

Research and development of hierarchical models of automated control systems for the parameters of the radio-line of the cognitive radio system

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Abstract. The paper considers a five-level model of a cognitive radio communication system. It was revealed that 1 - it was established that the value of the influence of natural factors and the effects of the enemy is comparable, but several times less than the state of the radio communication system; 2 - the observer's device and the regulator are important for the effective transmission of information and the controlled process and the internal state of the information transmission system are less important; 3 - the goal of reducing the number of errors in the transmission of information and increasing the speed of information transmission are important for the effective transmission of information, in comparison with a reduction in the computational load on the formation of signal-code structures and a decrease in the amount of energy used for transmission; 4 - the highest efficiency of the radio system can be achieved through the use of optimal signal processing algorithms, and high power of the transmitted signal; 5 - increasing the speed of information transmission without the necessary power of the radio link and signal processing algorithms will not give a tangible effect when transmitting information in difficult conditions..

1. Introduction

According to the definition of the International Telecommunication Union (ITU), a cognitive radio system [1] is a radio system using technology that allows it to gain knowledge about its operating environment and geographic environment, about established rules and its internal state to dynamically and autonomously adjust operational parameters and protocols according to acquired knowledge to achieve pre-set goals and be trained on the basis of the results obtained. Thus, the radio stations included in such a system must contain devices for analyzing the state of the radio station itself, as well as the external geographic, situational, and jamming environment.

The solution of problems of controlling dynamic objects includes the formation of a mathematical model with the subsequent study of the properties of this model and the synthesis of the controller. The objects of control in the information system are receivers and transmitters of information. Moreover, there may be control over the parameters of both a separate transmitter, for example, power control, and simultaneous control of the receiver and transmitter, for example, when choosing the best communication channel.

In digital systems, solving a similar problem is very flexible and has many options [2]. The choice of structural solutions in the design of digital systems is largely determined by the characteristics of the problem being solved. One of the approaches to solve this problem is the multi-agent approach [3]. A separate agent is considered as a mechanism capable of influencing the achievement of a goal and decision making. Each of the agents solves their problem, but is able to exchange information with

each other. To organize the process of decomposition of a task in multi-agent systems, either a distributed problem solving system or a decentralized artificial intelligence is created. To assess the influence of agents in the cognitive radio system, we apply the analytic hierarchy process by T. Saaty [4,5]. Today, there are examples of successful application of the method of analyzing hierarchies in various fields of application: project management for the development of engineering applications [6-10], a separate review of the application of the method from its inception in [11], the development of industrial plants for multi-stage step processing of materials [12], the analysis of accreditation indicators of universities [13], the evaluation of applications for participation in competitions for the development of complex systems [14], the ranking of highly qualified athletes [15], increasing the effect efficiency of enterprises [16].

2. Representation of the cognitive radio system in the form of a hierarchy

The system of cognitive radio communication is influenced by the forces generated by natural geographic factors, by the enemy, creating an active jamming environment and by processes occurring in the working electrical part of the network of transceivers of radio signals. Radio stations included in such a system should contain devices for analyzing the state of the radio station itself, as well as the external geographic, situational and jamming conditions, dynamic and autonomous adjustment of operational parameters and protocols according to the knowledge gained to achieve pre-set goals. The system should also have a learning mechanism based on the results obtained by the system (figure 1).

We will consider the radio transmission system as a hierarchical system. Select the system levels $I = \{I_i\}, i = \overline{1, m}$. At each level of the hierarchy there are complex interactions with higher levels of the hierarchy. To formalize the decision-making process on improving the efficiency of the cognitive communication system, we apply the analytical hierarchy process by T. Saaty.

Consider the levels of the system I .

The top of the system is represented by the level I_0 , showing how the cognitive radio system works.

The first level of the system I_1 consists of forces (1),

$$W_{I_1} = \{W_{I_1 j}\}, j = \overline{1, n_{I_1}} \quad (1)$$

affecting the quality of the reception and transmission of signals. As already noted, the forces will be: the forces generated by the processes occurring in the operating electrical part of the network of transceivers ($W_{I_1 1}$), enemy, creating a jamming environment ($W_{I_1 2}$) and natural geographical factors ($W_{I_1 3}$).

The second level of the system I_2 consists of active elements (actors), who direct forces. We introduce similarly (2)

$$W_{I_2} = \{W_{I_2 j}\}, j = \overline{1, n_{I_2}}, \quad (2)$$

where $W_{I_2 1}$ – internal state of system, $W_{I_2 2}$ – observer's device (for common reasoning) – a receiver of digital signals (a decoder or, in the case of simultaneous demodulation and decoding, a modem), $W_{I_2 3}$ – a regulator that generates controls acting on the receiver, transmitter and modem, $W_{I_2 4}$ – controlled process of transmitting signals (the code of control actions is recorded in an information message transmitted over the reverse channel. The forward and reverse channels can be both the same and different in modulation type, transmission rate and type of code used).

When designing such a system is required to ensure the implementation of conflicting tasks. Information should be transmitted with maximum speed, received with maximum reliability and at the same time to spend a minimum of energy and computing resources.

Select the level of goals I_3 and its elements (3)

$$W_{I_3} = \{W_{I_3 j}\}, j = \overline{1, n_{I_3}}, \quad (3)$$

where W_{I_31} – maximizing of data transfer rate, W_{I_32} – maximizing transmission reliability, W_{I_33} – minimization of energy consumption, W_{I_34} – minimization of computing resources.

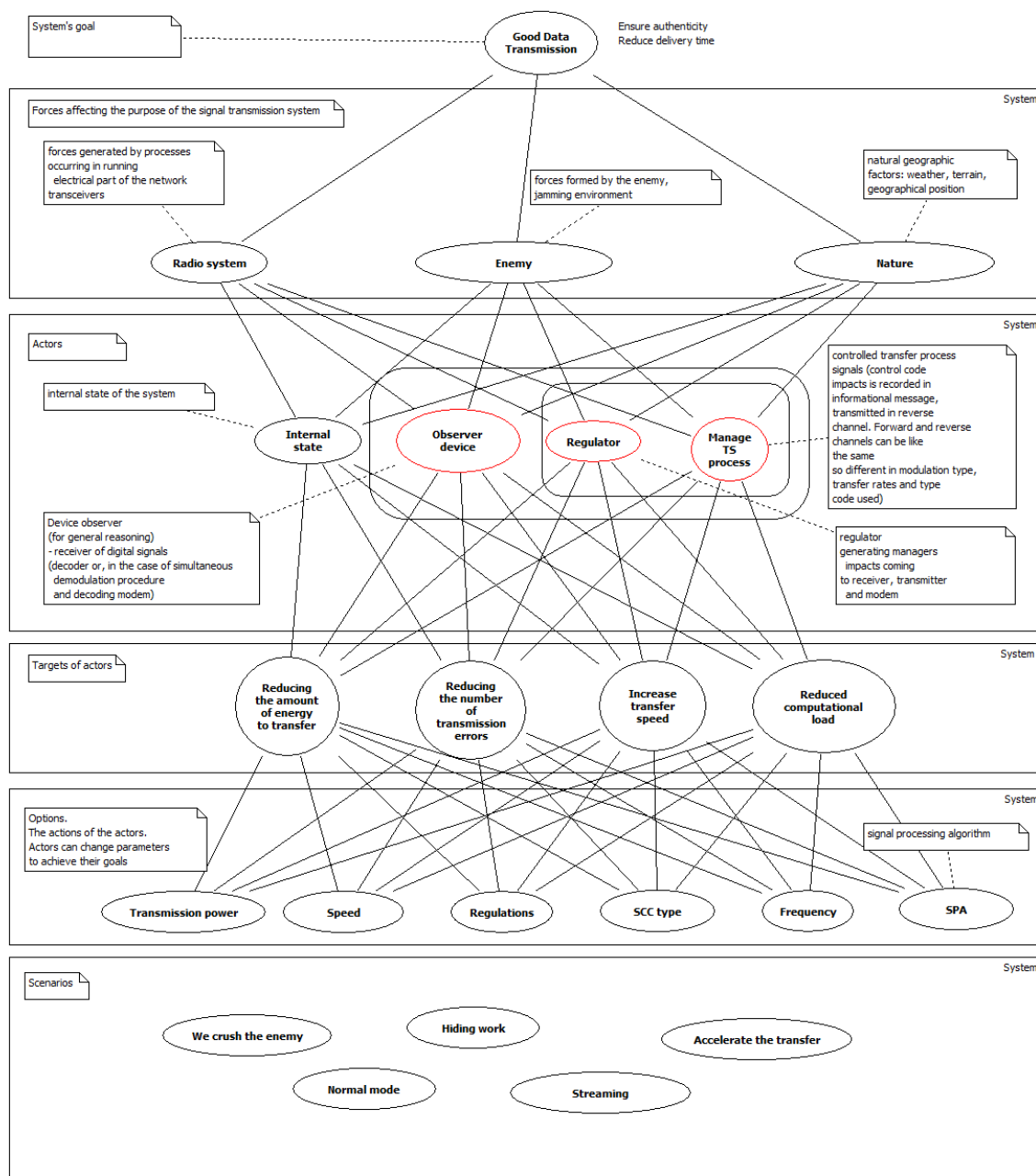


Figure 1. Cognitive radio system's hierarchical model.

The objectives of the actors can be achieved through possible actions - the level I_4 . Select it's elements (4)

$$W_{I_4} = \{W_{I_4j}\}, j = \overline{1, n_{I_4}}, \quad (4)$$

where W_{I_41} – transmitter power control, W_{I_42} – rate control, W_{I_43} – carrier frequency control, W_{I_44} – management of communications regulations, W_{I_45} – control of the type of received signal code constructs, W_{I_46} – signal processing control.

Possible combinations of controlled parameters form the script level I_5 , consisting of many of its elements $W_{I_5} = \{W_{I_5,j}\}, j = \overline{1, n_{I_5}}$.

Our goal is to establish the influence of elements at the level of I_4 at the top of hierarchy.

3. Application of the analytical hierarchy process to the task of identifying element weights

Establish the effect $I_1 \rightarrow I_0$ of forces, located at I_1 on the system's goal I_0 . For this we will compare the importance of elements in pairs. $W_{I_1} = \{W_{I_1,j}\}, j = \overline{1, n_{I_1}}$ on a scale of relationships [1;9], where the dominance of element $W_{I_1,k}$ in relation to $W_{I_1,m}$ is denoted by an integer from the scale of relations a_{km} . Having made $C_{n_{I_1}}^2$ comparisons we will fill in the matrix $A_{I_1} = [a_{ij}]$ of pair comparisons, of dimension $n_{I_1} \times n_{I_1}$.

To fill the matrix A_{I_1} it is necessary to answer the question: what elements in relation to the effective work of the cognitive communication system do I_1 taken in pairs. Level I_1 consists of 3 elements: "The system of radio stations" - the forces generated by the processes occurring in the working electrical part of the network of transceivers ($W_{I_1,1}$), "Opponent" - the forces formed by the enemy, creating a disturbance environment ($W_{I_1,2}$) and "Nature" - natural and geographical factors ($W_{I_1,3}$). We present the comparison in table 1.

Table 1. The influence of forces $I_1 \rightarrow I_0$ located at level I_1 on the system's goal I_0 .

№	Comparison	Result	Explanation
1	$W_{I_1,1}$ & $W_{I_1,2}$	$a_{12}=7$ very strong influence	$W_{I_1,1}$ - correct operation of the radio station system has a much greater effect on the result, compared to $W_{I_1,2}$ - the opposition of the enemy, since in conditions of mountainous terrain, it is difficult to carry out a broadband interference for receiving and transmitting radio signals.
2	$W_{I_1,1}$ & $W_{I_1,3}$	$a_{13}=5$ strong influence	$W_{I_1,1}$ - correct operation of the system has a strong influence on the result, in comparison with $W_{I_1,3}$ - natural-geographical factors, because The technical devices of the radio system are designed to overcome these factors.
3	$W_{I_1,2}$ & $W_{I_1,3}$	$a_{23}=1$ equal effect	Impact $W_{I_1,2}$ - natural and geographical factors (lack of direct visibility: elevation drops up to 4000 m, sudden rainfall, dense clouds, dense vegetation in canyons up to 1800 m, difficulty in interacting with the ionosphere - thunderstorm clouds) in mountainous areas has an equal impact on the result, in comparison with an action, an adversary $W_{I_1,3}$ who finds it difficult to carry out broadband interference in hard-to-reach areas.

Fill matrix A_{I_1} , setting by T. Saati that the comparison of the effect influence $W_{I_1,m}$ to I_0 towards $W_{I_1,k}$ replaced by the inverse of the influence $W_{I_1,k}$ to I_0 towards $W_{I_1,m}$ $a_{mk} = \frac{1}{a_{km}}$. It is necessary to take into account the equal importance of the influence of the element in comparison with itself $a_{kk} = 1$. The result is given in table 2.

Finding the right eigenvector ω'_{I_1} of the matrix A_{I_1} , corresponding to the maximum eigenvalue of solving the equation (5)

$$A_{I_1} \omega'_{I_1} = \lambda_{\max I_1} \omega'_{I_1}, \quad (5)$$

We introduce an iterative procedure [17] for finding the eigenvector corresponding to the maximum eigenvalue.

Table 2. Pair comparison of the effect of forces on the target system ("good signal transmission" - to ensure accuracy, reduce delivery time).

A_{I_1}	W_{I_11}	W_{I_12}	W_{I_13}
W_{I_11}	1	$a_{12} = 7$	$a_{13} = 5$
W_{I_12}	$\frac{1}{a_{12}} = \frac{1}{7}$	1	$a_{23} = 1$
W_{I_13}	$\frac{1}{a_{13}} = \frac{1}{5}$	$\frac{1}{a_{23}} = 1$	1

Let $y^{(0)} = \{1, \dots, 1\}$ unit vector of dimension n_{I_1} . Run an iterative process $y^{(k)} = A_{I_1} y^{(k-1)} = A_{I_1}^{k-1} y^{(0)}$ before reaching (6)

$$\varepsilon^{(k)} = \left| \frac{y_j^{(k)}}{y_j^{(k-1)}} - \frac{y_j^{(k-1)}}{y_j^{(k-2)}} \right| \leq \varepsilon, \quad (6)$$

where ε - computing error, $\lambda_{\max I_1} = \frac{y_j^{(k)}}{y_j^{(k-1)}}$.

The resulting vector of the iteration process $y^{(k)}$ is a solution of matrix equation $A_{I_1} \omega'_{I_1} = \lambda_{\max I_1} \omega'_{I_1}$.

After normalizing the vector ω'_{I_1} by the sum of its coordinates, we obtain the vector (7)

$$\omega_{I_1} = \left\{ \frac{\omega'_{I_1 i}}{\sum_{j=1}^{n_{I_1}} \omega'_{I_1 j}} \right\}, i = \overline{1, n_{I_1}} \quad (7)$$

where ω_{I_1} is influence vector of $I_1 \rightarrow I_0$ forces, located at I_1 to system's goal I_0 .

As a result of the calculations we get $\omega_{I_1} = (0,75; 0,12; 0,13)$. These weights indicate that weather factors and the adversary make an equal contribution to the successful operation of the system (table 3). The total contribution of the enemy factors and the weather give a 25% impact on the successful work.

Table 3. The influence of forces on the system's goal.

Forces	I_0
	ω_{I_1}
W_{I_11} - forces generated by the processes occurring in the operating electrical part of the network of transceivers	0,75
W_{I_12} - the enemy, creating interference environment	0,12
W_{I_13} - natural and geographical factors	0,13

$$OC = 0,05 < 0,1$$

As a measure of the correctness of judgments, a consistency relation is introduced (CR) – the ratio of the consistency index (CI) of the pair comparison matrices A_{I_j} to random index (RI) – IC for a square matrix of dimension $n \times n$ filled with random numbers. For matrices of dimension $n \times n$ CI is calculates

by $HC = \frac{\lambda_{\max} - n}{n - 1}$. $OC \leq 0,1$ is considered acceptable for consistency of the pairwise comparison matrix.

Having performed similar calculations, we get all the influence vectors $\omega_{I_j}, j = \overline{1,4}$ of the levels $I_j \rightarrow I_{j-1}$ in hierarchy I .

4. Formation of evaluation matrices

Table 4. Matrix of pairwise comparisons $A_{I_{21}}$ and the normalized value of the vector of influence of actors on the provision $W_{I_{21}}$ - the correct operation of the radio station system $I_2 \rightarrow I_{11}$.

Actors I_2	$W_{I_{21}}$	$W_{I_{22}}$	$W_{I_{23}}$	$W_{I_{24}}$	$\omega_{I_{21}}$
$W_{I_{21}}$	1	5	3	1	0,40
$W_{I_{22}}$	0,2	1	1/3	1/3	0,08
$W_{I_{23}}$	1/3	3	1	1/3	0,16
$W_{I_{24}}$	1	3	3	1	0,36

$$OC \approx 0,07 < 0,1$$

Remaining level matrices I_2 are formed similarly (tables 5, 6). Matrices describe the influence of actors on countering natural factors and deliberate interference.

Table 5. Matrix of pairwise comparisons $A_{I_{22}}$ and the normalized value of the vector of influence of actors on overcoming $W_{I_{22}}$ - counter enemy $I_2 \rightarrow I_{12}$.

Actors I_2	$W_{I_{21}}$	$W_{I_{22}}$	$W_{I_{23}}$	$W_{I_{24}}$	$\omega_{I_{22}}$
$W_{I_{21}}$	1	0,5	1/3	3	0,16
$W_{I_{22}}$	2	1	1	7	0,37
$W_{I_{23}}$	3	1	1	7	0,41
$W_{I_{24}}$	1/3	1/7	1/7	1	0,05

$$OC \approx 0,04 < 0,1$$

Table 6. Matrix of pairwise comparisons $A_{I_{23}}$ and the normalized value of the vector of influence of actors on overcoming $W_{I_{23}}$ - natural and geographical factors $I_2 \rightarrow I_{13}$.

Actors I_2	$W_{I_{21}}$	$W_{I_{22}}$	$W_{I_{23}}$	$W_{I_{24}}$	$\omega_{I_{23}}$
$W_{I_{21}}$	1	0,5	1/3	3	0,17
$W_{I_{22}}$	2	1	3	3	0,44
$W_{I_{23}}$	3	1/3	1	5	0,31
$W_{I_{24}}$	1/3	1/3	0,2	1	0,08

$$OC \approx 0,14 > 0,1.$$

Write the priority vectors $\omega_{I_{2i}}, i = \overline{1, |I_1|}$ for evaluation matrices $A_{I_{2i}}, i = \overline{1, |I_1|}$ of the level I_2 in the form of a matrix $W_{I_2} = \{\omega_{I_{2i}}\}, i = \overline{1, |I_1|}$, where $|I_1|$ - a plurality of power level elements I_1 (table 7).

Go to level I_3 : $W_{I_{31}}$ - maximize data transfer rate, $W_{I_{32}}$ - maximizing transmission reliability (reducing the number of errors), $W_{I_{33}}$ - minimization of energy consumption, $W_{I_{34}}$ - minimizing the consumption of computing resources. Consider its effect on the level elements I_2 .

Table 7. Matrix $W_{I_2} = \{\omega_{I_2 i}\}, i = \overline{1, |I_1|}$ of the influence of system actors on the forces that affect the quality of the reception and transmission of signals.

Forces I_1	$W_{I_1 1}$ - «System of radio stations»	$W_{I_1 2}$ - «Enemy»	$W_{I_1 3}$ - «Nature»
Actors I_2	$\omega_{I_2 1}$	$\omega_{I_2 2}$	$\omega_{I_2 3}$
$W_{I_2 1}$ – internal state of the system	0,40	0,16	0,17
$W_{I_2 2}$ – observer device	0,08	0,37	0,44
$W_{I_2 3}$ – control regulator	0,16	0,41	0,31
$W_{I_2 4}$ – controlled signaling process	0,36	0,05	0,08

The matrices of pairwise comparisons are formed in the same way as the previous level (as a result of the table 8).

Consider the level's I_4 influence: $W_{I_4 1}$ – transmitter power control, $W_{I_4 2}$ – rate control, $W_{I_4 3}$ – management of communications regulations, $W_{I_4 4}$ – control of the type of received signal code constructs, $W_{I_4 5}$ – signal processing control.

The matrices of pair level comparisons and the formation of the normalized vector of the influence of elements on the higher level will be carried out according to the scheme described above (the result in table 9).

Table 8. Matrix $W_{I_3} = \{\omega_{I_3 i}\}, i = \overline{1, |I_2|}$ of the influence of the objectives of the actors on the actors of the system.

Actors I_2	$W_{I_2 1}$ – internal state of the system	$W_{I_2 2}$ – observer device	$W_{I_2 3}$ – control regulator	$W_{I_2 4}$ – controlled signaling process
Actor's goals I_3	$\omega_{I_3 1}$	$\omega_{I_3 2}$	$\omega_{I_3 3}$	$\omega_{I_3 4}$
$W_{I_3 1}$ – maximize data transfer rate	0,43	0,12	0,05	0,11
$W_{I_3 2}$ – maximizing transmission reliability (reducing the number of errors)	0,11	0,43	0,63	0,59
$W_{I_3 3}$ – minimization of energy consumption	0,12	0,41	0,27	0,26
$W_{I_3 4}$ – minimizing the consumption of computing resources	0,34	0,04	0,05	0,04

Table 9. Matrix $W_{I_4} = \{\omega_{I_{4i}}\}, i = \overline{1, |I_3|}$ of influence of actions of actors on the goals of actors.

Goals I_3	$W_{I_{31}}$ – maximize data transfer rate	$W_{I_{32}}$ – maximizing transmission reliability (reducing the number of errors)	$W_{I_{33}}$ – minimization of energy consumption	$W_{I_{34}}$ – minimizing the consumption of computing resources
Actions I_4	$\omega_{I_{41}}$	$\omega_{I_{42}}$	$\omega_{I_{43}}$	$\omega_{I_{44}}$
$W_{I_{41}}$ – transmitter power control	0,47	0,10	0,04	0,07
$W_{I_{42}}$ – rate control	0,09	0,12	0,06	0,24
$W_{I_{43}}$ – management of communications regulations	0,33	0,09	0,22	0,15
$W_{I_{44}}$ – control of the type of received signal code constructs K	0,04	0,37	0,26	0,05
$W_{I_{45}}$ – signal processing control.	0,07	0,10	0,42	0,49

Thus, the influence of the elements of the lower level of the hierarchy can be calculated as (8)

$$\omega_{I_4} = W_{I_4} \omega_{I_3} = W_{I_4} W_{I_3} \omega_{I_2} = W_{I_4} W_{I_3} W_{I_2} \omega_{I_1} \quad (8)$$

5. Calculation results

The results of the calculations are given in tables 10 - 13.

Table 10. Influence of $I_1 \rightarrow I_0$.

Influence $I_1 \rightarrow I_0$	ω_{I_1}
$W_{I_{11}}$ – forces generated by the processes occurring in the operating electrical part of the network of transceivers	0,75
$W_{I_{12}}$ – the enemy, creating interference environment	0,12
$W_{I_{13}}$ – natural and geographical factors	0,13

Table 11. Influence of $I_2 \rightarrow I_0$.

Influence of $I_1 \rightarrow I_0$ ω_{I_1}	I_1			Influence of $I_2 \rightarrow I_0$ ω_{I_2}
	$W_{I_{11}}$	$W_{I_{12}}$	$W_{I_{13}}$	
$W_{I_{21}}$ – inner state of the system	12,47%	4,77%	2,16%	19,40%
$W_{I_{22}}$ – observer device	33,19%	0,97%	4,96%	39,12%
$W_{I_{23}}$ – regulator, producing control actions	23,16%	1,90%	5,50%	30,56%
$W_{I_{24}}$ – managed process Signaling	5,89%	4,30%	0,73%	10,92%

Table 12. Influence of $I_3 \rightarrow I_0$.

Influence of $I_2 \rightarrow I_0$ ω_{I_2}	I_2				Influence of $I_3 \rightarrow I_0$ ω_{I_3}
	$W_{I_2,1}$	$W_{I_2,2}$	$W_{I_2,3}$	$W_{I_2,4}$	
	19,40%	39,12%	30,56%	10,92%	
$W_{I_3,1}$ – speed maximization data transmission	8,32%	4,67%	1,66%	1,15%	15,80%
$W_{I_3,2}$ – confidence maximization transmission (reducing the number of errors)	2,13%	16,75%	19,11%	6,47%	44,45%
$W_{I_3,3}$ – minimization of energy consumption	2,28%	15,99%	8,13%	2,86%	29,26%
$W_{I_3,4}$ – minimization of consumption computing resources	6,68%	1,71%	1,66%	0,44%	10,49%

Table 13. Influence of $I_4 \rightarrow I_0$.

Influence of $I_3 \rightarrow I_0$ ω_{I_3}	I_3				Influence of $I_4 \rightarrow I_0$ ω_{I_4}
	$W_{I_3,1}$	$W_{I_3,2}$	$W_{I_3,3}$	$W_{I_3,4}$	
	15,80%	44,45%	29,26%	10,49%	
$W_{I_4,1}$ – power control transmitter	0,71%	14,47%	13,77%	0,72%	29,67%
$W_{I_4,2}$ – speed control transmission	0,94%	4,31%	2,68%	2,49%	10,41%
$W_{I_4,3}$ – rule management connections	3,42%	5,45%	9,62%	1,57%	20,06%
$W_{I_4,4}$ – received signal code constructions type's management	4,11%	3,80%	1,15%	0,57%	9,63%
$W_{I_4,5}$ – control signal processing algorithm	6,62%	16,43%	2,04%	5,15%	30,23%

6. Main conclusions on the work

Consider and interpret the main results of modeling a cognitive radio system. To do this, consider the effect of each level, the purpose of the system is the efficient signal transmission.

Consider the level effect I_1 . According to Table 5, the influence of forces acting on the purpose of signal transmission is presented (level I_1) on the system's goal (level I_0). The table shows that the value of the influence of natural factors and the effects of the enemy is comparable, but several times less than the state of the radio communication system. This suggests that a properly working radio system is able to withstand the destabilizing factors of a natural nature and intentional interference.

Table 11 presents the influence of system actors (level I_2) on the system's goal (level I_0). From the presented diagram it is clear that the observer's device and the controller are important for the effective transmission of information and the controlled process and the internal state of the information transmission system are less important. This is due to the fact that the observer device includes the main parameters of the receiving paths of the radio equipment of the system. When operating the radio system, it is very important, because The radio exchange always starts at the initial parameters of the radio system, and its operation at this moment depends on the possibilities of detecting and decoding the signal at the initial settings and on the perception of the regulating influence. In the future, according to the results of the evaluation of the communication channel and the formation of control processes on the internal state of the radio system, the parameters are adjusted to improve information transfer.

According to table 12, the impact of the objectives of the actors of the system (level I_3) on the system's goal (level I_0). The table below shows that the goal of reducing the number of errors in the transmission of information and increasing the speed of information transmission is important for the effective transmission of information, in reducing with a reduction in computational load and a decrease in the amount of energy used for transmission. This is true, because The main task of a radio communication system is the transmission of information, and not the saving of computing and energy resources. In addition, the parameters for increasing the exchange rate and reducing the number of errors are inversely related to saving system resources.

According to table 13, the influence of the radio system parameters (level I_4) on the system's goal (level I_0). The table shows that the highest efficiency of the radio system can be achieved through the use of optimal signal processing algorithms, and high power of the transmitted signal. Increasing the speed of information transmission without the necessary energy of the radio link and signal processing algorithms will not give a tangible effect when transmitting information in difficult conditions.

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