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Wireless network of controlled energy-efficient LED lighting source

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Abstract

The development and implementation results for a branching network of controlled LED light sources with the architecture of standard IEEE 802.15.4 are presented. The network includes a physical PHY layer as a RF transceiver with low-level control mechanism and channel sublayer MAC, providing an access to the physical channel.

Keywords: Wireless network; IEEE 802.15.4 standard; Data packet; Testing; Configuration; Control; Firmware complex.

1. Introduction

Represented work continues a series of publications aimed at optimizing the light environment for human life in residential and industrial premises. The Refs. [1,2] showed the results of a comprehensive study and optimization of energy-efficient, dynamically controlled LED light sources (EDCLLS) on the basis of new lighting technologies and microelectronic LED and microelectronic base.

EDCLLS provide white-light emission with spectral-color and brightness characteristics which are able to follow a given program of variation with time.

In creating a network EDCLLS, which forms the LR-WPAN (low-rate wireless personal area network) device, the main task is to transfer relatively small amounts of data over short distances, and the network must have a minimum consumption by implementing the necessary monitoring and control schemes for solving lighting network problems.

The technology of building EDCLLS using the IEEE 802.15.4 standard with its software add-ZigBee as the base is the most promising in this case. This standard and its software describe the different levels of the classical scheme of the open systems interconnection.

IEEE 802.15.4 standard describes only two scheme lower levels: the physical (PHY) one and the channel (MAC) one, whereas the specification ZigBee is a complete set of seven levels, which set supporting the creation of networks for monitoring and controlling on the standard base.

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Standard IEEE 802.15.4, being the basis for a software upgrade [3], was a success, and many manufacturing companies are developing devices based on it. At the same time, products using ZigBee technology are under development, and a number of pilot implementations.

In the world practice, commercially available systems using ZigBee technology are few and far between. This is due to insufficient study of the basic version of the ZigBee protocol stack, that causes imposing a number of restrictions on its use, primarily, the need for steady supply of intermediate node-relayers. In addition, certification for ZigBee is not a cheap process (testing the device, a buy of a MAC range of addresses, and the like) that forces developers to save in the use of the ZigBee logo. All of the preceding determined the choice of building technology of branched EDCLLS network based on the IEEE 802.15.4 standard.

2. Architecture of IEEE 802.15.4 standard

Architecture of IEEE 802.15.4 standard [4,5] defines a stack of levels, each being responsible for one part of the standard and provides service to the above-cited level.

LR-WPAN device is the PHY level, comprising a radio frequency (RF) transceiver with low-level control mechanism, and a MAC sublayer, which provides access to a physical channel for all types of transmissions.

The physical PHY layer provides an information service and control service that performs checking functions and maintains a database of controlled objects associated with the physical layer. Information PHY service transmits and receives through radiolink of protocol data units PPDU (PHY Protocol Data Unit).

PHY in the EDCLLS network performs the following tasks:

activation and deactivation of the radiotransceiver;
a choice of a channel frequency;
data reception and transmission;

the idle channel assessment CCA (clear channel assessment) for access mechanisms CSMA-CA (carrier sense multiple access with collision avoidance).

Radio-equipment operates on an unlicensed frequency band of 2400.0–2483.5 MHz permitted to use in the Russian Federation.

O-QPSK (offset-quadrature phase-shift keying) modulation is used, and direct extension of the DSSS spectrum (direct sequence spread spectrum is a method of forming a broadband RF-signal, wherein the original binary signal is converted into a pseudo-random sequence used for modulating the carrier frequency).

This allows to reach low values of the signal-to-noise and signal-to-interference ratios. The main characteristics of the method are the following: a frequency is 2.00 Mchip/s, the data transmission rate is 250 kbit/s, the frequency of symbols is 62.5×10^4 symbols/s, symbols 16-ary are orthogonal; a mean channel frequency (F_m) is

$$F_m = 2405 + 5(k - 11) \text{ MHz},$$

where k is a channel number, $k = 11–26$.

Low signal-to-noise ratio allows the standard signals to coexist successfully with alternative radiation sources at a common frequency (Wi-Fi, Bluetooth). The standard also provides (15, 16, 21, 22) channels which do not overlap in frequency with the competitors, thereby implementing the network even in the immediate vicinity of the very powerful radiation sources.

An important standard condition is the fact that the radio link being in the active mode is half-duplex and the in-time access is possible only to one channel. For example, the device wire-tapped by channel 15 will not be done by channels from 11 to 14 and from 16 to 26.

The MAC sublayer provides informational MAC-service and a service of control MAC-level; it provides an interface of control network and supports database on control objects of the MAC sublayer. Informational MAC service provides reception and transmission of protocol blocks of the MAC level (MPDU) via PHY informational service.

A data transfer analyzer is related in a unique fashion to the network topology. The ‘Star’ topology is used in the EDCLLS network (see Ref. [2]), making possible two types of communication for data transfer: first, to the coordinator (personal computer (PC) or the remotely controlled desk (RCD), which informs the network device (EDCLLS); second, from the coordinator to the network device.

EDCLLS refer to a PAN network without beacons support. In this network, the informational frame is sent to the coordinator using direct reduction scheme CSMA-CA.

3. Format of the data frame

The structure of the data frame formed by the upper layers of the network hierarchy is shown in Fig. 1.

The data field (data payload) is transmitted to the MAC sublayer and is considered as a service data unit MAC MSDU (MAC service data unit). MAC data field is prefixed as MHR (MAC header), followed by

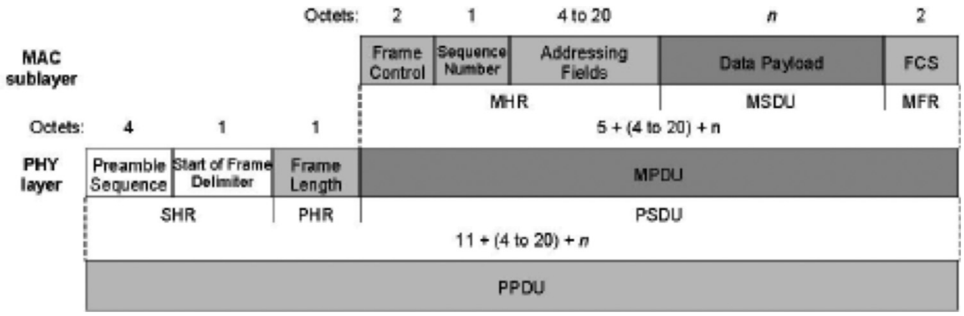

Fig. 1. The packet of data and of physical layer frames.

Octets: 2	1	0/2	0/2/8	0/2	0/2/8	variable	2
Frame control	Sequence number	Destination PAN identifier	Destination address	Source PAN identifier	Source address	Frame payload	FCS
		Addressing fields					
MHR						MAC payload	MFR

Fig. 2. The general format of the MAC frame.

Bits: 0–2	3	4	5	6	7–9	10–11	12–13	14–15
Frame type	Security enabled	Frame pending	Ack. request	Intra-PAN	Reserved	Dest. addressing mode	Reserved	Source addressing mode

Fig. 3. The field format of the frame control (see explanations in the text).

MFR (MAC footer). MHR contains a frame control field (frame control), an ordinal of data DSN (data sequence number), address fields (addressing fields). MHR, MSDU and MFR form a field of the MAC frame MPDU (MAC protocol data unit). MPDU is transmitted to the physical layer in a PSDU (PHY service data unit), which becomes a data field PHY. PSDU has a prefix SHR (synchronization header), containing the preamble sequence (preamble sequence), field SFD (start of frame delimiter) and field PHR (PHY header), which receives the length of the data field in octets PHY (frame length). Fields SHR, PHR and PSDU form a package PHY PPDU (PHY protocol data unit).

4. PPDU format

Each PPDU packet includes the following elements:

SHR synchronization header, which enables the receiving device to synchronize with the bit stream;

PHY header (PHR, frame length), which contains data on the frame length;

PSDU data field of variable length, which carries a frame of the MAC sublayer MPDU.

The length of the preamble field is 4 octets. SFD field length for all PHY carries the code of 11100101. PHR frame length is 7 bits, and 1 bit being reserved.

Hence, the data format at the level of physical medium of EDCLLS network is the following:

a preamble is 4 bytes 0×00;
a starting byte is $0 \times A7$;
a frame length is 1 byte (including the checksum CRC16);
data should contain no more than 127 bytes.

The general format of the MAC frame is formed by fields MHR, MAC payload data field and MFR (Fig. 2).

The MHR fields follow in a fixed order, but the addressing fields may be absent in some frames.

Frame control field (its format is shown in Fig. 3) has 2 octets and contains information identifying the type of frame (frame type), the address fields destination addressing mode and source addressing mode, and also other control flags.

Security issues in the EDCLLS network are not considered, since the requirement of low cost leads to limited processing power and random access memory. The safety is connected with a redundancy in software and is typically implemented at higher network layers.

Frame type subfield has 3 bits ($b2$, $b1$, $b0$) and takes on a value of 001-Data.

Security enabled subfield has a length of 1 bit and is set to zero.

Frame pending subfield contains zero on transmission and ignored on receipt.

Acknowledgment request subfield contains zero, and the recipient is not to send an acknowledgment.

Intra-PAN subfield is for compression of PAN-ID; it is equal to zero, and in the presence of a sender and a recipient addresses the data frame will contain the fields of PAN identifiers of both the sender and recipient (source PAN identifier and destination PAN identifier).

Destination addressing mode, source addressing mode. These subfields have 2 bits in length each and contain values of $b1$, $b2$–10 describing "the address field contains a 16-bit short address."

If all of the above-mentioned subfields contain zeros, and the frame type subfield takes a value of 001 (data), destination addressing mode subfield and source addressing mode subfield shall be nonzero. This is an indication that the frame comes from the PAN coordinator with identifiers being in the field of the PAN sender's identifier and in the field of the PAN identifier of the destination.

Sequence number field (see Fig. 2) measures 1 octet and specifies the ordinal of the DSN frame.

Destination PAN identifier field measures 2 octets and characterizes the unique PAN identifier of the frame recipient. The value of $0 \times$ FFFF in the given field signifies the broadcast PAN-ID which is heard by all devices. This field is included in the MAC-frame if destination addressing mode subfield of the frame control field is not equal to zero.

Destination address field is of 2 octets in accordance with the value in destination addressing mode subfield of the frame control field. It characterizes the address of the intended recipient of the frame. Sixteen-bit value of this field is $0 \times$ FFFF and means broadcast short address perceived by all devices. This field is included in the MAC-frame if the subfield of the destination address mode of the frame control field is non-zero.

Source PAN identifier field of a sender is 2 octets long and characterizes the unique identifier for PAN-device which has sent the frame. This field is to be included in the MAC-frame if the source addressing mode and the Intra-PAN subfields are non-zero and equal to zero in the frame control field, respectively.

Source address field is the sender's address of 2 octets, in accordance with the value of the source addressing mode subfield in the frame control field and determines the address of the frame source. This field is included in the MAC-frame if the source addressing mode subfield is not equal to zero.

Frame payload. This is a field of the frame data (see Fig. 2); it is variable and includes information for certain types of the frame.

5. Practical implementation of the EDCLLS network

The wireless EDCLLS network contains the following components:

- terminal devices (lamps), LED light sources playing their role;
- remotely controlled desk (RCD), which coordinates the network and controls its work in all modes;

PC that also serves as the network coordinator when setting up the network and some modes of its work.

The EDCLLS network itself includes the following devices:

- power supply for the standby mode;
- the main power supply of 40 W;
- LED drivers power management;
- LED bars with nine series-connected LEDs.
- Depending on the requirements to the white light quality, the number of bars of diodes varies from 4 to 6.

An analysis of all transmission indices shows that RGBA and RGBW four-colored versions of color mixing provide satisfactory results [2]. The set of five spectral bands of semiconductor LEDs is optimal for the synthesis of high-quality white light over a wide temperature range $T_c = 2500$–10,000 K.

The choice of five-colored LED module is due to the quest for raising and aligning the partial indices of color rendering for each color temperature T_c and emphasizing certain colors for specific lighting conditions (microscopy, facilities for surgery and museums).

The optical scheme with elements providing the necessary radiation pattern and the requirements to the lamp cooling determine its structure: a standard mechanical unit being a radiator with a fan, their site being the location place for printed circuit boards, optical components, as well as the EDCLLS body parts. In addition to these functions, the radiator with a fan stabilizes the thermal regime of EDCLLS network.

The EDCLLS software allows for emergency turning-off when the radiator temperature exceeds a value, specified by operating conditions, and does for regulation of the fan rotational speed (if necessary).

RCD is designed as a unit being inserted into an AC outlet, with a color TFT-display (diagonal size is 3.5 in.) and a keyboard consisting of six buttons. RCD provides a discrete specifying the color temperature, brightness of each LED array, the mode or time of a day to change it. The microcontroller incorporates a quartz watch.

Remote control must ensure the EDCLLS at a distance up to 35 m. Data transmission range of wireless network is determined by the receiver sensitivity, the transmitter power and the presence of interference (obstacles, including walls, and other sources of signal strength).

Circuitry and specifications of the RCD RF-channel and controlling the EDCLLS microcontroller are completely identical, due to the use of the device ZigBit 2.4 GHz Single chip Wireless Module ATZB-S1-256-3-0-C [6, 7], which supports the standard IEEE 802.15.4.

The high sensitivity of the receiver (−97 dBm at the error probability PER = 1%) and optimal output power of the transmitter (+3 dBm) provide a unique link budget (up to 100.6 dB). The effective range of the radio channel in the open space in the line of direct sight, at the location of the transceiver at a height of 0.5 m from the ground level is 170–570 m.

Various combinations of orientation (polarization) of the transmitter and receiver and special conditions with minimal or full absence of interference from other sources are supposed in this case. Actual operating conditions give rise to multi-path reflections from obstacles, interference and other factors, which significantly reduce the range of the radio channel.

The RCD power is carried out from the mains with the power consumption in the “programming” mode being no more than 5 W, and in operation mode – 0.5 W.

Since the EDCLLS network control with remote control is associated with non-stop operation, the reduction of power consumption in the standby mode is actual.

The problem is solved through a power supply unit developed for a transmitter with a microcontroller both for the RCD and the EDCLLS; the latter in the reception mode consumes 60–80 mW, and in the standby mode – (1–5) μW.

Low values of energy consumption due to small currents of microcontroller ATZB-S1-256-3-0-C: they are 9.6 mA, 16.4 mA and 0.6 μA in receive, transmission and standby modes, respectively.

The AC/DC converter of the RCD is similar to the standby AC/DC one of the EDCLLS and made on a UP-LNK574 chip, provides ultralow consumption remote control for day and night operation.

In the EDCLLS network, three types of short addresses are used; they are as follows: an individual factory one, a broadcast one and a multicast one.

Describing the transmitted messages in the EDCLLS network is given below.

Search for devices of the network. Network coordinator (PC) sends a request with a broadcast destination address (with ID PAN = 0 × FFFF and device address 0 × FFFF). The source address (PC) may be anything. All the EDCLLSes receiving a request, send a data packet to the network coordinator (PC) indicating a network identifier (PAN) and individual factory the EDCLLS address. The transmission is carried out by domainless mechanism CSMA-CA. As a search result is a table of devices lying in the zone of a radio accessibility.

Transmission of information on control. The network coordinator (PC) transmits the information connected with the EDCLLS control to any address obtained from the table. The work control is carried out visually (without confirmation).

Connection of the device to the group. Each device having received at its command to connect the factory to the group, stores the network identifier (PAN PC).

The transfer of the controlling information to a multicast address. This transfer is made at 0 × FFFE address for all devices with the selected network ID group (without confirmation). Thus, the number of possible groups of the independently controlled EDCLLS is 65534 (excluding addresses 0 × 0000 and 0 × FFFF).

6. Software of the EDCLLS network

Software network allows for realization of the following modes:

control, possible with the RCD, with an extensive network of the EDCLLS over the RF channel in a round-daily power saving mode;

programming the unique serial address for each device to form a network in operation (at the stage of manufacturing the RCD and the EDCLLS);

the EDCLLS testing and the network setting from a PC, the RCD being replaced by a PC with USB-adapter made in firm Atmel ATZB-X-233- USB;

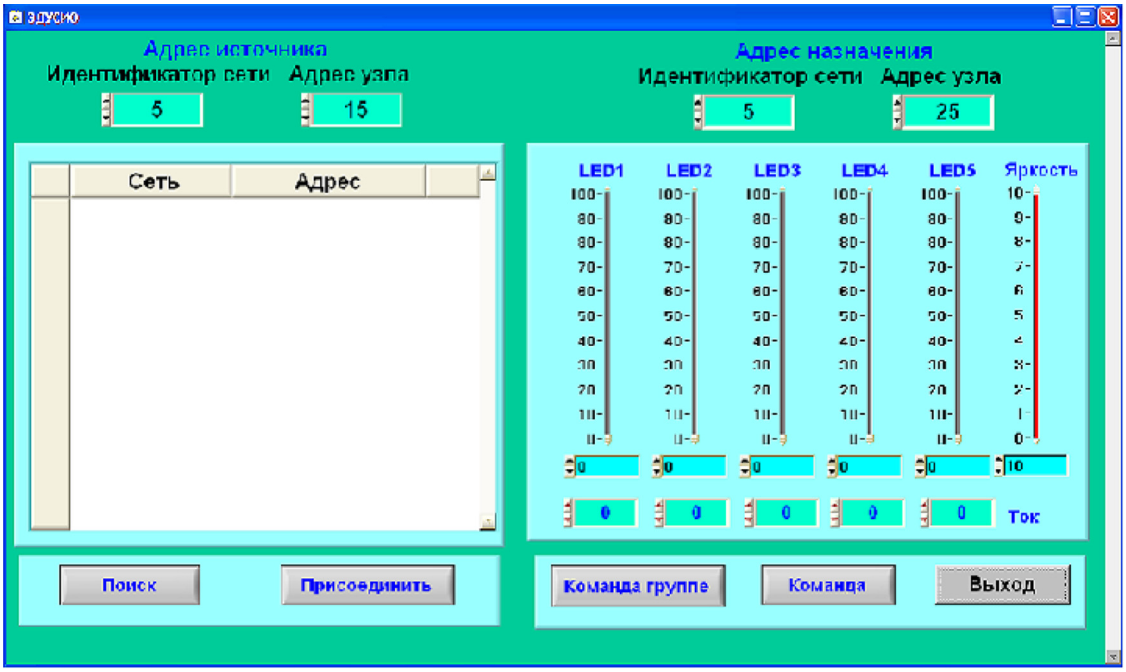

Fig. 4. The main window of the program PC-Net; (LED1–LED5) are five lines of LEDs.

programming working modes and installing the program in the RCD, with connection of the PC via the adapter ATZB-X-233-USB.

The software includes a specific set of programs. A list of them is as follows:

1. The EDCLLS control – “RGB_Lamp.c”.
2. The RCD control – “PDU.c” (PDU corresponds RCD).
3. The control of USB-bridge – radiochannel – “Bridge_USB.c”.
4. Formation of the file serial number device – “PC_Address.exe”.
5. Formation and setting the EDCLLS network – “PC_Net.exe”.
6. Formation of modes of operating the EDCLLS and recording them in the RCD “PC_ PDU.exe”

Hardware and software system designed to provide collaborative PC, the EDCLLS and the RCD for their testing, configuration and management, as well as setting up the network control.

Control program “PC_ PDU.exe”, “PC_Address.exe” and “PC_ PDU.exe” designed to work on PC and developed in C language in the Measurement Studio Lab Windows/CVI 2013 made by the company National Instruments.

Each program is delivered to directories, respectively cvidistkit_PC_PDU, cvidistkit_PC_Address and cvidistkit_PC_Net. Programs install on setup.exe. program starting.

7. Working with the program PC_Net

The PC and ATZB-X-233-USB adapter are used for work. After selecting the desired COM port the main screen appears (Fig. 4), it displays the sender’s address (the computer’s) and destination (EDCLLS), as well as the network ID and the node address.

With the EDCLLS being on (in the “search” mode, the left window) a table of senders answered the “search” appears; they sent their network characteristics: a 16-bit address of the network to which they are attached and a 16-bit unique serial address.

The network and device address are displayed as 0 × 0001 and 0 × 1002. All EDCLLS addresses start with 0 × 1000, the remote control do with 0 × 4000. In deciding on a desired device the network ID and the address of the selected device are to appear in the destination address. In the "Command" mode, the PWM value and a current of each LED bar are set (the value of network ID and the source address do not matter).

On combining EDCLLS in a group all EDCLLS have factory address and execute commands on the multi-

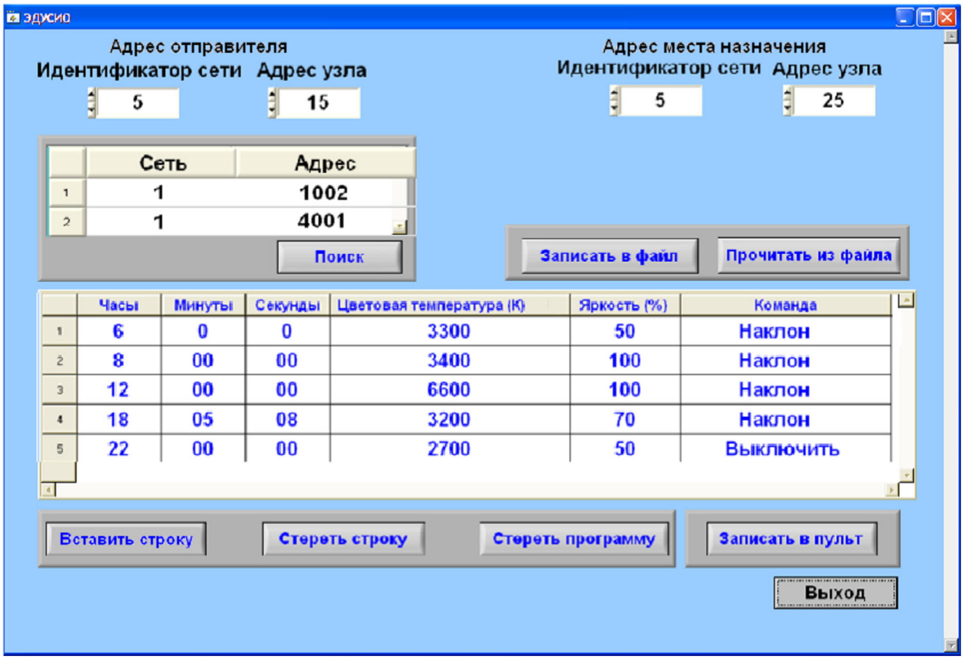

Fig. 5. The main window of the program.

cast address 0 × FFFE and on the selected network address. To attach EDCLLS to the group one must select EDCLLS (PANi = 0 × 0001, Ai – factory), set the desired address group (PAN-group) call the command "Connect" in the network address of the sender ID. At equality of the network ID and the source address specified group, all EDCLLS will simultaneously execute commands in the "Command to group" mode, while the "Command" mode remaining the same.

8. Working with the PC_PDU program

The program PC_PDU is designed to control EDCLLS and is to be recorded in the remote control using the PC and the ATZB-X-233-USB adapter. After selecting the appropriate COM port the interface of the main window appears (see Fig. 5).

The program allows a user to change the data in the cells of the table where the ranges of the following physical quantities are given (see Fig. 5):

time (hours, minutes, seconds); color temperature (from 2500 to 10,000 K with spacing of 200 K);
brightness (from 0 to 100%).

The cells "Team" take three options:

off;
slope (changing in the mode parameter from this line to the next one goes on continuously);
level (changing in the mode parameter of the given string to the next one does not occur, when the time of the next line comes the mode changes abruptly).

When recording a program in the remote control, the last must be in “programming” mode. In the “search” mode the first line corresponds to EDCLLS, and the second one does to the remote control (the address begins with 0 × 4000).

When a user marks a second line the addresses of remote control will rewritten to destination addresses. In the “Write to console” mode (see Fig. 5), the program will appear on the screen of the remote control. The program is stored in the remote control in the volatile memory, and when the power turns on the remote control is not erased.

9. Working with the program PC_Address

Sixteen-digit unique address (for EDCLLS the rang is from 0 × 1001 to 0 × 3FFF, for the remote control it is from 0 × 4001 to 0 × 4FFF) in the “New File” mode is placed in the file XXXX.hex. Address record into the microcontroller is carried out in the package design Atmel Studio 6.2 via Atmel-ICE adapter from Atmel firm in the user memory area and a signature does not change when erasing the program memory.

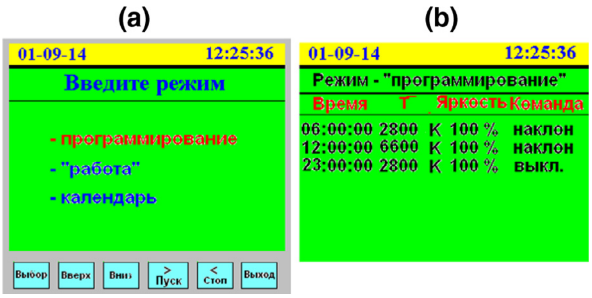

Fig. 6. The remote control screen with the original interface (a) and in the programming mode (b).

10. Using the desk of the remote control

The remote control interface is shown in Fig. 6. The date is displayed in the upper left corner, the current time of the internal clock is in the right one. There are six buttons at the bottom of the console (Fig. 6a). The remote control provides three operation modes of the network: “programming”, “work” and “calendar”, in the “work” mode, the time, temperature, brightness and the value of the command being executed (Fig. 6b).

11. Summary

The present article focuses on the practical implementation of an extensive wireless network of energy-efficient LED light sources (EDCLLS) based on the standard IEEE 802.15.4, which provides a service packet data of physical layer PHY and channel MAC-sublayer. Developed software and hardware complex provide testing, configuration, and control the network in different modes. Practical recommendations are given for the operation of the EDCLLS network. The proposed development provides new opportunities to create an enabling environment for human light, which has a positive effect on its functional state.

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References

[1] A.V. Aladov, V.N. Aladov, V.P. Valyukhov, A.L. Zakgeim, A.F. Tsatsulnikov, Svetoekologiya i novye tekhnologii osveshcheniya (Light ergonomics and new lighting technologies), Arkhit. i stroit. nauk. 1, 2 (18, 19) (2014) 2–5.

[2] A.V. Aladov, V.P. Valyukhov, A.L. Zakgeim, A.E Chernyakov, A.F. Tsatsulnikov, Type LED dynamically controlled light sources for novel lighting technology, St. Petersburg State Polytech. Univ. J.: Phys. Math. 4 (206) (2014) 38–47.

[3] E. Baranova, IEEE 802.15.4 i ego programmnaya nadstroika ZigBee (IEEE 802.15.4 and ZigBee specification), 2008. Available at: www.telemultimedia.ru/art.php/?id=292.

[4] IEEE 802.15. 4 Part 15.4. Wireless medium access control (MAC) and physical layer (PHY) specification for low-rate wireless personal area networks (WPANs), 2003. Available at: user.engineering.uiowa/~mcover/lab/802.15.4-2003.pdf.

[5] Yu. Semenov, 4.1.8.7 Besprovodnye seti ZigBee i IEEE 802.15.4 (4.1.8.7 wireless ZigBee and IEEE 802.15.4 networks). Available at: http://book.itep.ru/4/41/zigbee.htm.

[6] ZigBee Specification. Document 053474r20. Available at: http://www.zigbee.org/en/members_area/documents/ZigBee Specifications/1.Zig-Bee%20Specification/docs-05-3474-20-0csg-zigbee-specification.pdf.

[7] Atmel ZigBit 2.4 GHz single chip wireless module ATZB-S1-256-3-0C [Datasheet]. Available at: http://www.atmel.com/images/atmel-42191-wireless-zigbit-atzb-s1-256-3-0-c_datasheet.pdf.