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DEVELOPMENT OF DYNAMICALLY OPTIMIZED WIRELESS TRANSMISSION SYSTEM FOR WIRELESS SENSOR NETWORKS IN HIGH-RISE APARTMENT BUILDING HEATING SYSTEMS

V. Isakovs[1], K. Kondratjevs[2], N. Kunicina[3], B. Freliha[4], A. Zabasta[5]

[1,4]Kipsala-Zunds Ltd, 15 Matrozu Str., Riga, LV-1048, LATVIA
[2,3,5]Riga Technical University, Faculty of Power and Electrical Engineering, Institute of Industrial Electronics and Electrical Engineering,
12-1 Azenes Str., office 503, Riga, LV-1048, LATVIA
e-mail: Anatolijs.Zabasta@rtu.lv

Smart meters will be at the centre of the integrated solutions, including interaction with other networks in the next decade. The developed solution for multi-apartment building ventilation and heating parameter monitoring aims to increase energy efficiency and optimal control of the existing system. Dynamic control of heat and ventilation systems, heat loss detection, calculation and mitigation, and individual heat energy accounting are difficult tasks to accomplish. This article deals with the data transmission system using battery powered ISM band radio transmitters. The temperature measurement sensors with cumulative temperature reading are used as sensor part for this solution. The offered approach to monitoring system is used for overall building and individual apartment monitoring. Data coding and antenna designs are explained for this particular application.

Keywords: *apartment heating and ventilation, cumulative temperature, sensors, system monitoring, temperature measurements, wireless sensor systems.*

1. INTRODUCTION

The urbanization challenges imposed by an infrastructure dynamic control are complex and, therefore, innovative, holistic and integrative solutions are needed. According to the Smart Cities and Communities European Innovation Partnership (EIP) SET-Plan, the development of a new generation of low carbon technologies, with a focus, among other things, on the competitiveness of new technologies relating to renewable energy, energy storage, and sustainability of energy networks needs to be implemented in the next decade. Cities will have a major role to play in monitoring and reducing greenhouse gas (GHG) emissions and mitigating climate change as well as air pollution, since they are closely linked. ‘Smart cities’ are the best, and arguably only, option to delink a high quality of life with high resource consumption, and to reduce the corresponding pollution. To monitor older multi-apartment buildings, it is planned to use a modern, remote-controlled, wireless solution, developed and produced in Latvia.

In previous paper [1], the upgrading of the DH (district heating) system through installing WSNs (wireless sensor networks), a technology, by which to monitor and control quality operation of the DH system, will lead to more effective use of thermal energy, enabling also the provision of quality customer services. The use of WSNs offers improvements of service quality by providing critical infrastructure information in timely and stated amounts. Over the last decades, the use of WSN systems to enable the quality monitoring of heat production and supply process has been widely discussed. As the DH is an efficient tool to monitor heat supply at infrastructure level, this research aims to offer the WSN solution for individual multi-apartment building maintenance in terms of heat and ventilation automation.

The developed smart solutions allow for online control of building ventilation parameters. According to the information of the European Technology Platform on Renewable Heating and Cooling, within the next decade heating and cooling systems will become increasingly integrated. Smart meters will be at the centre of the integrated solutions, including interaction with other networks (ICT, power supply, water distribution networks, etc.). Smart meters are expected to facilitate this process by mutual recognition of collected data from different and technically incompatible networks.

The building automation system is based on the concept of building management system (BMS). Generally, the BMS opens an opportunity to reduce electricity usage, to lower operating and maintenance costs, to reduce human errors, to decrease fault repair and problem resolution time, and to improve microclimate inside premises. The application of programmable logical controllers (PLCs) as well as SCADA system allows automatizing the building management process, transmitting data between connected devices, and implementing the building management system.

Future development of sensors and other BMS compatible solutions will take place in order to accomplish the following tasks:

- To explore a solution to comfortable building management process and to define system functions; to explore devices with the opportunity to communicate with the main station, to choose the most suitable solution and create the BMS.
- To develop new modular metering data processing system; to allow an in-depth analysis of the real time data by accessing the measurement devices and to optimise data transmission and analysis methods, by allowing the introduction and co-existence of new device types and data formats and variations of installed device parameters; the balancing of demand – supply on a building level and use of a building automation system will bring 10 % energy saving, in combination with new building materials and technologies, balancing with infrastructure – central water/ electricity supply will bring 15 % savings.
- To use a modular BMS compatible wireless sensor system for cooling management: high-efficiency central air conditioner, high-efficiency room air conditioner, displacement ventilation, etc. will bring 10 % energy saving during the heating season.

- To use a modular BMS compatible wireless sensor system for heating management: the central district heating system transmits hot water or steam from a central heat plant to customers. Once the hot water is transported to the customer, a maximum amount of energy per volume of water should be extracted and used for heating purposes, such as hot tap water and space heating control will bring 10 % energy saving during the heating season.

2. SYSTEM DESCRIPTION

A typical sensor network for the building management system consists of many separate devices (sensors with radio modules), which can be distributed all over the building, as well as a data concentrator or even two for a building. The reading devices transmit the obtained values to the concentrator, which in turn sends them via the Internet to a database.

The radio module of the measuring devices is a small form factor (approx. 7 x 6 cm) and can be easily fixed on a wall or in any other place in the building, where measurements have to be obtained.

This makes it possible to acquire a very wide range of information from very different parts of the building. The measurements can be carried out in rooms (by windows, by inside or outside walls, at a floor or ceiling level), technical premises (cellar, attic), ventilation shafts, etc. This makes it possible to monitor a variety of parameters: the spatial distribution and changes in time of air temperature, humidity and possibly also CO_2 level in any type of room (a living room, lecture hall, office etc.). It also allows obtaining:

1. The distribution and changes in time of temperature of heat carrier in the heating system (temperature measurements on the pipe surface);
2. The temperature and consumption of hot water.

The installation would be carried out in the following steps:

1. Preparation of the sensor system for each building (manufacturing and testing the devices) and adaptation of the sensor system for certain rooms or groups of rooms (living rooms in a dormitory and lecture or meeting halls in public buildings);
2. Installation of the devices in the selected places.

The number of measurement points in each building can reach 1,000, which means that approximately 4,000 points could be monitored during the trial deployment.

This is a typical system used for the MBS. In the following chapters, the authors describe in detail system elements, which were developed and tested: firstly, the transmission system architecture, and secondly, the data format and coding system.

3. TRANSMISSION SYSTEM ARCHITECTURE

For signal reception inside multi-apartment buildings, it is needed to optimise the signal reception from the temperature sensors. As experience shows, traditional omnidirectional antennas used for ISM RF [2] transmission range are effective in the areas of 1–3 floor building; however, in the multi-storey building area, due to attenuation caused by concrete walls and floor panels, omnidirectional antennas are not so effective [3]. As a traditional solution, signal repeaters may be used; however, the application of additional equipment increases wireless network costs [4]. The authors conducted research on the antenna effectiveness within the project "Transmitters and Sensors for Remote Usability Study of the Measurement of Apartment Buildings at High Transmitter Density".

A transmission system has the best performance when the polarisation of the transmitter and the receiver antenna are identical to each other. Circular polarisation at one end and linear polarisation at the other give 3 dB loss compared to the ideal case. If both antennas are linearly polarised but 90° turned to each other, theoretically no power is received. The same phenomenon happens if one antenna is right-hand circularly polarised and the other one left-hand circularly polarised. In an indoor environment, reflections in the transmission path may change the polarisation, which makes the polarisation of the received wave difficult to predict. If one of the antennas is portable, we have to make sure that it works in any position. Circular polarisation at one end and linear polarisation at the other end result in a principal loss of 3 dB, but the case of a total blackout is avoided, where no power is received.

For this purpose, we will use the Friis transmission equation for free space to model the application specific case. Basically, we will calculate distance R in metres between two ports or antennas with known parameters: gain dBi and return losses or matching, typically for our antennas it is15 dB [5].

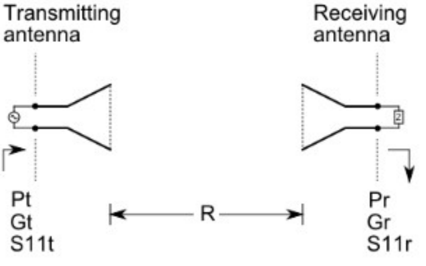

Fig. 1. Transmitting and receiving nodes Tx /Rx.

A modified form of the basic Friis equation allows taking into account all needed system factors, including antenna mismatch, absorption in the propagation, cable losses, etc.

$$P_r = G_t G_r \left(\frac{\lambda}{4\pi R} \right) \left(1 - \left| \Gamma_r \right|^2 \right) P_t , \tag{1}$$

where:

G_t – the gain of the transmitting antenna;

G_r – the gain of the receiving antenna;

R – the distance between the antennas;

P_t – the power delivered to the transmitting antenna;

Γ_r – the reflection coefficients of the receiving antenna.

Friis transmission equation, where: $S_{11t} = 20\log|\Gamma_t|$

S_{11} (reflection coefficients on a logarithmic scale) = -15 dB; F=868 MHz;

Tx power =20 dBm;

Rx=- 95 dBm;

Rx antenna gain 7.5 dBi;

Tx antenna gain -3 dBi.

After calculation, we have R=25 km. This is for perfect conditions, in the free space. In reality, signal transmission is affected by floors, which typically has additional attenuation 10–15 dB (1;2) per floor. For example, propagation calculation in a five-floor building: from a link budget 50 dB (5 x 10 dB) should be minus and finally Rx should be -35 dBm. In addition, after calculation we have distance R=25 m [6].

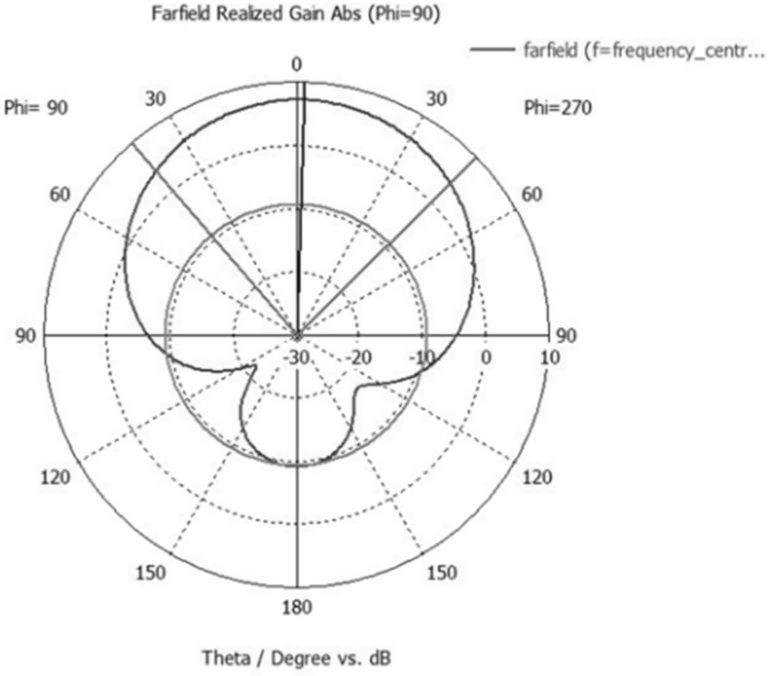

Fig. 2. Directional antenna design for use in multi-apartment building attics and basement for heating temperature monitoring of apartments.

In fact, there are many uncertainty factors, which directly influence signal propagation: moisture of materials, wave polarisation changes due to reflections, multipath propagation, and interference from other networks, which can significantly reduce the transmission distance. Therefore, for such kind of links a conclusion is to use devices with max EIRP (equivalent isotropically radiated power). For sensors, tactically there are limitations: by power (20 dBm max) and antenna dimension – gain. Therefore, depending on the available place it is possible to use effective patch antennas with gain up to 15 dBm.

For this purpose, a circular polarised antenna design is suggested (Figs. 2, 3) for directional signal reception. The mechanical design provides benefits compared to an equivalent of 3–4 element Yagi antenna design: more compact, suitable for integration with receiving hardware into a mono-body design. The parameters of antenna are: frequency = 0.87 Hz; main lobe magnitude = 7.14 dB; main lobe direction = 2.0 deg.; angular width (3 dB) = 85.7 deg.; side lobe level = -16.4 dB.

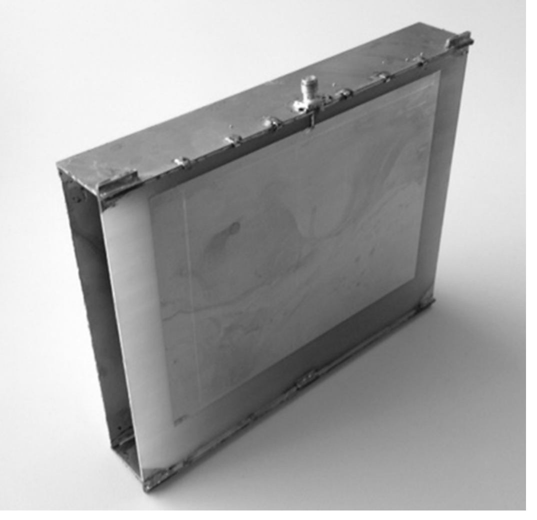

Fig. 3. Antenna trial.

The installation consists of two gateways located in the attic and basement of each building, using a custom-made 85 degree lobe directional antenna that receives the values transmitted by the meter. Dense apartment installations (Fig. 4) typical of Latvia cause multipath propagation that increases the collision probability, but also improves message reception from weak signal sources from the centre of the building.

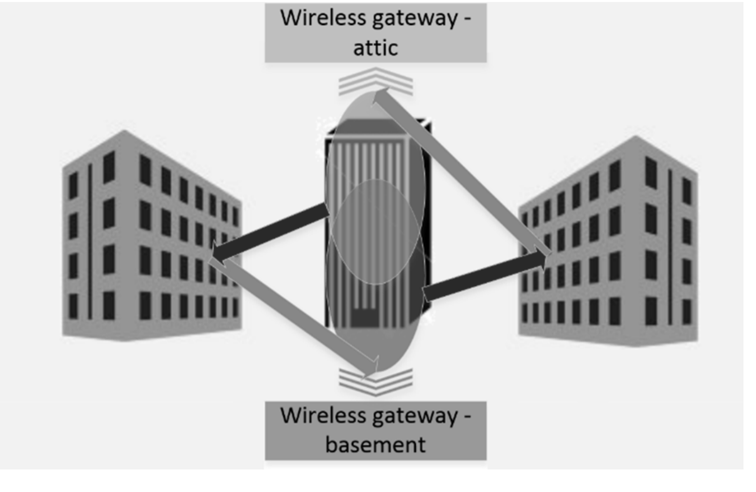

Fig. 4. Layout of wireless transmission paths in a dense multi-apartment building scenario.

4. DATA FORMAT AND CODING

The existing systems used for data transmission in the BMS under the conditions of high-density installations and multi-storey buildings suffer from collisions, multipath data transmission and, as a result, from traffic overload [7]. The authors of the research offer the cumulative method of data coding system, which is more effective under the conditions of high-density installations in comparison with instantaneous readout coding.

Experimental evaluation of the radio transmitter using GFSK modulation and Manchester coding at a data rate of 4800 bps has shown minimum packet loss using a preamble of 6 bytes and 2 synchronization bytes. The packet length has been kept minimal to include layer definitions and various sensor data parameters with future compatibility of multi-packet messages. The data block (Fig. 5) consists of 12 bytes for static minimum length telegrams – in this example, metering data would then contain 4 bytes.

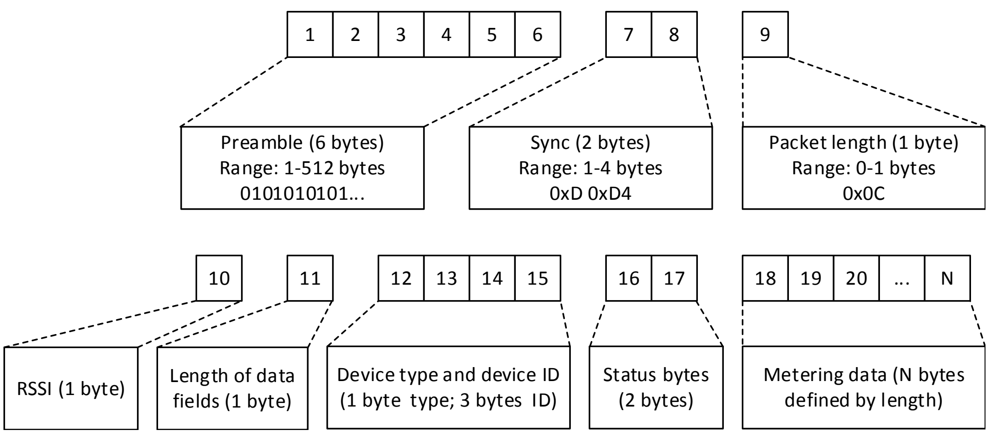

Fig. 5. Layout of wireless transmission paths in a dense multi-apartment building scenario.

Bytes 12–15 are used for device identification, where the first byte is the device type – the remaining three bytes are serial number coding with hardware revision information.

Fields: 1), 2) date and time without a year – stored from the internal clock, needed to solve and offline data reception using a disconnected gateway or in walk/drive-by scenarios. The time offset can be then corrected from any in sync telegram received during this period. 3) RSSI – the received signal strength indication (for the first telegram 8D = 141). 4) Telegram length (for the first telegram the data field should contain 10 = 16 bytes. 5) Device code and ID field. 6) Status field – where the second byte is the BCD (binary-coded decimal) decoded battery voltage of 3.2 V. 7) 16 byte data field for measurement values.

Status field coding: the 6th field contains the status information. The status information field consists of 2 bytes (1st byte – Status 1; 2nd byte – Status 2), where bit groups contain coded status information needed for equipment diagnostics and complex message transmission scenarios.

	Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0
Status 1	Reserved				Transmitted packet number 0..15			
Status 2	Repeater index		Battery BCD code					
	0..3		0..3 V		0..9 V/10			

Fig. 6. Status field coding.

Battery voltage represents the remaining charge; this voltage is stored using binary-coded decimals. In computing and electronic systems, a BCD is a class of binary encoding of decimal numbers, where each decimal digit is represented by a fixed number of bits, usually four or eight, although other sizes (such as six bits) have been used historically. Special bit patterns are sometimes used for a sign or other indications (e.g., error or overflow).

In byte-oriented systems (i.e., most modern computers), the uncompressed BCD usually implies a full byte for each digit (often including a sign), whereas the packed BCD typically encodes two decimal digits within a single byte by taking advantage of the fact that four bits are enough to represent the range from 0 to 9 [8].

For the case of one cell LiPo battery, two bits are sufficient to store the voltage and 4 bits for the decimal part of the voltage. Unlike conventional NiCad or NiMH battery cells that have a voltage of 1.2 volts per cell, LiPo battery cells are rated at 3.7 volts per cell. The benefit: fewer cells are necessary to make up a battery pack. This is useful in sensor systems, where the available space for sensing system is limited.

Table 1

Sample Cumulative Telegrams with Decoded Fields

	Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0
Status 1	Reserved				Transmitted packet number 0..15			
Status 2	Repeater index		Battery BCD code					
	0..3		0..3 V		0..9 V/10			

Cumulative coding provides benefits of getting average temperature readout in case of lost transmission. Table 1 shows an example of metering telegrams with some missing transmissions and the calculation results. The darker columns show decoded data, where:

(1) Hexadecimal data field length; (2) decoded length to decimal;

(3) Hexadecimal device code, where 19 represents a device type;

(4) Status field – not of particular interest, but clearly shows the binary coded decimal 32, which corresponds to a battery voltage of 3.2 V of the sensor device;

(7) Data field – for this particular device code contains 2 bytes (8) of readout number and 4 bytes (11) of cumulative temperature;

(12) Decoded temperature for the sample given.

To calculate the average temperature from the received sensor readouts, the impulse difference and cumulative temperature difference are needed from two successive messages. This approach minimises the error of the averaging temperature in case of lost messages caused by signal strength collisions and other effects.

Example:

$$M_1 = hex2dec(23F0) = 9200$$
$$M_2 = hex2dec(23F7) = 9207$$
$$T_1 = hex2dec(006BFD35) = 7077173$$
$$T_2 = hex2dec(006C12E1) = 7082721$$
$$\Delta M = 7$$
$$\Delta T = 5548$$
$$T = \frac{\Delta T}{\Delta M} \Big/ 16 = 49.5357\ ^oC$$

Where:

M_1 – the first consecutive readout number;
M_2 – the second consecutive readout number;
T_1 – the first consecutive temperature sum;
T_2 – the second consecutive temperature sum;
ΔM – the number or readouts between M_1 and M_2;
ΔT – the cumulative temperature difference between T_1 and T_2.

For the trial deployment, two gateways in combination with directional antennas were enough to cover the full multi-apartment 9-storey building from aerated concrete. The design provided a robust transmission system, where all installed sensors were receivable (Fig. 7) by the gateway with the radio receivers.

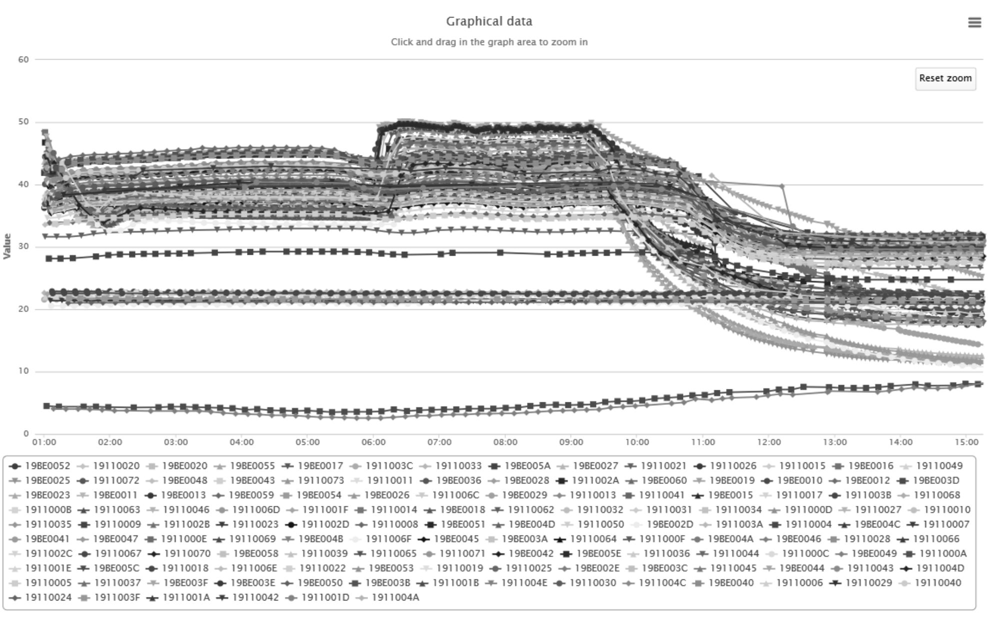

Fig. 7. Trial sensor installation metering data chart of a 24-hour cycle.

5. CONCLUSIONS

Temperature monitoring in a multi-apartment 9-storey building is a challenging task and has to take into account application specific requirements. An optimised coding scheme with short burst telegrams allows high-density installations with smaller collision probability. The cumulative method of data coding system is compact and efficient for use in battery-powered sensors as the sensor readout, coding and transmission are efficient in terms of calculation costs. Cumulative data coding minimises the error of average temperature calculation, when data transmissions are lost because of interference or collisions, and provides sufficient results for the particular application.

Antenna designs for directional signal reception in this trial have shown excellent results compared to omnidirectional designs. Dense apartment installations typical of Latvia cause multipath propagation. This undesirable effect demonstrated some benefits in dense high-rise apartment buildings as the data telegrams are transmitted through alternate paths, where no straight communication is possible. In addition, the effect provides a possibility of transmission to nearby building receivers. As the multipath effect causes polarisation changes, the proposed circular polarised antenna provides an optimal solution for the particular applications. In addition, the proposed antenna design provides a base for hardware integration into the antenna body itself.

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OPTIMIZĒTAS DINAMISKĀS BEZVADU SENSORU TĪKLU PĀRRAIDES RISINĀJUMA IZSTRĀDE DAUDZSTĀVU ĒKU APKURES SISTĒMAS PARAMETRU IZGŪŠANAI UN VADĪBAI

V. Isakovs, K. Kondratjevs, N. Kuņicina, B. Frēliha, A.Zabašta

K o p s a v i l k u m s

Daudzstāvu ēkas, kuras nav sākotnēji plānotas integrācijai ar ēku vadības sistēmām, rada kompleksu problemātisko vidi modernizācijai. Vadu sensoru sistēmu uzstādīšana šādās ēkās kļūst nepraktiska vai pat neiespējama. Šī iemesla dēļ ir nepieciešamas efektīvas bezvadu sensoru sistēmas, kas spētu nodrošināt mērījumu nogādi, ņemot vērā daudzstāvu ēku specifiku.

Rakstā tiek piedāvāts bezvadu sensoru tīkla risinājums efektīvai datu pārraidei siltumapgādes sistēmas parametru izgūšanai. Tiek izstrādāta un aprobēta specializētā virziena antena efektīvai radio telegrammu savākšanai no dzīvokļiem, nogādājot mērījumus datu koncentratoros. Ziņojumu telegrammu efektīvai pārraidei tiek piedāvāta datu kodēšanas kumulatīvā metode. Piedāvātais risinājums pielietojams gan jaunām, gan esošām ēkām. Izgūtie dati ir pielietojami siltuma apgādes sistēmas uzraudzībai, regulēšanai, kā arī individuālā siltuma patēriņa tarifikācijai.

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