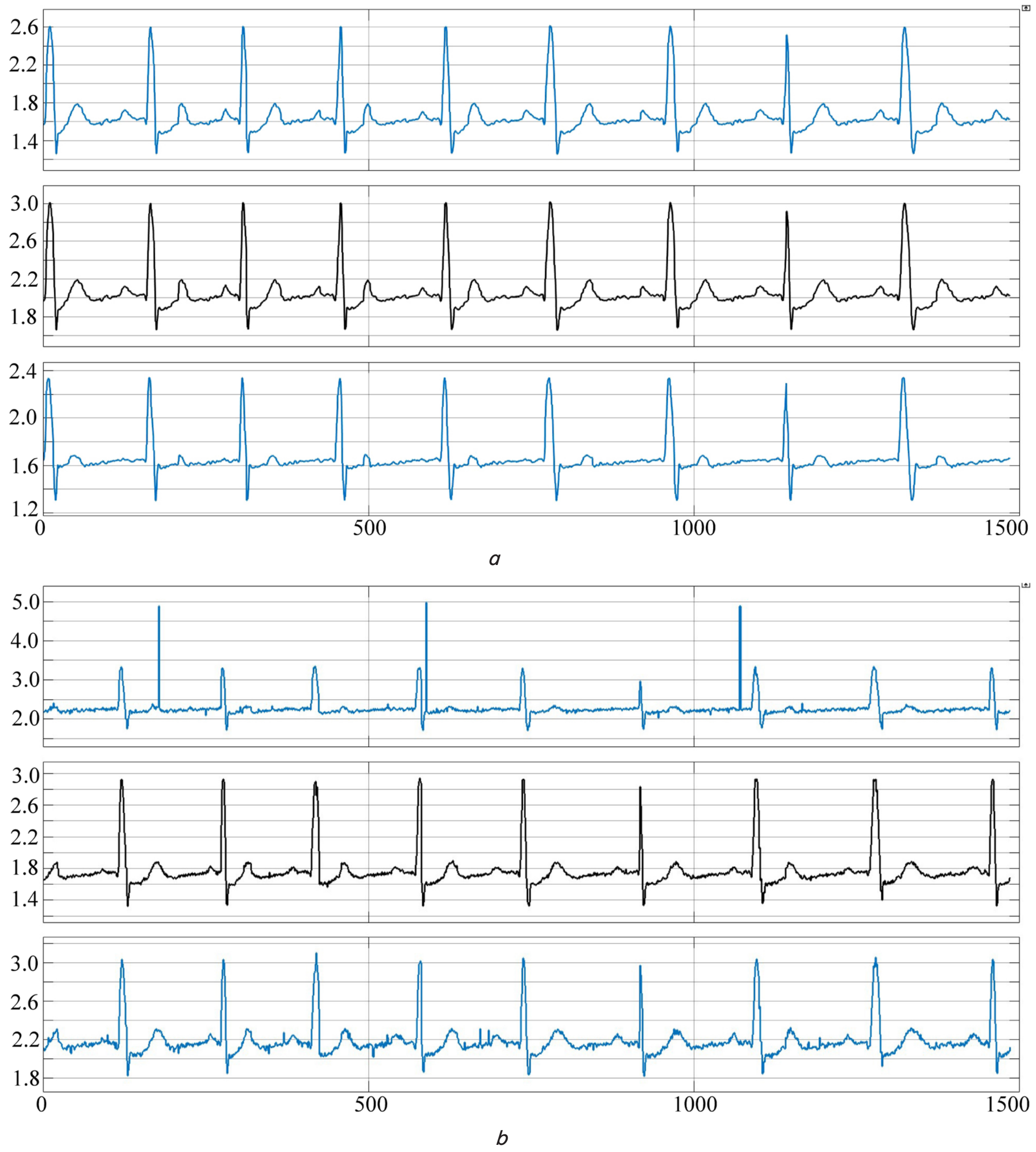
During the work, a study was conducted concerning the energy consumption of the ECS-signal transmitter. For this purpose, a shunt with a resistance of 0.1 Ohm was used, connected to the power supply circuit in series with the transmitter. The current passing through the resistance causes a voltage drop on it, which is measured and fed first to the AD8232 amplifier-filter (with a gain coefficient k_{gain}=100), and then to the oscilloscope. Fig. 11 shows an oscillogram recording a rectangular voltage pulse at the moment of signal transmission.

The voltage value during signal transmission (Active mode) U_a is 2.5 V, when there is no transmission (Modem-sleep mode), the voltage U_s is 0.5 V. Based on these values, taking into account the gain factor, it is possible to determine the current consumption under the active mode I_a and under the “modem sleep” mode I_s. The results of measuring the parameters of the transmitter operating modes are given in Table 1.

Table 1

Results of measuring the parameters of the transmitter operating modes

Transmitter mode	Mode duration, ms	Current of consumption, mA
Active mode	3	250
Modem-sleep mode	1747	50



a

b

Fig. 8. Simulation results: *a* — input signals; *b* — output signals


АКИП Stop
TRIGGER
Type
Edge
Source
CH1
Slope
Mode
Auto
Set Up
<10Hz
CH1⎓ 1.00V
CH2⎓ 1.00V
M 250ms
M Pos:24.19ms

Fig. 9. Oscillograms of input and output signals from one lead

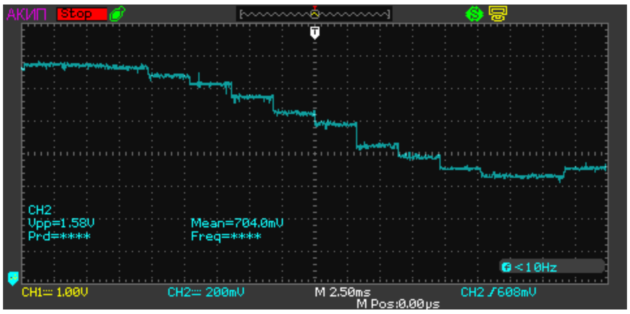

АКИП Stop
CH2
Upp=1.58V
Prd=****
Mean=704.0mV
Freq=****
<10Hz
CH1⎓ 1.00V
CH2⎓ 200mV
M 2.50ms
M Pos:0.00μs
CH2 608mV

Fig. 10. Output signal oscillograms in enlarged scale

To calculate the total current consumption by the transmitter $I_{\text{п}}$, formula (3) is used, where the total time T$_\Sigma$ is the sum of the time of the "modem sleep" mode T_s, which is 1747 ms (based on the fact that the duration of the entire cycle is 1750 ms) and the time of the active mode T_a=3 ms (Fig. 11):

$$I_{\text{п}} = \frac{T_a \cdot I_a + T_s \cdot I_s}{T_\Sigma}. \qquad (3)$$

Taking into account the current consumption of three AD8232 microcircuits (according to the passport data [25], one microcircuit consumes 170 μA), the total value of the current consumption I_Σ will be equal to 50.5 mA.

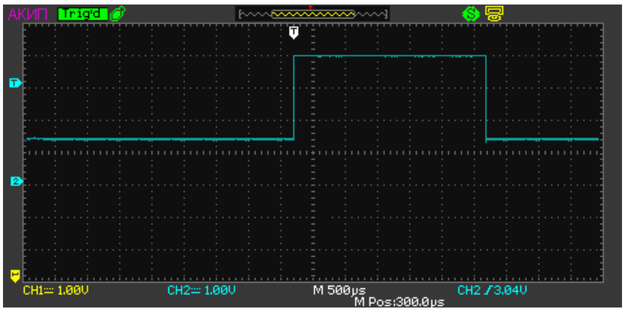


Fig. 11. Pulse of transmission of the ECS information packet via the local network

The operating time of two Li-ion INR18650 HE4 batteries can be calculated using formula (4), where the capacity of one battery C is 2500 mAh. A correction factor of 0.70 is introduced to take into account external factors that can affect the battery life:

$$T_{\Sigma} = \frac{C}{T_{\Sigma}} \cdot 0.7. \tag{4}$$

Thus, the autonomous operation time of the patient's wearable device was 69 hours. To verify the calculation, the measuring-debugging system was tested with the transmitter operating under an autonomous mode. The result showed that the transmitter is capable of continuous operation for 60 hours (2.5 days). Without the use of the proposed algorithms, the time was 14 hours.

6. Discussion of results of investigating a local Wi-Fi network for transmitting biomedical signals

The proposed algorithm of the program, aimed at synchronizing the measurement cycles of biosignals and reducing the energy consumption of the Wi-Fi transmitter, has made it possible to increase the battery life of the wearable device (2.5 days). This result was achieved by implementing algorithms for increasing the duty cycle of the Wi-Fi biosignal transmission process. When there was no transmission, the ESP32 microcontroller was switched to a special low-power mode Modem-sleep mode. Thus, the higher the duty cycle, the less energy consumed by the transmitter. According to calculations, the duty cycle of the packet transmission of biosignals *S* was 575. At the same time, by changing the duration *T* of the measurement cycle, it is possible to control the duty cycle of the packet transmission of biosignals.

Unlike the device proposed in [26], in which the total battery life is 3 hours, the battery life of the developed system is significantly longer when using batteries of the same capacity. The estimated battery life of the transceiver, taking into account the correction factor according to formula (4), was 69 hours. This is slightly different from the time obtained as a result of the experiment (60 hours). The deviation can be explained by the fact that the capacity of the batteries may actually be less than stated in the technical documentation. Nevertheless, owing to the proposed algorithms, it was possible to reduce the average current consumption of the ESP32 microcontroller to 50.5 mA. This is significantly less than the current consumption under Wi-Fi or Bluetooth transmission mode, which is in the range of 160 to 260 mA [26]. The battery life is comparable with devices using BLE technology [27] but unlike them, the developed device has a longer communication range. This is possible due to the advantages of using Wi-Fi technology.

Continuity of biosignal measurement and wireless transmission is achieved by a software algorithm for dividing these processes between two ESP32 module cores. Comparative analysis of the obtained oscillograms (Fig. 9) revealed that the signal from the bioamplifier output and the output signal from the receiver after the wireless transmission process have minor acceptable discrepancies that do not affect the quality of the transmitted signal. Thus, the developed software algorithms and the selected sampling frequency of 333.3 Hz ensure continuity of measurement and transmission, while avoiding the loss of diagnostic ECG features. It should be noted that in the study, an electrocardiogram signal in 3 standard leads was used as biomedical signals. Based on this, the biosignal measurement frequency and the duty cycle of packet transmission were selected. This is associated with restrictions on the transmission of electromyogram or electroencephalogram signals. In this case, it will be necessary to recalculate the sampling frequency and the duty cycle of the transmitted signal.

A caveat of our paper is an insufficiently comprehensive study on the issue of saving energy consumption by an autonomous Wi-Fi transmitter. As noted above, the energy consumption of a Wi-Fi transmitter directly depends on the duty cycle of the transmitted signal, i.e., the ratio of the period of the sequence of transmission of information pulses to the duration of the packet of transmitted information. It was proposed to increase the duty cycle by increasing the volume of the packet of transmitted information, but this technique has certain hardware limitations of the ESP32 microcontroller. Another possible option for increasing the duty cycle is to use various data compression methods without losing the reliability of the transmitted information, such as various encoding algorithms or, for example, the wavelet transform. Such studies will require the use of additional procedures, as well as hardware and software. Therefore, this is one of the directions for the development of our research. In addition, in order to expand the capabilities of the designed wireless network, it is advisable to consider the development of an algorithm for recognizing morphological elements of biosignals using classical and alternative [29] identification methods.

7. Conclusions

1. A procedure for reducing the energy consumption by a Wi-Fi transmitter is proposed by synchronizing cycles and controlling the duty cycle of the packet data transmission process. Thus, when there is no data, the Modem-sleep mode transmitter was used. To implement synchronization, the hardware timers of the ESP32 modules were configured. As a result of our studies, the optimal data packet size was selected, which ensures the required quality of the transmitted signal with a sufficiently long operation of the transmitter under an autonomous mode (2.5 days).

2. The implemented software algorithm, based on the serial-parallel division of the program execution process

between two cores of the ESP32 module, provides the continuity of measurement and transmission of electrocardiological information. In addition, the structure of the algorithm fragment was determined for setting the frequency of measuring the input ECS signal, ensuring its minimal distortion on the receiving side and at the same time not degrading the quality of diagnostics.

3. The value of the biosignal measurement frequency was determined based on the duration of the shortest Q wave of the ECG. As the experimental results showed, the selected sampling frequency of 333.3 Hz allowed us to minimize biosignal distortion and prevent the loss of ECG diagnostic features.

4. A hardware implementation of a wireless local Wi-Fi network based on the ESP32 microcontroller using the developed algorithms has been proposed. The hardware and software system allowed us to conduct experimental studies on the energy efficiency of the ECG receiving-transmitting system. Analysis of the results revealed that the wireless transmission process was performed without loss of ECG diagnostic features. At the same time, the developed algorithms, due to an increase in the duty cycle of the packet transmission of biosignals, allow us to significantly reduce energy consumption.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

Funding

This research is funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP19677288).

Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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