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USING ESP32 MICROCONTROLLER FOR PHYSICAL SIMULATION OF THE WIRELESS REMOTE CONTROL MODEM

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ABSTRACT

Context. Due to the need for practical implementation of the theoretical provisions of the proposed method of the wireless transmission of the commands for controlling a moving object in conditions of intentional interference.

Objective of the work is a practical verification of the possibility of using a phase-pulse modulation of the linear-frequency-modulated signal for transmission a control commands through physical modeling using microcontrollers.

Method. Analytical calculations of the change in time of the voltage at the input and output of the device for optimal processing of the linear frequency-modulated signal were carried out exclusively using the computing capabilities of the microcontroller. The graphs of changes in time of the relevant parameters were built with the help of Excel using the data output to the monitor of the serial port of the Arduino IDE software environment. A digital oscilloscope with a USB host was used to monitor the operation of a wireless modem to transmit control commands to a moving object.

Results. Analytical calculations and physical modeling using a modern microcontroller proved the operability of the low-frequency part the wireless remote control modem with using phase-pulse modulation of the linear frequency-modulated signal.

Conclusions. The possibility of using phase-pulse modulation of the linear-frequency modulated signal for the transmission of control commands is considered. This method of transmitting the information component, unlike the existing methods, does not require changing the parameters of the linear frequency modulated signal. The use in the receiver of optimal processing of a linear-frequency-modulated signal of sufficiently big base will allow of the wireless transmission of the commands for controlling a moving object in conditions of the intentional interference. The use of modern microcontrollers made it possible to conduct a practical test of the functionality of the low-frequency part the wireless remote control modem with phase-pulse modulation of the linear-frequency modulated signal through physical modeling.

KEYWORDS: wireless, remote control, linear frequency modulation, phase-pulse modulation, simulation.

ABBREVIATIONS

LFM is a linear frequency modulated;
CSS is a chirp spread spectrum;
FHSS is a frequency hopping spread spectrum;
DSSS is a direct-sequence spread spectrum;
TH is a time hopping;
CDMA is a code-division multiple access;
GFSK is a Gaussian frequency-shift keying;
DBPSK is a differential phase-shift keying;
MU-MIMO is a multi-user MIMO;
MIMO is a multiple-input and multiple-output;
LoRa is a “long range”;
PPM is a phase-pulse modulation;
DAC is a digital-to-analog converter;
ADC is an analog-to-digital converter;
IoT is an Internet of Things.

NOMENCLATURE

τ_c is an impulse duration;
$u(t)$ is a voltage of the LFM signal;
Um is an amplitude of the radio pulse;
f_c is an average frequency of the signal;
Δf is a signal frequency deviation;
$f(t)$ is a change of the frequency of the LFM signal;
$V(t)$ is a pulse characteristic of the matched filter of the signal with LFM;
$f_V(t)$ is a change the frequency of the pulse characteristic of the matched filter;
C is a constant value;
$\dot{K}(f)$ is a frequency characteristic of the optimal filter of the LFM signal;
$\dot{g}^*(f)$ is a complex conjugation spectrum of the LFM radio impulse;
$w(t)$ is a voltage of the signal component at the output of the optimal filter;
τ is a duration of the pulse at the filter output;
i is a command number;
$x_i(t)$ is a command structure;
B is a base of the signal.

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INTRODUCTION

Modern conditions of operation of radio-electronic communication complexes place increased demands on their work. This is because qualitative changes in the means of radio-electronic warfare of the leading countries of the world in the last few decades allow them to create a significant impact on the operation of radio-electronic communication complexes. Radio communication in range of short waves has special place in military communication [1]. Most of the short wave and ultra-short wave communication means use narrowband signals that are transmitted at a fixed frequency of the communication channel to transmit speech. A transmitter of sufficient power tuned to the same frequency can suppress a narrowband signal. This lack of protection against conventional radio signal interference led to the need to expand the spectrum of the emitted signal. At the same time, a much wider frequency band than the spectrum width of the information signal is used for information transmission. This leads to a decrease in the spectral power density of the signal emitted by the radio communication device. At the same distance from the means of radio frequency monitoring, the probability of detecting the radiation of a broadband signal transmitter will be less than that of a narrowband one with the same power. Drone communication channels are also vulnerable to cyberattacks [2]. Therefore, the study of the possibility of increase the interference protection of radio communication channels is an urgent scientific task. One of the problematic issues in the creation of a test sample is the verification of the correctness of theoretical calculations by conducting physical modeling using the latest elemental base.

The object of research is the process of the wireless transmission of commands for controlling a moving object.

The subject of the study is the wireless remote control modem of the moving object with using phase-pulse modulation (PPM) of the linear frequency-modulated (LFM) signal.

The purpose of the work is to a physical simulation of the operation the low-frequency part of the wireless remote control modem using of the modern microcontrollers.

1 PROBLEM STATEMENT

As a moving object, consider a car with a camera, for control of which it is enough to send five commands. The duration of command transmission should not exceed one second. During this interval, each command with the number i=1,...,5 will be transmitted by a pulse packet of a certain structure:

$$x_i(t) = \sum_{i=1}^{5} u\left(t + (i-1)\tau_c\right),$$

$$u(t) = U_m \cos\left(2\pi\left(f_c t + \frac{\Delta f t^2}{2\tau_c}\right)\right). \quad (1)$$

Each command to provide for a change in the time position of the pulse of the packet by a certain amount corresponding to the command number. The minimum value corresponds to the command with the number one. As the command number increases, the time shift increases by an amount equal to the pulse duration τ_c. The change of the signal frequency during the duration of the pulse should be less than 25 kHz. In order to increase the interference protection of the radio communication channel, optimal signal processing should be carried out in the receiver. We will assume that frequency conversion cascade is used in the transceiver. Therefore, the formation and processing of the signal can be carried out at a frequency significantly lower than the operating frequency of the transmitter.

To carry out a physical simulation of the operation of the wireless modem to transmit control commands, it is necessary to choose a controller based on which the modem will be implemented. It is also advisable to conduct mathematical modeling to determine signal parameters for command transmission. Next, using the mathematical principles of forming and processing the signal develop the program code for the controller. After that, conduct a physical simulation of the operation of the wireless modem using the selected microcontroller to check the possibility of practical implementation of the proposed solutions.

2 REVIEW OF THE LITERATURE

An overview of the promising directions of increasing the secrecy of operation and interference protection of communication means is carried out in [3–5]. There are several methods of expanding the spectrum of signals, which differ among themselves by the principles of obtaining a wide frequency band: the direct sequence method – DSSS, the frequency hopping method – FHSS, the method of expanding the spectrum with linear frequency modulated signal – CSS, the time-hopping method – TH. For example, the CDMA mobile communication system uses DSSS technology with signal spectrum spreading by mutually orthogonal Walsh-Hadamard functions. The IEEE 802.11 standard provides for the use of various options for expanding the signal spectrum for the organization of a wireless data transmission. The width of the spectrum of the radio signal is much greater than the data transmission rate, and the correlation function is significantly narrower than the correlation function of a narrowband signal. In particular, the use of FHSS technology with GFSK modulation of the radio signal, or DSSS and DBPSK modulation technology with the provision of data transmission at a speed of no more than 1 Mbit/s over a radio channel in the 2.4 GHz frequency range. As a perspective for a wireless local network, the IEEE 802.11ac standard with a radio channel in the 5 GHz frequency range and the use of MU-MIMO spatial multiplexing technology with the formation of an adaptive directional pattern can be considered. When designing complex electronic circuits, it is important to simulate their operation using appropriate software. The experience and results of

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mathematical modeling in the MATLAB software environment to study the problem of synchronization in the receiver based on the technology of multiplexing with orthogonal frequency distribution – OFDM is given in [6]. The CSS spectrum expansion technology was used in the creation of a LoRa physical radio interface [7–9]. The frequency redundancy of the broadband radio signal determines its high interference protection. The CSS frequency of the radio signal can both increase and decrease. However, the LoRa technology, optimal processing of the CCS signal is not carried out, since the information is transmitted by the signal frequency hopping. The necessary range of the information transmission is provided by the change duration of the signal.

The most technologies of the signal spectrum expansion are aimed at use in the ultra-high frequency range. At the same time, the question arises about the possibility of implementing technologies for increase the interference protection of short-wave and ultra-short-wave communication means and to ensure their operation in the conditions of creating deliberate obstacles. A variant of expanding the signal spectrum using Walsh functions with a frequency separation of channels and frequency manipulation of the carrier is considered in [10]. It is proposed to use Walsh functions with a duration of an elementary symbol of 0.5 μs to expand the signal spectrum. At the same time, the width of the signal spectrum much exceeds the frequency band allocated in this range for one channel. The frequency band of the radio channel of the narrowband means of communication does not exceed 25 kHz. Therefore, when implementing the proposed method, it will be difficult to ensure the necessary value of the frequency band with the existing restrictions [11]. Therefore, it is necessary to offer the wireless method of transmitting control commands with increased interference protection within the frequency band allocated for the operation of one channel.

One of the possible options is the transmission of control commands using the method, which based on the LoRa technology, but instead of the signal frequency hopping will changing the pulse repetition frequency of the LFM pulses in accordance with the command being transmitted. So, it method of transmitting the information component, unlike the existing methods, does not require changing the parameters of the LFM signal and we will named is a PPM of the LFM signal. The frequency deviation of the LFM signal of a certain duration should not exceed 25 kHz. The optimal LFM signal processing in the receiver will provide increase the interference protection of the radio communication channel. Therefore, it is necessary to carry out a practical check of the possibility of creating blocks for the formation and processing of signal of the wireless modem with PPM of the LFM signal using the microcontrollers.

3 MATERIALS AND METHODS

To conduct research, we define the following parameters of the LFM signal: an average frequency and frequency deviation are ten kHz, an impulse duration is 0.1 sec. To carry out a physical simulation of the operation of the wireless remote control modem with PPM of the LFM signal, it is necessary to choose a controller based on which the modem will be implemented. For determinate conditions, it is advisable to consider of use of the microcontroller ESP-WROOM-32. It is based on the popular two-core 32-bit Xtensa LX6 processor with a variable clock frequency from 80 MHz to 240 MHz. ESP-WROOM-32 has a RAM of 520 kilobytes and a rich peripheral that includes such inter-faces as UART, SPI, I2C, I2S, a twelve-bit ADC, and an eight-bit DAC [12]. Choosing this controller is also advisable in case of use on the moving object the latest small size camera module ESP32-CAM. Based on this module, it is also possible to build a demodulator of the receiving device.

ESP32-CAM can be widely used in various the Internet of Things (IoT) applications, suitable for home smart devices, industrial wireless control, wireless monitoring, wireless positioning system signals and ets. Using low-power dual-core 32-bit CPU, can be used as an application processor. Main frequency up to 240MHz, built-in 520 KB SRAM, external 8MB PSRAM. Support UART/SPI/I2C/PWM/ADC/DAC and other interfaces and OV2640 and OV7670 cameras with picture WiFi upload [13].

In addition, by choosing these controllers, we can provide a connection to a Wi-Fi access point, or transfer data via the Bluetooth interface. Moreover, the use of the combination of the IoT and edge computing will allow control of network security and access to the data transmission channel [14]. The presence of the SPI interface allows you to connect a transceiver module that uses "LoRa" technology or an NRF24L01 radio module to the microcontroller. Based on the NRF24L01 radio module, it is possible to organize a mini-network in which up to 6 transmitters and 1 receiver can work on one frequency. Line-of-sight communication ranges up to 100 m is provided [15]. ESP32 microcontrollers also use ESP-NOW technology – a simplified WiFi communication protocol with the transfer of short packets between devices. The ESP-NOW technology provides communication distance near 190m in conditions of non-existence of local internet network [16].

The process of formation and optimal processing of the LFM signal is not much different from the methods used in radiolocation [17]. To use the digital method of forming and processing the LFM signal, consider the mathematical representation of the signal. Analytically, a single rectangular radio pulse with LFM duration τ_c is described by the expression (1).

The law of change of the frequency of the LFM signal can be obtained by differentiating the phase of the LFM signal (1):

$$f(t) = f_c + \frac{\Delta f}{\tau_c} \cdot t . \quad (2)$$

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The impulse characteristic of the matched filter of the signal with LFM, within the limits of the signal duration τ_c has the form

$$V(t) = CU_m \times \times \cos\left(2\pi\left(f_c(t_0 - t) + \frac{\Delta f}{2\tau_c}(t_0 - t)^2\right)\right). \tag{3}$$

The law of changing the frequency of the pulse characteristic of the matched filter of the signal with LFM at $t_0 = {}^{\tau_c}\!/_2$ will have the form

$$f_V(t) = f_c + \frac{\Delta f}{2} - \frac{\Delta f}{\tau_c} t . \tag{4}$$

and within the duration of the signal will decrease linearly in time, in contrast to the frequency of the signal with LFM, which increases linearly with time.

The synthesis of the optimal filter of the LFM signal can be carried out both according to its frequency and impulse characteristics. As is known, the frequency characteristic of the optimal filter is determined by the expression

$$\dot{K}(f) = C \dot{g}^*(f) \exp\{-j2\pi f t_0\}. \tag{5}$$

The frequency spectrum of the LFM-radio pulse is given by the expression

$$\dot{g}^*(f) = \frac{U_m\sqrt{\tau_c \Delta f}}{2\Delta f} \times \times \exp\left\{-j2\pi\frac{(f - f_c)^2}{2\Delta f}\tau_c\right\}, \quad |f - f_c| \le \frac{\Delta f}{2}. \tag{6}$$

Then the frequency characteristic of the optimal filter matched to the LFM signal will be represented by the expression:

$$\dot{K}(f) = \frac{CU_m\sqrt{\tau_c \Delta f}}{2\Delta f} \times \times \exp\left\{j2\pi\left[\frac{(f - f_c)^2}{2\Delta f}\tau_c - f t_0\right]\right\}, \quad |f - f_c| \le \frac{\Delta f}{2}. \tag{7}$$

The voltage of the signal component at the output of the optimal filter at time t can be obtained using the inverse Fourier transform of the frequency spectrum of the signal at the filter output:

$$w(t) = C\int_{-\infty}^{\infty} \dot{g}(f)\,\dot{g}^*(f)\exp\{j2\pi f(t - t_0)\}df = = C\frac{\sin(\pi\Delta f(t - t_0))}{\pi\Delta f(t - t_0)}\cos(2\pi f_c(t - t_0)). \tag{8}$$

The voltage at the input and output of the optimal filter of the LFM signal is shown in Fig. 1.

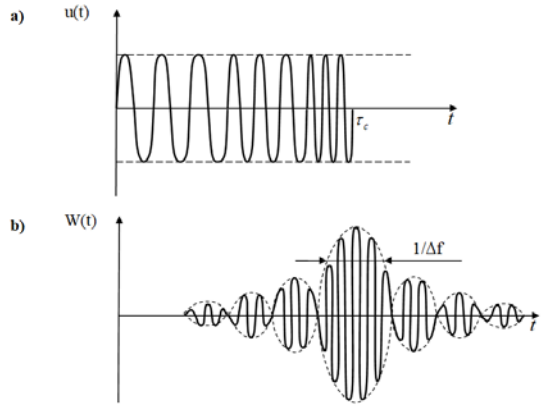

Figure 1 – Compression of the LFM signal in the optimal filter

An LFM signal is applied to the input of the filter (Fig. 1, a), and the output signal of the optimal filter (Fig. 1, b) is a harmonic oscillation $\cos(2\pi f_c t)$ with the envelope signal of the form $\sin(x/x)$. The maximum value of the output signal is reached at the moment ending of the input signal τ_c. The duration of the output pulse τ is inversely proportional to the width of the signal spectrum ${}^{1}\!/_{\Delta f}$. Since the base of the LFM signal $B = \tau_c \Delta f$, then $\tau = \frac{1}{\Delta f} = \frac{\tau_c}{B}$. Thus, the duration of the signal at the output of the optimal filter is less in base times than at its input. At the same time, the signal-to-noise ratio by the power at the output of the optimal filter will be greater than the signal-to-noise ratio by the power at its input.

4 RESULTS

A simplified structural diagram of the transceiver, which uses the PPM of the LFM signal, is shown in Fig. 2. The transmitter includes a modulator with phase-pulse modulation and the generator LFM. Since the phase-pulse modulation involves a change in the time position of the LFM pulse by a certain amount corresponding to the command number, then the modulator contains a “command-time” converter and a pulse shaper for starting the LFM generator. Since the phase-pulse modulation involves a change in the time position of the LFM pulse by a certain amount corresponding to the command number, then the modulator contains a “command-time” converter and a pulse shaper for starting the LFM generator. If a digital method of signal formation is used in the LFM generator, then the transmitter additionally includes a digital-to-analog converter (DAC), a fre-

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quency converter, a high-frequency amplifier, and a band-pass filter. The receiver consists of a high-frequency amplifier, a frequency converter, an analog-to-digital converter (ADC), a matched LFM signal filter, and a demodulator, which contains a converter “time-command”. At the same time, the PPM modulator and the LFM signal generator can be implemented on one ESP32 microcontroller. The LFM signal can be generated at an intermediate frequency and with a defined deviation value. The frequency converter will be carried out the generated signal to the frequency of the channel selected for operation. In the receiver, the selection of the required frequency channel will be carried out by changing the frequency of the local oscillator. From the output of the intermediate frequency amplifier, the signal is sent to the ADC, where it is converted to a digital form. An ADC, a matched LFM filter and a demodulator can be implemented on an ESP32CAM microcontroller. This controller also functions as a decoder for control commands coming to the flight controller.

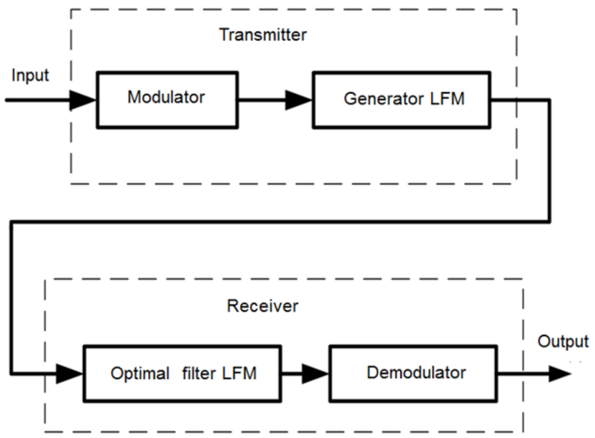

Figure 1 – Structural diagram of the receiver-transmitter

The results of mathematical modeling of the laws of change in time of the frequency of the LFM signal with a deviation of 10 kHz and the impulse characteristic of the filter matched to this signal using Excel are shown in Fig. 3. As can be seen, the LFM signal with a duration of $\tau_c = 0.1$ sec relative to the average signal frequency of 10 kHz occupies the frequency range Δf=10 kHz. Therefore, the width of the spectrum occupied by the LFM signal is determined by the frequency deviation Δf and does not depend on the duration of the signal τ_c.

The impulse characteristic of the optimal filter of the LFM signal is a mirror image of the input signal, which is evidenced by the nature of its frequency change.

Expression (1) was implemented programmatically based on the ESP-32 microcontroller. For a better visualization of the law of frequency change over time, the value of the frequency of the LFM signal variable from zero to one kHz. The voltage values of the signal, which output to the serial port of the Arduino-IDE software environment from the DAC output of the microcontroller, are shown in Fig. 4. As can be seen from the given data, the change in voltage over time at the analog output of the microcontroller is a signal with a linearly increasing frequency value within the duration of the signal, which corresponds to the analytically calculated value according to expression (1).

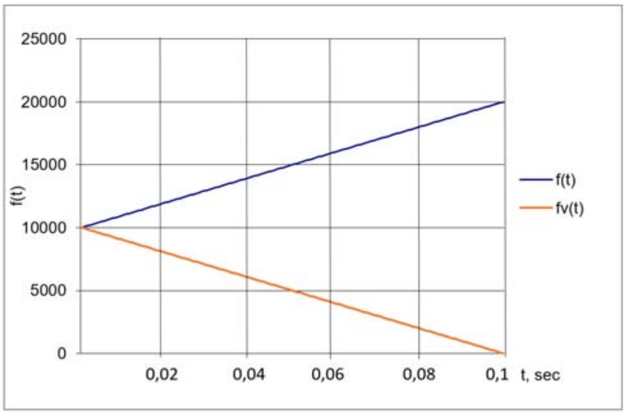

Figure 2 – Changing the frequency of the LFM signal and the impulse characteristic of the matched filter

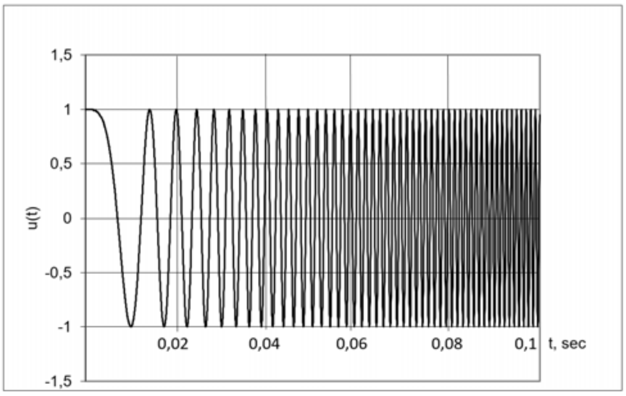

Figure 3 – Changing in time of the LFM signal

The result of the optimal processing of the LFM signal for command number two from the output of the serial port of the Arduino-IDE software environment is shown in Fig. 5. The value of the voltage at the output of the optimal processing block of the LFM signal for command number two is shown in Fig. 6. As can be seen from the given data, indeed, the duration of the signal at the output of the optimal processing block of the LFM signal is shorter than at its input. The time interval between the maximum values of the output signal of the optimal processing block is equal to 0.2 sec, which corresponds to command number two and proves the correct operation of the PPM modulator.

Fig. 7 show oscillograms that can be used to determine the operation of the remote control modem for the case of command number two. At the same time, it can be seen from the upper (violet) oscillogram that the pulse repetition interval of the LFM pulses is equal is 0.2 seconds, which corresponds to the command number two.

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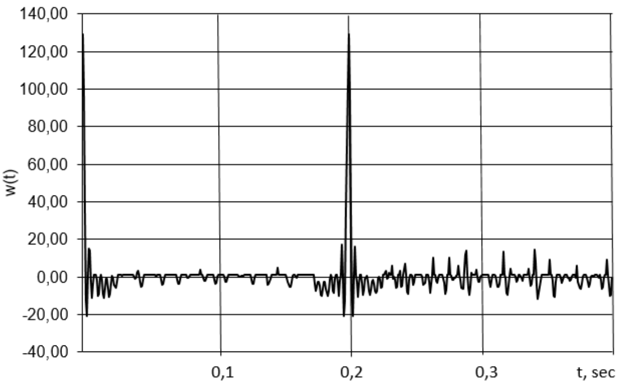

Figure 5 – The result of the optimal processing of the LFM signal for command number two

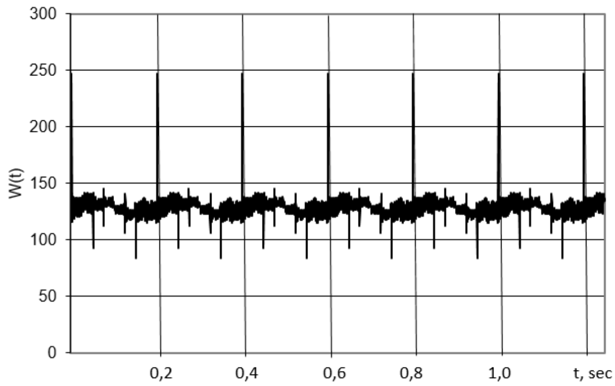

Figure 6 – The value of the voltage at the output of the optimal processing block of the LFM signal for command number two

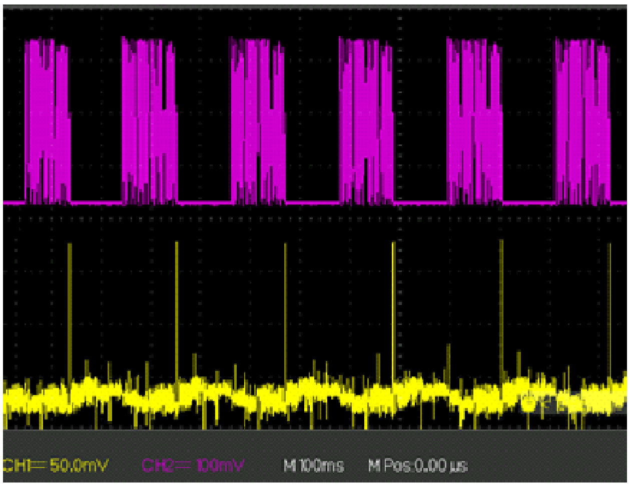

Figure 7 – The oscillograms of the voltage at the input and output of the optimal processing block of the LFM signal for command number two

The voltage at output of the optimal processing block of the LFM signal is showed to the lower (yellow) channel of the digital oscilloscope with use the second DAC of the ESP-32 microcontroller. The maximum value of the output signal is corresponds to the end of the input LFM signal. At the same time, the duration of the compressed pulse is much shorter than the duration of the LFM signal, which was equal to 0.1 sec. This corresponds to the graphs of the voltage at the output of the optimal processing block of the LFM signal shown in Fig. 6.

Testing of the modem operation was also carried out for the number one command with the minimum pulse repetition interval of the LFM signal, and the oscillograms corresponding to the conditions of transmission of the command number one are shown in Fig.8. The results of testing the low-frequency part of the wireless remote control modem for the conditions of transmission of the command number three are shown in Fig. 9.

Analysis of the given results confirms the possibility of using the proposed method of command transmission to control a moving object using a PPM of the LFM signal.

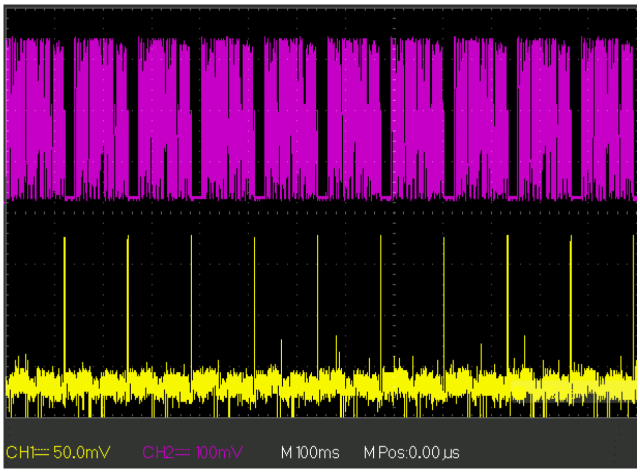

Figure 8 – The oscillograms of the voltage at the input and output of the optimal processing block of the LFM signal for command number one

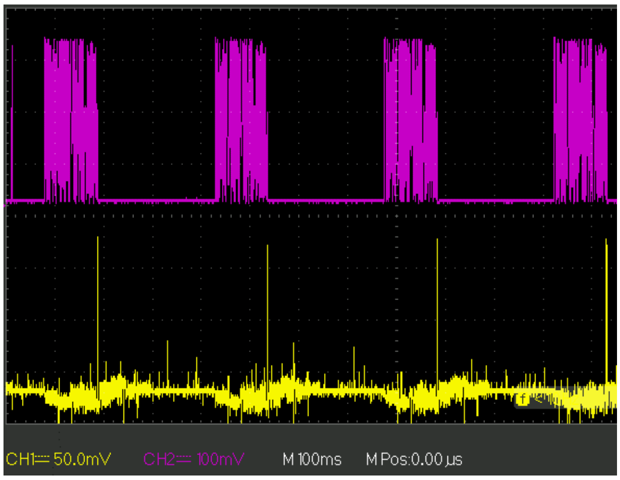

Figure 9 – The oscillograms of the voltage at the input and output of the optimal processing block of the LFM signal for command number three

Therefore, the possibility of conducting a practical test of a low-frequency part of the wireless remote control modem using an ESP32 microcontroller has been proven.

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6 DISCUSSION

The paper investigates the possibility of using a PPM of the LFM signal to transmit commands for controlling a moving object. The use of digital methods makes it possible to form and process the LFM signal with defined parameters at a reduced frequency. Transfer to the operating frequency and power amplification will provide high-frequency cascades. Thus, the wireless remote control modem of the moving object consists of the low-frequency and high-frequency parts. The low-frequency part of the modem performs PPM of the LFM signal on at a reduced frequency. Each command corresponds to the given value of the change in the time position of the LFM pulse. The duration of command transmission does not exceed one second. During this time, several LFM pulses are received, which can be used to increase the reliability of identification of the command number. However, without the development of a suitable demodulator, it is almost impossible to gain unauthorized access to the radio control channel.

Therefore, the conducted physical simulation using the ESP-32 microcontroller proved the correct operation of the PPM modulator, the generator LFM signal and the DAC of the transmitter. In the receiving part the testing were covered the ADC and the optimal processing block of the LFM signal. The practical implementation of the modem on the ESP 32 microcontroller showed that the DAC and an ACD have a rather low conversion rate. The frequency deviation of the LFM pulse does not exceed 10 kHz. Therefore, even when forming the LFM signal with an average frequency of 10 kHz, it is quite difficult to ensure the required number of transformations during the duration of the signal. This leads to slight distortions of the LFM signal at the output of the DAC of the microcontroller, which can be observed on oscillograms. However, these distortions did not significantly affect the operation of the optimal processing block of the LFM signal.

CONCLUSIONS

The scientific problem The scientific problem by the need to carry out a practical check of the signal formation and processing blocks of the wireless remote control modem by means of physical modeling using microcontrollers. The scientific novelty of obtained results is that using phase-pulse modulation of the linear-frequency modulated signal for the transmission of control commands is firstly proposed. This method of transmitting the information component, unlike the existing methods, does not require changing the parameters of the linear frequency modulated signal. The use in the receiver of optimal processing of a linear-frequency-modulated signal of sufficiently big base will allow of the wireless transmission of the commands for controlling a moving object in conditions of intentional interference.

The practical significance. Used the possibility of a PPM of the LFM signal for the wireless transmission of the commands for controlling a moving object has been proven.

Conducted a practical test of the wireless remote control modem using an ESP32 microcontroller. The results of the physical modeling of the transmitting and receiving parts of the radio modem are presented.

The direction of further research consists in the development of the high-frequency part of the modem and checking the possibility of using of the wireless transmission of the commands for controlling a moving object in conditions of intentional interference.

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ВИКОРИСТАННЯ МІКРОКОНТРОЛЕРА ESP32 ДЛЯ ФІЗИЧНОГО МОДЕЛЮВАННЯ БЕЗДРОТОВОГО МОДЕМА ДИСТАНЦІЙНОГО КЕРУВАННЯ

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АНОТАЦІЯ

Актуальність обумовлена необхідністю практичної реалізації теоретичних положень запропонованого способу бездротової передачі команд керування рухомим об’єктом в умовах навмисного втручання.

Метою роботи є практична перевірка можливості використання фазово-імпульсної модуляції лінійно-частотно модульованого сигналу для передачі команд керування шляхом фізичного моделювання з використанням мікроконтролерів.

Метод. Аналітичні розрахунки зміни в часі напруги на вході та виході пристрою оптимальної обробки лінійно-частотно модульованого сигналу проводились виключно з використанням обчислювальних можливостей мікроконтролера. Графіки змін у часі відповідних параметрів побудовані за допомогою програми Excel з використанням даних, що виводились у монітор послідовного порту програмного середовища Arduino IDE. Для контролю роботи бездротового модему передачі команд управління рухомому об’єкту використовувався цифровий осцилограф з USB-хостом.

Результати. Аналітичними розрахунками та фізичним моделюванням, з використанням сучасного мікроконтролера, доведено працездатність низькочастотної частини бездротового модему дистанційного керування з використанням фазово-імпульсної модуляції лінійно-частотно модульованого сигналу.

Висновки. Розглянуто можливість використання фазово-імпульсної модуляції лінійно-частотно модульованого сигналу для передачі команд керування. Цей спосіб передачі інформаційної складової, на відміну від існуючих способів, не потребує зміни параметрів лінійно-частотно модульованого сигналу. Використання в приймачі оптимальної обробки лінійно-частотно модульованого сигналу достатньо великої бази дозволить здійснювати бездротове передавати команд керування рухомим об’єктом в умовах навмисного втручання. Використання сучасних мікроконтролерів дозволило провести практичну перевірку працездатності низькочастотної частини бездротового модему дистанційного керування з фазово-імпульсною модуляцією лінійно-частотно модульованого сигналу шляхом фізичного моделювання.

КЛЮЧОВІ СЛОВА: бездротовий зв’язок, дистанційне керування, лінійно-частотна модуляція, фазово-імпульсна модуляція, моделювання.

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