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 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. 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. 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 energy used for transmission. 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. High speed of information transmission will not give a tangible effect when transmitting information in difficult conditions without the necessary power of the radio link and signal processing algorithms.

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 and geographic environment. Cognitive radio system uses established rules and its internal state to dynamically and autonomously adjust operational parameters and protocols according to acquired knowledge to achieve pre-set goals. Cognitive radio system be trained on the basis of the obtained results. Thus, the radio stations included in the such 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 controlling dynamic objects problems includes the formation of a mathematical model with the subsequent study of the properties of this model and the synthesis of the controller. The controlling objects 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, while choosing the best communication channel.
Digital systems, solving similar problems, are very flexible and have many options [2]. The choice of structural solutions in the digital systems design is largely determined by the characteristics of the solved problem. 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 works separately, but is able to exchange information with others. To organize the process of a task decomposition 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 analytic hierarchy process 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 complex systems development [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 natural geographical factors, by the enemy, creating an active jamming environment, and by processes occurring in the working electrical part of the radio signals transceivers network. Radio stations that included in such a system should contain devices for analyzing the state of the radio station itself, as well as the external geographic. It also should contain devices for analyzing 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 the 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 \( I = \{I_i \}, i=1, m \). At every hierarchy level 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 \( I_0 \). It shows how the cognitive radio system works.

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

\[
W_{i_1} = \{W_{i_1,j} \}, j=1, n_{i_1} 
\]

affecting the quality of the signals reception and transmission. As already noted, the forces will be: the forces generated by the processes occurring in the operating electrical part of the transceivers network (\( W_{i_1,1} \)), enemy, creating a jamming environment (\( W_{i_1,2} \)) and geographical factors (\( W_{i_1,3} \)).

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

\[
W_{i_2} = \{W_{i_2,j} \}, j=1, n_{i_2} 
\]

where \( W_{i_2,1} \) is internal state of system, \( W_{i_2,2} \) is observer's device (for common reasoning) - a receiver of digital signals (a decoder or, in the case of simultaneous demodulation and decoding, a modem), \( W_{i_2,3} \) is a regulator that generates controls acting on the receiver, transmitter and modem, \( W_{i_2,4} \) is 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 used type of code).

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.
Figure 1. Cognitive radio system’s hierarchical model.

Level of goals $I_3$ consists of $n_{I_3}$ elements (3)

$$W_{I_3} = \{W_{I_3j}\}, j = 1, n_{I_3},$$ (3)

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

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

$$W_{I_4} = \{W_{I_4j}\}, j = 1, n_{I_4},$$ (4)
where $W_{i1}$ is transmitter power control, $W_{i2}$ is rate control, $W_{i3}$ is carrier frequency control, $W_{i4}$ is management of communications regulations, $W_{i5}$ is control of the type of received signal code constructs, $W_{i6}$ is signal processing control.

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

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 $I_0$. According to this we will compare the importance of elements in pairs. $W_i = \{W_{ij}, j = 1, n_i\}$ on a scale of relationships [1;9], where the dominance of element $W_{ik}$ in relation to $W_{im}$ is denoted by an integer from the scale of relations $a_{km}$. Making $C^2_{n_i}$ comparisons we will fill in the matrix $A_i = [a_{ij}]$ of pair comparisons, of dimension $n_i \times n_i$.

To fill the matrix $A_i$ it is necessary to answer the question: what elements in relation to the cognitive communication system effective work 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 transceivers network ($W_{i1}$), "Opponent" - the forces formed by the enemy, creating a disturbance environment ($W_{i2}$) and "Nature" - natural and geographical factors ($W_{i3}$). We present the comparison in table 1.

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

| №  | Comparison | Result | Explanation |
|----|------------|--------|-------------|
| 1  | $W_{i1}$ & $W_{i2}$ | $a_{12} = 7$ | very strong influence |
|    |            |        | $W_{i1}$ is correct operation of the radio station system has a much greater effect on the result, compared to $W_{i2}$ is 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  | $W_{i1}$ & $W_{i3}$ | $a_{13} = 5$ | strong influence |
|    |            |        | $W_{i1}$ is correct operation of the system has a strong influence on the result, in comparison with $W_{i3}$ is natural-geographical factors, because The technical devices of the radio system are designed to overcome these factors. |
| 3  | $W_{i2}$ & $W_{i3}$ | $a_{23} = 1$ | equal effect |
|    |            |        | Impact $W_{i2}$ is 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 $W_{i3}$ who finds it difficult to carry out broadband interference in hard-to-reach areas. |

Fill matrix $A_i$, setting by T. Saati that the comparison of the effect influence $W_{im}$ to $I_0$ towards $W_{ik}$ replaced by the inverse of the influence $W_{ik}$ to $I_0$ towards $W_{im}$ $a_{mk} = \frac{1}{a_{km}}$. It is necessary to
take into account the equal importance of the element’s influence in comparison with itself \(a_{ik} = 1\). The results are given in table 2.

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

| \(A_{i_k}\) | \(W_{i_1}\) | \(W_{i_2}\) | \(W_{i_3}\) |
|---|---|---|---|
| \(W_{i_1}\) | 1 | \(a_{12} = 7\) | \(a_{13} = 5\) |
| \(W_{i_2}\) | \(\frac{1}{a_{12} = 1/7}\) | 1 | \(a_{23} = 1\) |
| \(W_{i_3}\) | \(\frac{1}{a_{13} = 1/5}\) | \(\frac{1}{a_{23} = 1}\) | 1 |

The task is to Find the right eigenvector \(\omega'_i\) of the matrix \(A_{i_k}\), corresponding to the maximum eigenvalue of solving the equation (5)

\[
A_{i_k} \omega'_i = \lambda_{\text{max}, i_k} \omega'_i, \quad (5)
\]

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

Let’s take \(y^{(0)} = \{1, \ldots, 1\}\) unit vector of dimension \(n_{i_k}\). Run an iterative process \(y^{(k)} = A_{i_k}y^{(k-1)} = A_{i_k}^{-1}y^{(0)}\) before reaching (6)

\[
\varepsilon^{(k)} = \left| \frac{y_j^{(k)}}{y_j^{(k-1)}} - \frac{y_j^{(k-1)}}{y_j^{(k-2)}} \right| \leq \varepsilon,
\]

where \(\varepsilon\) is computing error, \(\lambda_{\text{max}, i_k} = \frac{y_j^{(k)}}{y_j^{(k-1)}}\).

The resulting vector of the iteration process \(y^{(k)}\) is a solution of matrix equation \(A_{i_k} \omega'_i = \lambda_{\text{max}, i_k} \omega'_i\).

After normalizing the vector \(\omega'_i\) by the sum of its coordinates, we obtain the vector (7)

\[
\omega_i = \left\{ \frac{\omega'_i}{\sum_{j=1}^{n_{i_k}} \omega'_i} \right\}, i = 1, n_{i_k},
\]

where \(\omega_i\) is influence vector of \(I_i \rightarrow I_o\) forces, located at the level \(I_i\) on the system’s goal \(I_o\).

As a calculations result we get \(\omega_i = (0.75; 0.12; 0.13)\). These weights indicate that weather factors and the adversary make an equal contribution to the successful system’s operation (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 | \(I_o\) |
|---|---|
| \(W_{i_1}\) is forces generated by the processes occurring in the operating electrical part of the network of transceivers | 0.75 |
| \(W_{i_2}\) is the enemy, creating interference environment | 0.12 |
| \(W_{i_3}\) is natural and geographical factors | 0.13 |

\(IC = 0.05 < 0.1\).
As a measure of the judgments correctness, a consistency relation is introduced \((CR)\) – the ratio of the consistency index \((CI)\) of the pair comparison matrices \(A_{ij}\) to random index \((RI)\) is the \(IC\) for a square matrix of dimension \(n \times n\) filled with random numbers. For matrices of dimension \(n \times n\) \(CI\) is calculated by \(IC = \frac{\lambda_{\text{max}} - n}{n-1}\). \(IC \leq 0.1\) is considered acceptable for consistency of the pairwise comparison matrix.

By performing similar calculations, we get all the influence vectors \(\omega_j, j = 1, 4\) of the levels \(I_j \rightarrow I_{j-1}\) in hierarchy \(I\).

4. Formation of evaluation matrices

Table 4. The matrix of pairwise comparisons \(A_{ij}\) and the normalized value of the vector of influence of actors on the provision \(W_{ij}\) is the correct operation of the radio station system \(I_2 \rightarrow I_{11}\).

| Actors \(I_2\) | \(W_{i1}\) | \(W_{i2}\) | \(W_{i3}\) | \(W_{i4}\) | \(\omega_{i1}\) |
|---------------|--------|--------|--------|--------|--------|
| \(W_{i1}\)    | 1      | 5      | 3      | 1      | 0.40   |
| \(W_{i2}\)    | 0.2    | 1      | 1/3    | 1/3    | 0.08   |
| \(W_{i3}\)    | 1/3    | 3      | 1      | 1/3    | 0.16   |
| \(W_{i4}\)    | 1      | 3      | 3      | 1      | 0.36   |

\(IC \approx 0.07 < 0.1\).

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. The matrix of pairwise comparisons \(A_{ij}\) and the normalized value of the vector of influence of actors on overcoming \(W_{ij}\) is the counter enemy \(I_2 \rightarrow I_{12}\).

| Actors \(I_2\) | \(W_{i1}\) | \(W_{i2}\) | \(W_{i3}\) | \(W_{i4}\) | \(\omega_{i2}\) |
|---------------|--------|--------|--------|--------|--------|
| \(W_{i1}\)    | 1      | 0.5    | 1/3    | 3      | 0.16   |
| \(W_{i2}\)    | 2      | 1      | 1      | 7      | 0.37   |
| \(W_{i3}\)    | 3      | 1      | 1      | 7      | 0.41   |
| \(W_{i4}\)    | 1/3    | 1/7    | 1/7    | 1      | 0.05   |

\(IC \approx 0.04 < 0.1\).

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

| Actors \(I_2\) | \(W_{i1}\) | \(W_{i2}\) | \(W_{i3}\) | \(W_{i4}\) | \(\omega_{i3}\) |
|---------------|--------|--------|--------|--------|--------|
| \(W_{i1}\)    | 1      | 0.5    | 1/3    | 3      | 0.17   |
| \(W_{i2}\)    | 2      | 1      | 3      | 3      | 0.44   |
| \(W_{i3}\)    | 3      | 1/3    | 1      | 5      | 0.31   |
| \(W_{i4}\)    | 1/3    | 1/3    | 0.2    | 1      | 0.08   |

\(IC \approx 0.14 > 0.1\).
Write the priority vectors $\omega_{ij}, i = 1, \ldots, |I_1|$ for evaluation matrices $A_{ij}, i = 1, \ldots, |I_1|$ of the level $I_2$ in the form of a matrix $W_{i1} = \{\omega_{ij}, i = 1, \ldots, |I_1|\}$, where $|I_1|$ is the plurality of power level elements $I_1$ (table 7).

Table 7. Matrix $W_{i2} = \{\omega_{ij}, i = 1, \ldots, |I_2|\}$ of the system actors influence on the forces that affect the quality of the reception and transmission of signals.

| Forces $I_1$ | $W_{i1}$ is «System of radio stations» | $W_{i2}$ is «Enemy» | $W_{i3}$ is «Nature» |
|--------------|----------------------------------------|---------------------|---------------------|
| Actors $I_2$ | $\omega_{i1}$                          | $\omega_{i2}$       | $\omega_{i3}$       |
| $W_{i1}$ is internal state of the system | 0.40 | 0.16 | 0.17 |
| $W_{i2}$ is observer device | 0.08 | 0.37 | 0.44 |
| $W_{i3}$ is control regulator | 0.16 | 0.41 | 0.31 |
| $W_{i4}$ is controlled signaling process | 0.36 | 0.05 | 0.08 |

Go to level $I_3$: $W_{i1}$ is maximize data transfer rate, $W_{i2}$ is maximizing transmission reliability (reducing the number of errors), $W_{i3}$ is minimization of energy consumption, $W_{i4}$ is minimizing the consumption of computing resources. Consider its effect on the level elements $I_2$.

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 $I_3$ influence: $W_{i1}$ is transmitter power control, $W_{i2}$ is rate control, $W_{i3}$ is management of communications regulations, $W_{i4}$ is control of the type of received signal code constructs, $W_{i5}$ is 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 $W_{i3} = \{\omega_{ij}, i = 1, \ldots, |I_2|\}$ is the influence of the objectives of the actors on the actors of the system.

| Actors $I_2$ | $W_{i1}$ is internal state of the system | $W_{i2}$ is observer device | $W_{i3}$ is control regulator | $W_{i4}$ is controlled signaling process |
|--------------|----------------------------------------|-----------------------------|--------------------------------|----------------------------------------|
| Actor’s goals $I_3$ | $\omega_{i1}$ | $\omega_{i2}$ | $\omega_{i3}$ | $\omega_{i4}$ |
| $W_{i1}$ is maximize data transfer rate | 0.43 | 0.12 | 0.05 | 0.11 |
| $W_{i2}$ is maximizing transmission reliability (reducing the number of errors) | 0.11 | 0.43 | 0.63 | 0.59 |
| $W_{i3}$ is minimization of energy consumption | 0.12 | 0.41 | 0.27 | 0.26 |
| $W_{i4}$ is minimizing the consumption of | 0.34 | 0.04 | 0.05 | 0.04 |
computing resources

Table 9. Matrix $W_i = \{ \omega_{i,j} \}, i = 1, \ldots, |I|$ of influence of actions of actors on the goals of actors.

| Goals $I_3$ | $W_{i,1}$ is maximize data transfer rate | $W_{i,2}$ is maximizing transmission reliability (reducing the number of errors) | $W_{i,3}$ is minimizing of energy consumption | $W_{i,4}$ is minimizing the consumption of computing resources |
|-------------|------------------------------------------|----------------------------------|------------------------------------------|------------------------------------------|
| Actions $I_4$ | $\omega_{i,1}$ | $\omega_{i,2}$ | $\omega_{i,3}$ | $\omega_{i,4}$ |
| $W_{i,1}$ is transmitter power control | 0.47 | 0.10 | 0.04 | 0.07 |
| $W_{i,2}$ is rate control | 0.09 | 0.12 | 0.06 | 0.24 |
| $W_{i,3}$ is management of communications regulations | 0.33 | 0.09 | 0.22 | 0.15 |
| $W_{i,5}$ is control of the type of received signal code constructs $K$ | 0.04 | 0.37 | 0.26 | 0.05 |
| $W_{i,5}$ is 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)

$$\omega_{i} = W_{i} \omega_{i} = W_{i,4} W_{i,3} \omega_{i} = W_{i,4} W_{i,3} W_{i,2} \omega_{i} = W_{i,4} W_{i,3} W_{i,2} W_{i,1} \omega_{i}. \quad (8)$$

5. Calculation results
The calculations results are given in tables 10 - 13.

Table 10. Influence of the level $I_1$ to the $I_0$.

| Influence $I_1 \rightarrow I_0$ | $\omega_{i}$ |
|-------------------------------|-------------|
| $W_{i,1}$ is forces generated by the processes occurring in the operating electrical part of the network of transceivers | 0.75 |
| $W_{i,2}$ is the enemy, creating interference environment | 0.12 |
| $W_{i,3}$ is natural and geographical factors | 0.13 |

Table 11. Influence of the level $I_2$ to the $I_0$.

| Influence of $I_1 \rightarrow I_0$ | $\omega_{i}$ |
|-------------------------------|-------------|
| $W_{i,1}$ | 74.71% | 11.94% | 13.36% |
| $W_{i,2}$ is inner state of the system | 12.47% | 4.77% | 2.16% | 19.40% |
| $W_{i,3}$ is observer device | 33.19% | 0.97% | 4.96% | 39.12% |
$W_{i,3}$ is regulator, producing control actions
$W_{i,4}$ is managed process Signaling

| Influence of $I_2 \rightarrow I_0$ $\omega_{i_2}$ | $W_{i,1}$ | $W_{i,2}$ | $W_{i,3}$ | $W_{i,4}$ |
|---------------------------------------------|-----------|-----------|-----------|-----------|
| 19.40%                                      | 39.12%    | 30.56%    | 10.92%    |

$W_{i,1}$ is speed maximization data transmission
$W_{i,2}$ is confidence maximization transmission (reducing the number of errors)
$W_{i,3}$ is minimization of energy consumption
$W_{i,4}$ is minimization of consumption computing resources

| Influence of $I_3 \rightarrow I_0$ $\omega_{i_3}$ | $W_{i,1}$ | $W_{i,2}$ | $W_{i,3}$ | $W_{i,4}$ |
|---------------------------------------------|-----------|-----------|-----------|-----------|
| 15.80%                                      | 44.45%    | 29.26%    | 10.49%    |

$W_{i,1}$ is power control transmitter
$W_{i,2}$ is speed control transmission
$W_{i,3}$ is rule management connections
$W_{i,4}$ is received signal code constructions type’s management
$W_{i,5}$ is control signal processing algorithm

| Influence of $I_4 \rightarrow I_0$ $\omega_{i_4}$ | $W_{i,1}$ | $W_{i,2}$ | $W_{i,3}$ | $W_{i,4}$ |
|---------------------------------------------|-----------|-----------|-----------|-----------|
| 29.67%                                      | 10.41%    | 20.06%    | 9.63%     |

### 6. Conclusion

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

Consider the level effect $I_i$. Table 5 shows the influence of forces acting on the purpose of signal transmission (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 geographical 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 information transmission and the controlled process. The internal state of the information transmission system is less important. This is because the observer device includes the main parameters of the receiving paths of the system radio equipment. When operating the radio system, it
is very important, because the radio exchange always starts at the initial parameters of the radio system. It’s 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, the parameters are adjusted to improve information transfer.

Table 12 presents the impact of the objectives of the system’s actors (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. Computation and energy used for transmission are less important. 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.

Table 13 shows the influence of the radio system parameters (level $I_4$) on the system’s goal (level $I_0$). According to the table 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. High speed of information transmission will not give a tangible effect when transmitting information in difficult conditions without the necessary power of the radio link and signal processing algorithms.

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