Critical infrastructure objects protection with focused radiation in the terahertz frequency band

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Abstract

It is presented a complex system design of critical infrastructure objects protection from unauthorized access with the help of focused radiation in terahertz frequency band. The approach concerning increasing efficiency of automated complex system use for critical infrastructure objects protection from unauthorized access of intruders, as compared with the existing ones, has some advantages. Those are achieved by complementing existing systems with the monitoring system, what secures organization of adaptive processes of information collection and its corresponding technical efficiency increase, and with terahertz frequency band sensors, what provides considerable improvement in the delivery speed of routing protocols and energy consumption while using signals in terahertz frequency band, as compared with the frequency bands lower than 6 GHz. Additionally, the system includes elements of a mobile network, which comprises SDN controller that secures load balancing optimization among aerial platforms and base stations and centralized complex system control, what not only allows more efficiently use resources but also increase system's maintenance quality.

Keywords

critical infrastructure objects, terahertz frequency band, unauthorized access, focused radiation

1. Introduction

Currently, securing critical infrastructure objects protection is a crucial necessity. Solution of this problem is only possible with careful and wise provision of the respective security systems with modern highly reliable protection means. Demand for the new and highly reliable security systems is quickly increasing, so manufacturing companies of such systems are constantly in a cut-throat competition, which stimulates them to quickly develop new solutions. It is from this point of view that development of highly efficient model of integrated complex security system for critical infrastructure objects is a topical task.

Research object is the process of introducing new technical elements into integrated critical infrastructure objects protection system.

2. Aim of the research

There are following aims of the research.

1. Improving the process of development and design, by the means of specialized software with some new features, complex protection systems for critical infrastructure objects what enables these systems to leverage modern technologies of the internet of things. It is supposed that the operation of these technologies will be centered on information transfer control.

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2. Developing and proposing engineering technique of terahertz frequency band radio line calculation for the information support system of ensuring functioning of the control system for critical infrastructure objects protection.

Practical value of the research lies in the fact that it determines the factors which should be taken into account while implementing technical solutions at the different stages of critical infrastructure objects protection system creation [1].

3. Literature review

There is a well-known complex of objects protection, which includes electric power source, control console and protective fencing. In this case, control console is connected to the electric power source, which, in its turn, in linked with the protective fencing [2].

The weak point of this solution is the fact that this complex has defensive nature because the impact is generated against the intruder only when the intruder touches the protective fencing. This makes it possible to overcome the protective measures with the help of materials that isolate from the electric current.

On can take into account another known system of the territory protection, which includes the source of electric current and interconnected defensive fencing that is grounded. In this case electric current source is designed to be able impact an intruder with incremental voltage [3]. The deficiency of such a system is the fact that current-carrying conductors are positioned in the soil, so the life-span of the system due to the corrosion of the conductors substantially decreases.

Another protection complex of a certain territory is described in the literature. It includes the following interconnected in a certain way elements: sub-terahertz (STHz) radiation generator, the object surveillance device, intrusion detection sensors, antenna and control unit. In this case, sub-terahertz frequency band radiation generator is made with the possibility to change wavelengths in atmosphere transparence intervals and energy flow density. Control unit is manufactured with the processing capability of the signal that come from the intrusion detection sensors and issuing the command to direct antenna radiation at the intruder's position. This device's antenna is capable to turn in the direction of the intruder. In this case, the first input/output of the sub-terahertz frequency band radiation generator is connected with the input/output of the antenna, the second input/output of the generator is linked with the first input/output of the object surveillance device. The second input/output of the surveillance device is connected with the input/output of the intrusion detection sensors while the output of the object surveillance device is connected with the input of the control unit. The output of the control unit is connected to the input of the sub-terahertz frequency band radiation generator [4].

The disadvantages of the mentioned complex include the fact that the influence on the violator, who is at some distance, is carried out from the radiating antenna, within the direct line of sight. At the same time, in a number of cases (for example, to stop mass riots, during special operations, during autonomous functioning of remote communication facilities, attacks on critical infrastructure facilities) in the interests of ensuring the covert nature of the influence, as well as in a view of the limited space on urban or rural streets, a non-lethal effect on those violators is required, which are behind the obstacle, namely outside the line of sight.

The complex of protection of zones and objects against unauthorized entry of violators is also known. The specified complex includes: installation of STHz electromagnetic radiation with a wavelength of 3...3.3 mm; object monitoring device; unit for calculating the wavelength of STHz electromagnetic radiation in the intervals of atmospheric transparency and energy flow density and the angle of directivity diagram of electromagnetic radiation on the reflecting surface. The first input/output of the STHz range electromagnetic radiation installation is connected to the input/output of the STHz range electromagnetic radiation wavelength calculation unit. The second input/output of the STHz electromagnetic radiation installation is connected to the first input/output of the object monitoring device. The second input/output of the object monitoring device is connected to the second input/output of the unit for calculating the wavelength of STHz electromagnetic radiation [5]. At the same time, the calculations are based on the fact that the surface that reflects electromagnetic radiation is billboards located along pedestrian sidewalks, the metal body of a van parked near the place of a special operation. It is possible to use both a car that happened to be in the place of a special operation, and a car van with a metal body, placed there on purpose.

The disadvantages of such a protection complex include the fact that an object surveillance device is used to determine the location of a hidden trespasser. Such a device, which is located on the roof or upper floors of neighboring buildings, communicates the coordinates of the hidden intruder to the operator of the STHz range radiation installation by appropriate radio means. At the same time, the beam in the zone where the violator is located generally represents the sum of the component beams of direct visibility and several component beams of multi-beam propagation. The multibeam effect is due to the action of three mechanisms: reflection, diffraction and scattering of the transmitted beam. These phenomena lead to distortion of the beam and cause its fading, as well as additional fading during the propagation of the beam. Therefore, a large number of different simplifications are necessary to obtain a simple but, at the same time, quite reliable model of the transmission channel for calculating the angle at which the electromagnetic radiation should be directed to the reflecting surface. In this regard, obtaining a complete set of propagation conditions requires a huge amount of data of this kind. In addition, usually, such solutions require a large volume of calculations, especially in complex conditions of radio wave propagation. Therefore, the detailed physical characteristics of the simulated situation must be known in advance, which is a time-consuming task for complex operational and dynamic conditions.

In this regard, to ensure the necessary level of radiation power flow density at the location of the violator, it is necessary to increase the power of the radiating telecommunications system. Also, the disadvantages of the specified security complex include the fact that it has large mass-dimensional characteristics and energy consumption of the STHz range radiation generator, which are due to high requirements for its power to ensure the necessary levels of influence on violators. In addition, when a group of violators penetrate, it becomes ineffective.

The closest technical solution, both in essence and in terms of the problem to be solved, is an automated complex for the protection of zones and objects from unauthorized access by intruders, which includes: a system of focused radiation of the terahertz frequency range with an antenna; UAV; object monitoring system and control system. At the same time, the output of the object observation system is connected to the input of the control system, the output of the control system is connected to the input of the focused radiation system of the terahertz range, and the input/output of the system of focused radiation of the terahertz range is connected to the UAV [6].

The disadvantages of this automated complex of protection of zones and objects against unauthorized entry of violators include its low energy efficiency and limited scalability due to high requirements for its power to ensure the necessary levels of influence on violators. In addition, it is also ineffective when a group of intruders penetrates a protected object.

4. Formulation of the research tasks

The basis of the technical solution proposed for development is the task of additional introduction into the automated complex of a monitoring system, routers of a sensor wireless hierarchical network, sensors of the terahertz range and a mobile network system that includes an SDN controller, as well as the implementation of a system of focused terahertz radiation range in the form of interconnected low-power installations of the rectifier system of the terahertz range, increase the efficiency of the infrastructure of the automated complex of protection of zones and objects of critical infrastructure from unauthorized penetration of a group of violators.

5. Presentation of the main research material.

5.1. Technical aspects of the construction and operation of an automated complex for the protection of critical infrastructure objects

5.1.1. General characteristics of the automated complex of protection of critical infrastructure objects

The key difference of this solution from the traditional modern solutions used at particularly important objects of critical infrastructure that are protected is the use of sensor devices in the terahertz range. This provides a significant improvement in routing protocol delivery speed and power consumption when using the terahertz frequency band compared to less than 6 GHz frequency band. In addition, the low-power radiating units of the terahertz range rectifier system, which are part of the terahertz range focused radiation system, which are spatially distributed among themselves in the protected zone/object, allow to potentially reduce the mass-dimensional characteristics of the system and the energy consumption of the components, and to expand the functionality and scalability of the emitting system through integration with the SDN controller of the mobile network system. This becomes possible through the creation of directed electromagnetic radiation by spatially distributed low-power radiating installations of the rectifier system with a flexible change in the parameters of the electromagnetic field in the frequency range of 0.1 - 40 GHz for impact in critical situations on groups of violators in the corresponding zone of the protected critical infrastructure object.

The essence of the technical solution is realized in the protection complex, which includes a system of focused radiation in the terahertz range with an antenna, a UAV, an object surveillance system, and a control system. In the proposed solution, the output of the object monitoring system is connected to the input of the control system. The output of the control system is connected to the input of the focused radiation system of the terahertz range. And the input/output of the terahertz focused radiation system is connected to the UAV.

The essence of the technical solution is that the system of complex monitoring, sensor wireless hierarchical network routers, sensors of the terahertz range and a mobile network system, which includes an SDN controller, are additionally included in the complex. At the same time, the system of focused radiation of the terahertz range is made in the form of interconnected low-power installations of the rectifier system of the terahertz range - the ground part and the UAV. The UAV additionally includes a low-power installation of a rectifier system of the terahertz range with an antenna, equipment for transferring the standard licensed frequency range to the terahertz frequency range, antennas for transmitting information in the terahertz range, and equipment for encapsulating data from routers of a sensor wireless hierarchical network into data that is transmitted to a mobile network of the type LTE/5G. Each of the routers of the sensor wireless hierarchical network includes equipment for transferring the standard licensed frequency range to the terahertz frequency range.

What is new in the technical solution is that the authors propose the integration of LTE/5G mobile communication technology into the protection complex management system. The specified system includes an SDN controller and is made with the possibility of calculating the angles of the directions of impact on the violator by electromagnetic radiation and the power levels of synchronously operating low-power units of the rectifier system in the terahertz range.

What is also new is that the low-power radiating installations of the terahertz range rectifier system, which are part of the terahertz range focused radiation system, are spatially separated from each other by the protected zone/object.

The technical result of the special-purpose complex for the protection of areas and objects of critical infrastructure with focused radiation of the terahertz wave range is to increase the reliability and efficiency of management in critical situations when a group of violators penetrate. The specified result is achieved by the fact that the proposed protection complex uses sensors of the terahertz range in a wireless sensor network, a terahertz channel between a router of a wireless sensor network and an aerial platform, integration of the technology of SDN software-configured networks of a mobile network of the LTE/5G type in a wireless sensor network, in the system focused radiation of the terahertz range and the monitoring system of the complex. In addition, the technical result is also a reduction in the mass-dimensional characteristics and energy consumption of the components and low-power radiating units of the rectifier system of the terahertz range, which are part of the system of focused radiation of the terahertz range, which are spatially separated from each other according to the protected zone/object by the use of energy-efficient solid-state amplifier devices.

5.2. Technical aspects of building a defense complex

The essence of the technical solution in the special-purpose complex for the protection of zones and objects with focused radiation of the terahertz wave range is explained with the help of drawings, where first of them, Figure 1, shows a block diagram of an automated system for the protection of areas and objects of critical infrastructure against unauthorized access of violators.

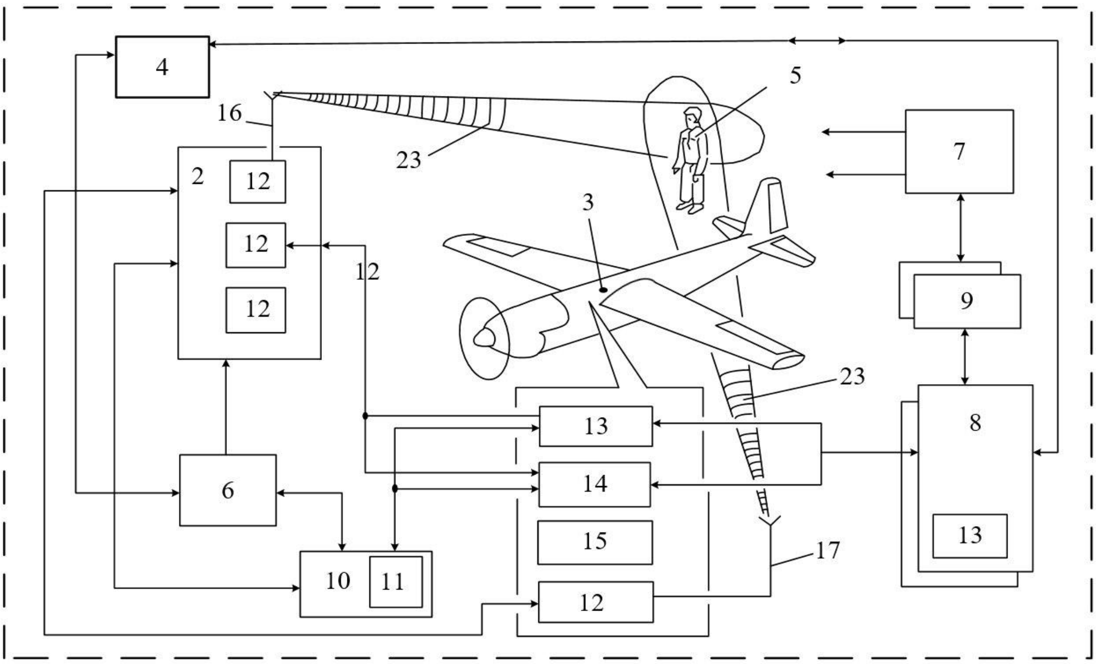

Figure 1: Automated complex of protection against unauthorized penetration

Figure 2 demonstrates a block diagram of the system of focused radiation in the terahertz range.

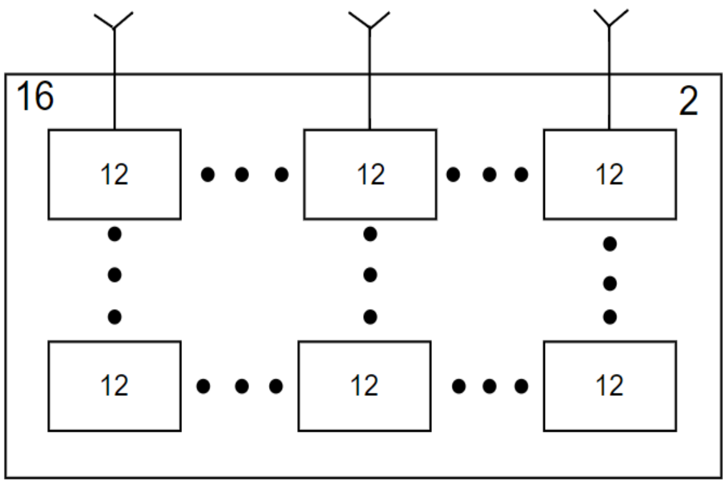

Figure 2: A system of focused radiation in the terahertz range

Figure 3 shows a block diagram of the equipment included in the UAV.

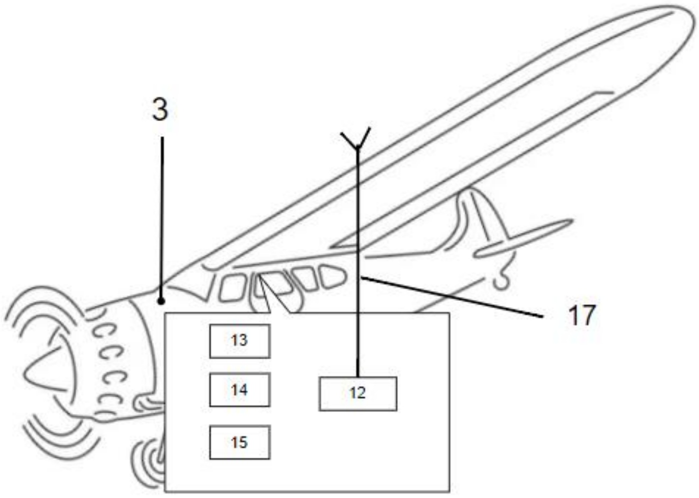

Figure 3: UAV equipment

A block diagram of the equipment included in the terahertz range focused radiation system is illustrated in Figure 4.

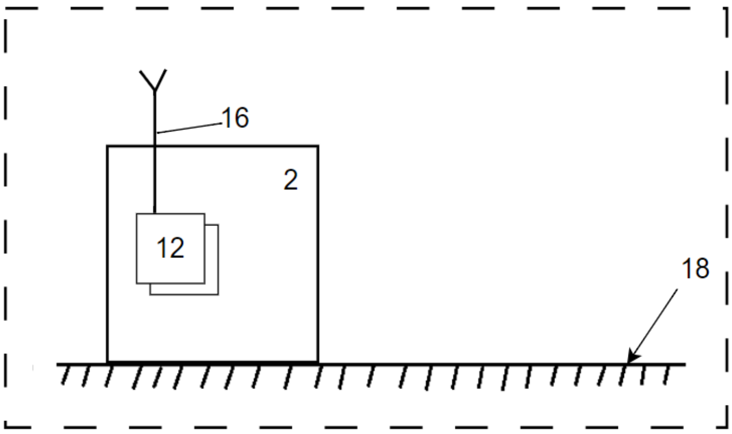

Figure 4: Equipment of the focused radiation system of the terahertz range

Figure 5 shows a block diagram of a sensor wireless hierarchical network router.

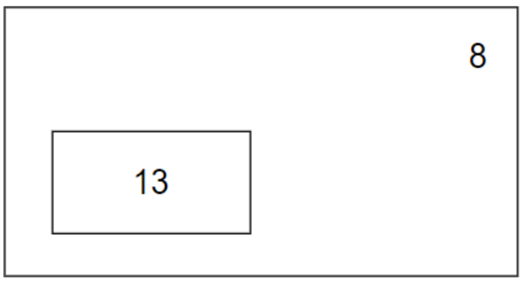

Figure 5: Sensor wireless hierarchical network router

The scheme of operation of the automated complex of protection of zones and objects of critical infrastructure against unauthorized penetration of violators is illustrated in Figure 6.

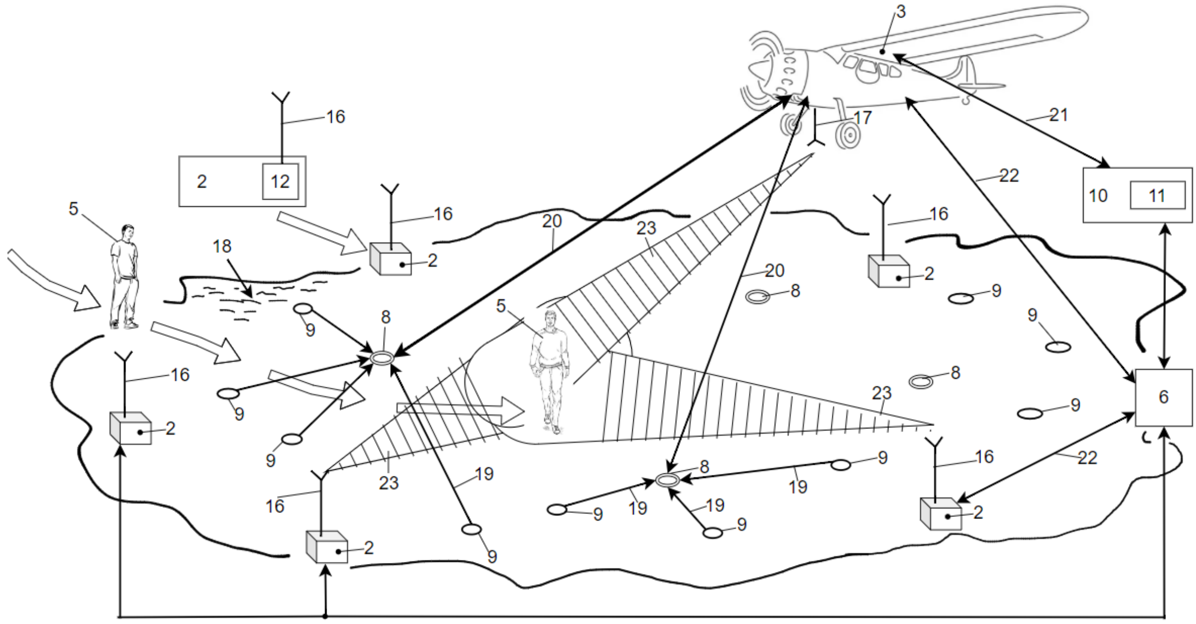

Figure 6: Functioning of the automated complex of protection against unauthorized penetration

Figure 7 shows the scheme of data transfer from the UAV, which UAV receives from the routers of the sensor wireless hierarchical network, to the mobile network system (LTE/5G type).

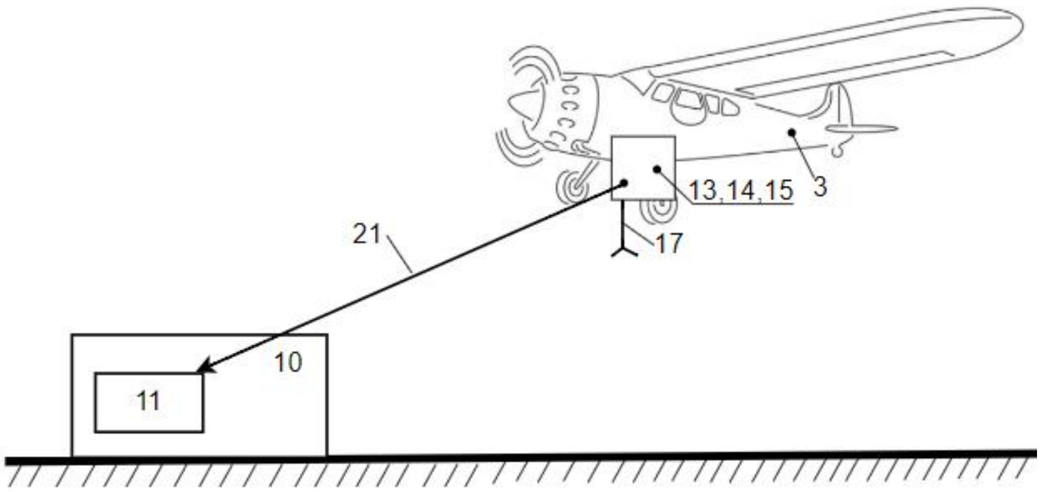

Figure 7: UAV data transfer scheme

Figure 8 demonstrates the calculation scheme performed by the mobile network system, which includes an SDN controller, of the angles β of the directions of influence on the violators by electromagnetic radiation and the power levels P of the synchronously operating low-power units of the rectifier system of the terahertz range (located on the ground and on the UAV).

The scheme of sending a command from the SDN controller (mobile network system) through the control system for the orientation (item "OP") of the antenna of the focused radiation system of the terahertz range (respectively, the ground and UAV antennas) to the location of the violators is shown in Figure 9.

Figure 10 demonstrate the diagram of the effect of electromagnetic waves of synchronously operating low-power installations of the terahertz range rectifier system (which are part of the terahertz range focused radiation system) - ground and UAV, at the location of the violators.

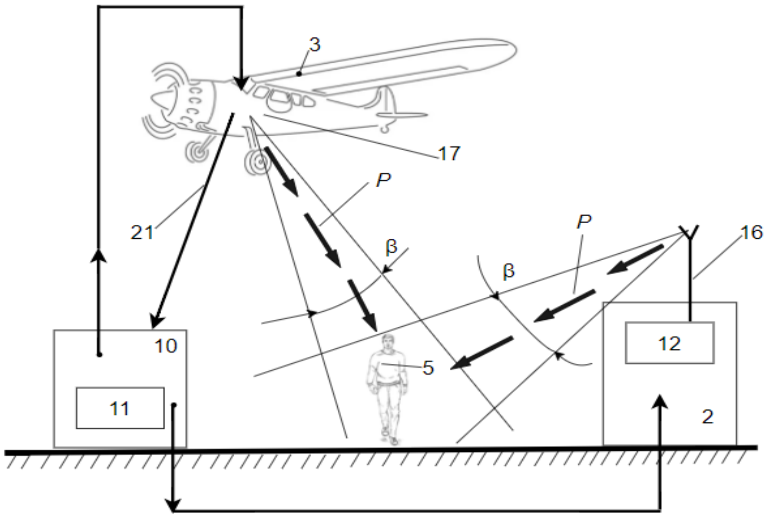

Figure 8: The scheme for calculating the angles β of the direction of influence and the power levels *P* of low-power installations

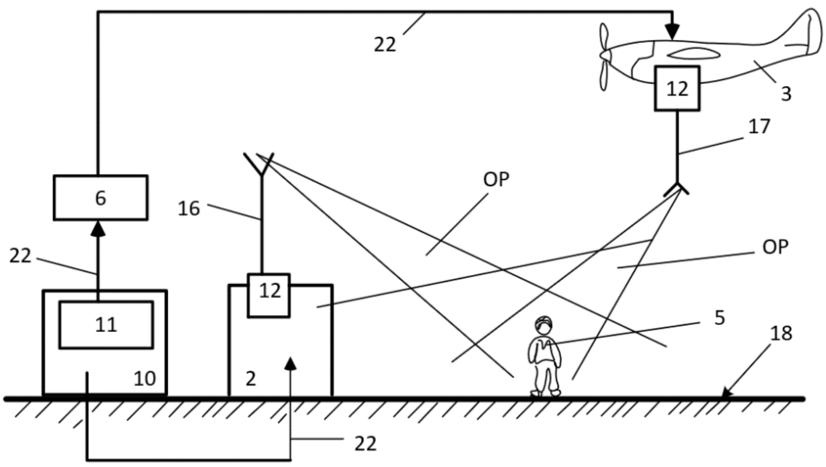

Figure 9: Scheme of submitting the command to the location of violators

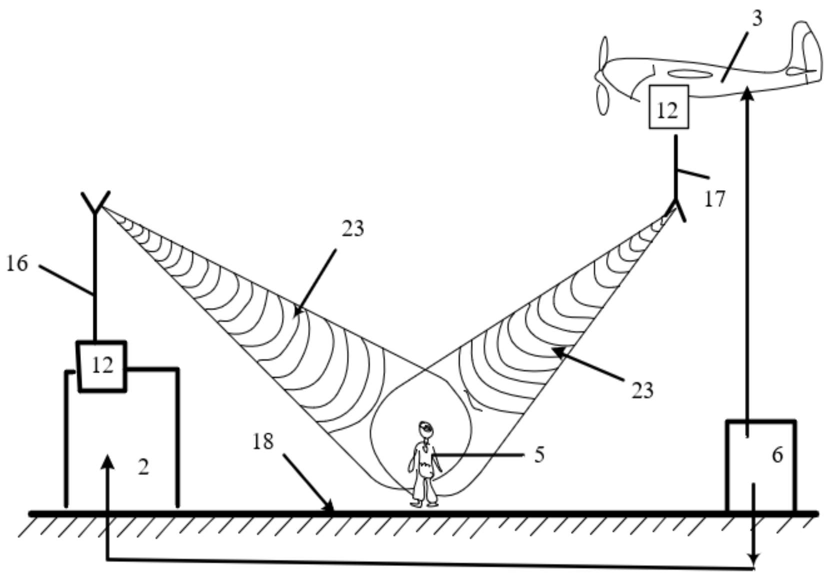

Figure 10: Scheme of action of low-power installations in the location of violators

The diagram of the influence of electromagnetic waves created by synchronously operating low-power installations of the rectifier system of the terahertz range (which are part of the system of focused radiation of the terahertz range) - ground and UAV, on the skin of the violator's body is shown in Figure 11.

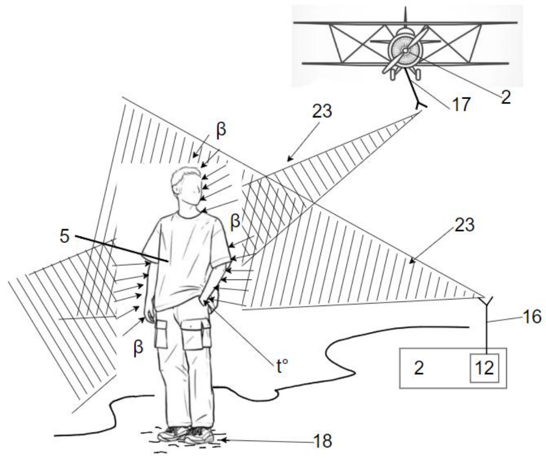

Figure 11: Scheme of effect of low-power installations on the skin of the body of violators

Figure 12 demonstrates the block diagram of the algorithm for monitoring the state of the proposed automated complex for the protection of zones and objects against unauthorized entry of violators.

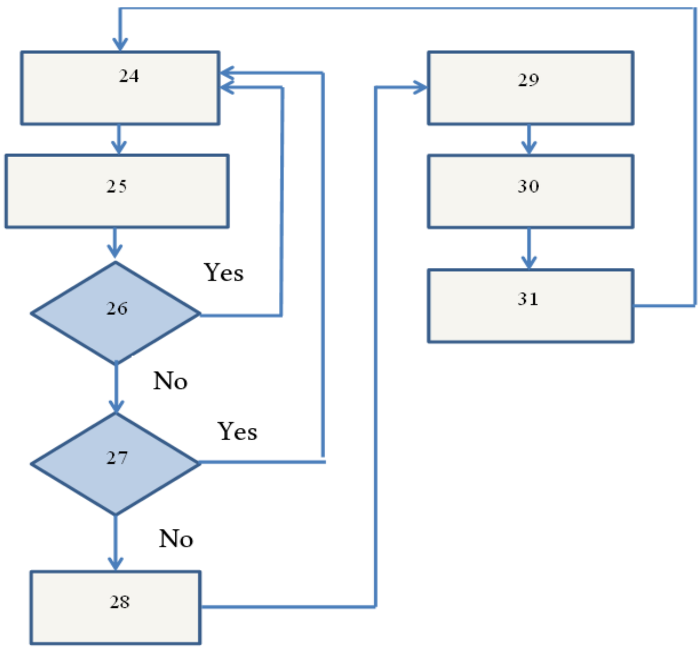

Figure 12: Data collection algorithm

The main purpose of the protection system, in particular the security system, is, first of all, the prevention of unauthorized entry into the area or premises under protection and the prompt and guaranteed notification of the owners of the object of protection and law enforcement services about the attempt to carry out illegal actions against the property in the premises or the premises itself in the protected object, including critical infrastructure objects. In addition, the ability to recognize intruders from video surveillance recordings or even detain them at the scene of the crime with the help of active security systems.

Security system is a general term for several types of systems, namely: access control systems (ACS), alarm systems, video surveillance, active security systems, etc. [7, 8, 9].

Ensuring reliable protection of critical infrastructure objects is impossible without the use of integrated complex security systems, which include a multi-level control system, high-tech and ultra-sensitive security and fire sensors, video surveillance systems with the ability to recognize objects, specialized warning systems, etc.

The following advantages of implementing such security systems can be listed [10, 11]:

- increased level of security of the facility as a whole – ensuring the continuity of control and management processes;
- organization of a network management structure with the implementation of functions of automatic control, processing, analysis and storage of information on the state of the system and the actions of the system operator from a single control panel;
- the possibility of integration at the information level (exchange protocol) with the systems of various subdivisions of the enterprise.

The implementation of the concept of security involves several directions of ensuring the security of the object - it is economic, scientific and technical, technological, ecological, informational, engineering and technical security. All of them are elements of a single complex security system of the protected object.

Complex 1 for the protection of zones and objects against the unauthorized penetration of violators contains (as a design option) system 2 of focused radiation of the terahertz range with an antenna, UAV 3, surveillance system 4 of object 5 (intruder), control system 6, monitoring system 7 of the complex, routers 8 of the sensor wireless hierarchical network, sensors 9 of the terahertz range and the system 10 of the mobile network, which includes the SDN controller 11 (see the block diagram in Figure 1).

At the same time, constructively and technologically:

- system 2 of focused radiation of the terahertz range is made in the form of interconnected low-power units 12 rectifier system of the terahertz range (more than two) - the ground part and the UAV 3 (see the block diagram in Figure 1 and Figure 2),
- a low-power unit 12 of the rectifier system of the terahertz range is additionally included in the composition of the UAV 3 (see the block diagram in Figure 1 and Figure 3),
- UAV 3 also includes equipment 13 for transferring the standard licensed frequency range to the terahertz frequency range, antennas 14 for transmitting information in the terahertz range, and equipment 15 for encapsulating data from routers 8 of the sensor wireless hierarchical network into data that is transmitted to the mobile network of the LTE type/ 5G (see block diagrams in Figure 1 and Figure 3),
- system 2 of focused radiation in the terahertz range includes antenna 16 (see diagram in Figure 4);
- low-power installation 12 of the rectifier system of the terahertz range, which is placed on the UAV 3, contains the antenna 17 (see the diagram in Figure 1 and the diagram in Figure 3);
- each of the routers 8 of the sensor wireless hierarchical network includes equipment 13 for transferring the standard licensed frequency range to the terahertz frequency range (see the block diagram in Figure 1 and Figure 5).

Structurally, the mobile network system 10, which includes the SDN controller 11, is made with the possibility of calculating the angles of the directions of influence on the violator (object 5) by electromagnetic radiation (item 16) and the power levels of the synchronously operating low-power units 12 of the rectifier system of the terahertz range.

Technologically, low-power installations 12 of the rectifier system of the terahertz range, which are part of the system 2 of focused radiation of the terahertz range, are spatially separated from each other in the zone/object (item 18) that are protected (see the diagram in Figure 2).

5.3. The principle of operation of the complex of protection of critical infrastructure objects in the infrastructure plane

Complex 1 for the protection of areas and objects of critical infrastructure against unauthorized penetration by an offender functions as follows (see diagram in Fig. 6).

In the event of unauthorized penetration of groups or several violators 5 into the territory 18 of the guarded zone/object, sensors of the 9 terahertz range are activated. Signals from sensors 9 of the terahertz range are received (item 19) in the routers 8 of the sensor wireless hierarchical network, where they are processed and transmitted (item 20) via the terahertz radio channel to the UAV 3 (see diagram in Figure 6).

UAV 3 using the equipment 13 for transferring the standard licensed frequency range to the terahertz frequency range, the antenna 14 for transmitting information in the terahertz range and the equipment 15 for encapsulating data from the routers 8 of the sensor wireless hierarchical network transmits (item 21) the received data to the system 10 of the mobile network (type LTE/5G) (see diagram in Figure 6 and diagram in Figure 7).

When receiving the above information from the UAV 3, the mobile network system 10, which includes the SDN controller 11, calculates the angles β of the directions of influence on the violators (item 5) by electromagnetic radiation and the power levels P of the synchronously operating low-power units 12 of the rectifier system of the terahertz range (located on the ground (see diagram in Figure 6 and diagram in Figure 8) and on UAV 3 (see diagram in Figure 8).

After that, the SDN controller 11 (system 10 of the mobile network) through the control system 6 sends (item 22) a command for the orientation (item "OR") of the antenna of the system 2 of focused radiation of the terahertz range (respectively, the terrestrial (item 16) and antenna 17 of the UAV 3) to the location of violators 5 (see diagram in Figure 9).

After the orientation of the antennas 16 and 17 in the required direction, the control system 6 starts the system 2 of focused radiation of the terahertz range and electromagnetic waves are emitted (item 23) at the location of the violators 5 by synchronously operating low-power units 12 of the rectifier system of the terahertz range (which are part of system 2 focused radiation of the terahertz range) - ground and UAV 3 (see the block diagram in Figure 10).

The violator (pos. 5), being under the influence (pos. "B") of terahertz range radiation (from low-power units 12 of the rectifier system of the terahertz range of the ground part and UAV 3 (see diagrams in Figure 6 and Figure 11), begins experiencing strong painful sensations. It is known that when emitted to a person (pos. "B"), radiation in the terahertz range is weakly absorbed by ordinary clothing and penetrates the skin to a depth of 0.5 mm, where the interaction with the water molecules of the intracellular fluid leads to an increase in its temperature.

Rapid heating t° of the skin (see the diagram in Figure 11) leads to massive disruption of thermo-receptors and the occurrence of a painful shock, similar to a burn [12-19].

This operation is performed by synchronously operating spatially distributed low-power units 12 of the rectifier system of the terahertz range (which are part of the system of 2 focused radiation of the terahertz range) - see the diagram in Figure 11.

High-temperature heating of the air space (over 9000K) with the help of narrowly focused radio radiation, the frequency of which corresponds to the frequency of maximum absorption of energy by molecules of atmospheric oxygen and water vapor, is the basis of the operation of synchronously operating spatially distributed low-power units of 12 rectifier systems in the terahertz range.

The principle of operation of the automated special-purpose complex for the protection of zones and objects by focused radiation of the terahertz wave range is as shown further. The low-power installation 12 of the rectifier system of the terahertz range generates a narrow directional (width up to 0.5 degrees) radio beam (item 23) in the frequency range of the "transparency window" of 94-96 GHz, which penetrates the human skin to a depth of 0.5 mm, heating it to and above 45°C (see diagram in Figure 11). At the same time, a person experiences unbearable pain. The pain reaction to radiation with an intensity of up to 100 W/m^2 is strong enough to force the violator 5 to leave the protected zone/object 18.

The reaction to the radiation occurs in the violator 5 for 2-3 seconds, becomes unbearable after 5 seconds and disappears after the low-power installation 12 of the rectifier system of the terahertz range is turned off or after the violator 5 leaves the protected area/object 18 in which the exposure takes place. If the trespasser 5 does not leave the protected area/object 18 within 250 seconds, he will receive a skin burn. At the same time, the predicted range of damage to the violator (biological objects) is within 1 km or more.

To ensure the effective functioning of the automated complex of special purpose for the protection of areas and objects of critical infrastructure with focused radiation of the terahertz wave range, the monitoring system 7 of the complex is deployed and configured (see Figure 1).

The basis of the functioning of system 7 of the complex monitoring is the use of intelligent algorithms based on trained models of artificial intelligence at the channel level, as well as at the level of the network control plane of the neural network infrastructure.

The work of these algorithms is focused on managing the use of information communication flows and, as a result, leads to the optimization of the use of network resources in emergency situations.

The functional metrics of the developed system for evaluating the performance of an overtrained neural network are the usual functional parameters of this solution: delay, efficiency of use of spectral resources of communication channels, and others. If the overtrained model for a certain algorithm leads to the deterioration of functional parameters, then this model should be returned for retraining or should be removed from the data storage module.

In order for intelligent control algorithms to produce the correct result, it is necessary to collect a sufficient set of data, by which is meant the optimal amount of data at which model training is considered complete and the so-called overfitting process is not observed.

To collect functional data, the SDN controller 11 of the system 10 of the mobile network is used (see Figure 1 and Figures 7-9), which directly carries out the process of collecting relevant data from the blocks of complex 1.

Each block of complex 1 is a source of information for machine learning (ML) algorithms. The main data processing before training neural networks is carried out on the SDN controller 11. If there is a change in the state of the blocks of complex 1, which requires retraining of the corresponding models, then the corresponding algorithms perform the necessary procedure of retraining them based on new parameters. After that, the corresponding trained models are replaced.

An important component of intelligent control algorithms is the direct collection of data for training. One of the features of the use of these algorithms in telecommunication radio networks of the terahertz frequency range is the variability of states in the complex, as well as the appearance of new and disappearance of current states, which requires additional data collection and retraining of neural networks.

The developed data collection algorithm (see Figure 12) provides for monitoring states of the blocks of the complex for rational data collection using changes in the values of both Euclidean distance metrics and functional technical parameters metrics in relation to the number of clusters.

This process is explained in Figure 12, on which is marked:

24 – Regular mode of operation of the proposed installation (PI) and monitoring and work optimization (MWO) using algorithms based on artificial intelligence.

25 - Monitoring of the state of operation of PI and MWO units based on *k*-means and *c*-means algorithms.

26 - Operation "Normal state of work of PI and MWO?".

27 - Operation "Known state of work of PI and MWO?".

28 - Data collection for training.

29 - Aggregation and sending of data to the SDN controller.

30 – Retraining of the neural networks in unit 5.

31 – Updating neural networks.

The novelty of the proposed approach is that it differs from the classical implementation in that the metrics of the signal/noise ratio are introduced, instead of the Euclidean distance metric, which makes it possible to take into account the spatial characteristics of signal propagation in the process of self-optimization of the developed structure and, accordingly, to increase its technical efficiency.

Thus, the algorithm whose block diagram is presented in Figure 12, monitors the state of each unit of the automated complex of special purpose for the protection of zones and objects by focused radiation of the terahertz wave range 1 against unauthorized penetration of violators.

5.4. Elements of the information support system for ensuring the functioning of the protection complex management system

Engineering method of energy calculation of a radio line in the terahertz range.

1. Initial data for calculation:

- band of operating frequencies – (71÷76); (81÷86); (92÷96) GHz;
- communication interval – D = 5 km;
- channel speed of data transmission – 1.0 Gbps;
- type of modulation – BPSK;
- antenna diameter – d = 200 mm; 400 mm;
- propagation conditions are normal (free space);
- trace – line of sight;
- there is no multiradiation.

2. The reliability of the communication on the interval is determined by the excess of the energy potential of the radio line over the total signal losses (an energy reserve for slow fading):

$$L_{S.F.} = M - L_{\Sigma}, \tag{1}$$

where $L_{S.F.}$ – an energy reserve for slow fading; M is the value of the energy potential, dB; L_{Σ} – total median signal loss on the communication interval, dB.

3. The value of the energy potential is determined by the formula:

$$M = P_{Tr} + 2G - P_{Re}, \tag{2}$$

where P_{Tr} is the power supplied to the antenna, dB/W; G is the gain of the antenna, dB; P_{Re} is the sensitivity of the receiver in the absence of external interferences, dB/W.

The sensitivity of the receiver is determined by the formula:

$$P_{Re} = 10\lg(KT\Delta f) + K_N + Ps/P_N, \tag{3}$$

$$\text{or } P_{Re} = -204 + 10\lg\Delta f + K_N + Ps/P_N, \tag{4}$$

where K = 1.38 10^{-23} W/Hz – Boltzmann constant; T – ambient temperature ~300˚; Δf – signal bandwidth, Hz; K_N is the noise coefficient of the receiver; Ps/P_N – signal/noise ratio to ensure the specified quality of signal reception that does not fade, dB.

The quality of transmission of discrete information is evaluated by the probability of an error, which depends on the signal/interference ratio. Usually, the probability of error is set at the level of 10^{-6}.

In systems with coherent phase modulation, this condition is fulfilled when the signal exceeds the interference by 10 dB.

The K_N noise coefficient is usually accepted (set) at 3 dB.

A 2.0 GHz frequency band is required for 1.0 Gbps data transmission and reception.

Then, according to (3) and (4), the sensitivity of the receiver will be:

$$P_{Re} = -204 + 10\lg(2\cdot 10^9) + 3 + 10 = -204 + 93 + 13 = -98 \text{ dB/W}.$$

4. Let us determine the wavelength for the average frequency of each of the subranges of operating frequencies according to the formula:

$$\lambda = c/f, \tag{5}$$

where λ is the wavelength, mm; s – speed of light, $3\cdot 10^{10}$ mm/s; f is the average frequency of the working subband.

Calculations are shown in Table. 1.

Table 1
Dependence of the wavelength (mm) on the average frequency of the subband (GHz)

f, GHz	73.5	83.5	94
λ, mm	4.05	3.6	3.2

Let's determine the width of antenna directional diagrams according to the formula [16]:

$$\Theta^{\circ} = 84(\lambda/d), \tag{6}$$

where d is the diameter of parabolic antennas.

The calculations are presented in the Table. 2.

Table 2
Dependence of the width of the directional diagram on the wavelength and diameter of the antenna

d, mm	λ, mm		
	4.05	3.6	3.2
200	1.7°	1.5°	1.34°
400	0.85°	0.75°	0.67°

From the Table 2, it can be seen that the directional patterns of the antennas are very narrow, therefore, there will be practically no reflected rays in direct line of sight.

The antenna gain coefficient is determined by the formula [14]:

$$G = 10\lg[S\cdot(\pi d/\lambda)^2], \tag{7}$$

where S is the utilization factor of the antenna area (usually ≈ 0.6 ÷ 0.7); d – antenna diameter, mm.

The calculation results are presented in Table 3.

Table 3
Dependence of antenna gain on wavelength and antenna diameter, G dB

d, mm	λ, mm		
	4.05	3.6	3.2
200	41.6	41.85	43.71
400	47.64	48.2	49.7

The calculation results correspond to the known data. Thus, in [14], the dependence of the antenna gain G on the d/λ ratio is given.

Table 4
Dependence of the antenna gain on the ratio of the antenna diameter to the wavelength

d/λ	20	30	40	50	60
G, dB	34	37	40	42	43

For the paths under consideration, the total median losses will be determined only by the losses during propagation in free space according to the formula:

$$L_{\Sigma} = L_{FS} = 20\lg 4^{\pi d/\lambda}. \tag{8}$$

The communication range is 5 km = $5 \cdot 10^6$ mm.
Calculations are given in Table 5.

Table 5
Dependence of median loss on antenna diameter

λ, mm	4.05	3.6	3.2
L_{FS}, dB	143.8	144.6	145

The energy potential determined by (2) for the 71...76 GHz subband is equal to:

$$M = P_{Tr} + 2 \times 41.6 - (-98) = P_{Tr} + 83.2 + 98 = P_{Tr} + 181.2 \text{ dB/W}.$$

The spare energy is determined as follows:

$$L_S = M - L_{\Sigma} = P_{Tr} + 181.2 - 143.8 = P_{Tr} + 37.4 \text{ dB/W}.$$

At a transmitter power of 10 mW (– 20 dB), the spare energy is 17.4 dB.

The results of calculating the spare energy for different frequency ranges for different sizes of antennas are shown in Table 6.

Table 6
Dependence of the spare energy upon the wavelength and diameter of the antenna, L_S dB

d, mm	λ, mm		
	4.05	3.6	3.2
200	17.4	17.5	20.42
400	29.48	29.80	30.40

If we take into account signal losses due to weather conditions and seasonal variations at the level of 10÷15 dB, then the results of the calculations suggest the possibility of creating communication lines in the millimeter wave range with an interval of 5 kilometers or more.

6. Conclusion

Increasing the efficiency of the use of an automated complex for the protection from unauthorized penetration of violators of critical infrastructure objects by focused radiation of the terahertz range of waves, in comparison with known ones, was achieved by implementing a system of focused radiation of the terahertz range in the form of interconnected low-power installations of a rectifier system of the terahertz range – ground unit and UAV. This provides a reduction in the mass-dimensional characteristics and energy consumption of the components and subsystems of the high-energy radiating telecommunication system of the sub-terahertz frequency range of 94...96 GHz due to the use of devices with semiconductor technology. This, in turn, allows one to potentially get a system of smaller size and weight, at a lower cost and with a reduced readiness time. In addition, at the same time, the technical operation of the complex is simplified and its functional capabilities are increased.

For the information support system for ensuring the functioning of the management system of the developed protection complex, the engineering methodology for the energy calculation of the radio line of the terahertz range is given.

Declaration on Generative AI

The authors have not employed any Generative AI tools.

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