System analysis of the cognitive radio system operation algorithm efficiency

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Abstract. The report presents an algorithm for optimal control of a cognitive radio communication system. The algorithm is based on the application of decision-making criteria in a dynamic environment. The basis of the algorithm is to solve the problem of maximizing the system efficiency coefficient in a given mode. Thus, the cognitive radio communication system can choose the most optimal mode of operation, both in a specific situation, and choose the general preferred mode of operation for a comprehensive assessment of the external situation. From the effectiveness of the radio system in analog and digital modes, we can conclude that in the event of time limitations it is more useful to control the transmitter power (increase the energy of the radio line). However, when working in digital modes, the decrease in efficiency is much slower than when using analog modes. An analysis of the operation under conditions of restrictions on the transmission power also shows a slower decrease in efficiency in digital modes with slow consumption of resources, while consumption increases sharply in analog mode.

1. Introduction

The use of software-defined and cognitive radio technologies when developing information transmission systems is prerequisite [1–5]. The stand of the chief designer (SCD) is actively used at the stages of preliminary design and technical design [6,7]. The mathematical support of the SCD allows optimization of technical solutions in the development of radio systems and devices. The development of control algorithms, which are an integral part of the cognitive system is one of these tasks.

The use of a mechanism for adapting to the changing external operating conditions of the system is required for technical systems operating in an unsteady environment. The development of the system with a focus on the "average" conditions leads to the fact that the system is able to work optimally only in these "average" conditions (the effectiveness of the functioning of the system decreases) [8]. Therefore, the introduction of an operating mode control algorithm that will change the control parameters of the system in order to support the effectiveness of its functioning in various operating modes is an urgent task.

The purpose of the study is to optimize the operation of the cognitive radio system by introducing an algorithm for controlling the system parameters in various operating modes.
2. Development mode control algorithm for cognitive radio system

We introduce the notation \( E_i, i = 1, m \) – specific mode of operation of the cognitive radio system. \( E_i \) is selected taking into account external conditions \( F_j, j = 1, n \), where \( n \) – considered combinations of coefficients of the objective function \( Y(1) \) and situation’s existing resources \( b(2) \), where \( b_1 \) – amount of energy; \( b_2 \) – time fund; \( b_3 \) – calculation resource fund. Function \( (1) \) – dimensionless efficiency index. It connects the control parameters of the system with the achievement of competitive goals: minimizing the energy consumption when transmitting information, maximizing the reliability of receiving messages, increasing the speed of receiving and transmitting messages and reducing the computing load on the computing system when receiving and transmitting messages (the efficiency coefficient was constructed by the authors in [9, 10]). The relationship is introduced by the hierarchical structure according to the hierarchy analysis method. The root of the hierarchy is the indicated system performance; at the second level of the hierarchy, forces have been introduced that affect the efficiency of the system; the third level is actors; fourth, goals; at the lower (fifth) level of the system are the control parameters. The global weight of the control parameters is included in the efficiency indicator by a coefficient \( Y(1) \). Variables \( x_i \in [0, \max x_i] \) of efficiency indicator are levels of activation the control parameters. The onset of an event \( F_j \) is characterized by probability \( q_j \).

\[
Y(\bar{c}, \bar{x}) = \sum_{i=1}^{k} c_i x_i \rightarrow \max ,
\]

\[
\begin{aligned}
\sum_{i=1}^{k} a_{ij} x_i &\leq b_1, \\
\sum_{i=1}^{k} a_{ij} x_i &\leq b_2, \\
\sum_{i=1}^{k} a_{ij} x_i &\leq b_3 ;
\end{aligned}
\]

\[\tilde{x} = \{x_i \in [0, \max x_i]\}, l = 1, k.\] (3)

Each \( E_i \) characterized by the maximum value of the goal function \( (1) \) obtained by the simplex method algorithm in every combination of \( F_j \) and \( q_j \) [11, 12]. Denote the maximum value of the goal function \( (1) \) of \( E_i \) regime at \( F_j \) throw \( e_{ij} \). We compose a decision matrix \( \{e_{ij}\}, i = 1, m; j = 1, n \).

To solve the problems of choosing optimal solutions for stochastic external situations, decision-making criteria have been developed [13–16]. According to the specific decision criteria \( Z_k \) each \( E_i \) characterize by \( e_{ij} \). So, the task of choosing the optimal mode of operation of the system is reduced to solving the decision-making problem:

\[
E_\omega = \{E_i : e_{ij} = Z_k, i = 1, m\}.\] (4)

We compose an extended decision matrix for \( l \) options for decision criteria \( Z_k \):
We will consider the set of decision-making criteria $Z_k$. Set $Z_k = \{Z_{MM}, Z_{BL}, Z_S\}$. Here $Z_{MM}$ – minimax criterion; characterized by extreme caution when making decisions. It is applied when it is necessary to exclude any risk.

$$Z_{MM} = \max \limits_i e_{i,\text{w}}, \ e_{i,\text{w}} = \min \limits_j e_{ij}; \quad (6)$$

$Z_{BL}$ – Bayes-Laplace criterion involves knowledge of the probabilities of occurrence of states $F_j$,

$$Z_{BL} = \max \limits_i e_{i,\text{w}}, \ e_{i,\text{w}} = \sum \limits_{j=1}^n e_{ij} q_j; \quad (7)$$

where $\sum \limits_{j=1}^n q_j = 1$;

$Z_S$ – Savage criterion; focused on finding obviously not the worst $E_i$,

$$Z_s = \min \limits_i e_{i,\text{w}}, \ e_{i,\text{w}} = \max \limits_j a_{ij}, \quad (8)$$

where $a_{ij} = \max e_{ij} - e_{ij}$; value of $a_{ij}$ is understood as the maximum possible result from the application in the state $F_j$ of the optimal variant for this state $E_i$.

For each of the criteria we define a set $E_o = \{E_i: e_{i,\text{w}} = Z_k, i = 1, m\}$. We will choose the optimal operating modes by choosing a preferred Criterion $Z_k$ or finding the intersection of sets $E_o$ for a group of preferred criteria (we define the preference of the criteria by the method of pairwise comparisons [17, 18]) for the considered external situations $F_j, j = 1, n$.

The operating modes of the cognitive radio system from the set $E_o$ are characterized by the maximum value of function (1) in each external situation. The maximum value of the objective function is achieved in each of the modes $E_i$ at a certain level of activation of control parameters $x_i$ (3) of goal function (1). So, the cognitive radio system can choose itself the most optimal mode of operation in a particular situation $F_j$ or the general preferred mode $E_i$ for an integrated assessment of the external situation.

Algorithm:
1. Calculate the vectors of the objective function $Y (1)$ according to the selected hierarchy of the influence of control parameters on the target of the system [19, 20].
2. Calculate resource consumption vectors for system control parameters (2).
3. Set restrictions on vector $b$ - resources stock and vector $q$ - probability of occurrence of an event.
4. Fill in the decision matrix $E = \{e_{ij}\}, i = 1, m; j = 1, n$ (5), by calculate $e_{ij}$ through the simplex method in the restrictions of clause 3 of the algorithm.
5. Generate a set of optimal solutions $E_o$ according to the preferred criterion from (6) - (8).
When changing the structure of control parameters, the algorithm starts from step 1. In the case of changing the system environment, the algorithm can be started from step 3. If the decision is again made for the environment of the system to adapt the algorithm to the tasks of the decision maker, it is possible to execute the algorithm from step 5.

3. The results of applying the control algorithm to the operating modes of the cognitive radio system

Consider the system in analog and digital signal transmission modes. Let us single out four characteristic situations $F_j$ in which the system has to work: $F_1$ - full resources; $F_2$ - half the battery capacity; $F_3$ - critical battery level; $F_4$ - lack of time.

| $E_i$ | Power, W | Order | Type SCS modulation type | Frequency, MHz | Band, kHz | $Y$, units. | The value of decision-making criteria, units |
|------|---------|-------|--------------------------|----------------|----------|-------------|------------------------------------------|
| 1    | 10      | Time simple x | A1A – amplitude telegraph | 3…30 HF        | 1        | 0.16 0.67 0.32 0.52 | 0.324 0.785 0.297 |
| 2    | 10      | Time simple x | J3E – Single-band amplitude telephony (up to –40 dB) | 3…30 HF | 3.1     | 1.24 0.76 0.45 0.42 | 0.428 0.858 0.168 |
| 3    | 3       | Time simple x | F3E – Frequency telephony | 30…300 VHF | 12.5    | 1.22 0.81 0.53 0.34 | 0.346 0.877 0.175 |
| 4    | 3       | Time simple x | F3E – Frequency telephony | 300…3000 UHF | 12.5    | 1.27 0.88 0.62 0.31 | 0.312 0.929 0.209 |
| 5    | 3       | Time simple x | A3E – two-way amplitude telephony | 30…300 VHF | 12.5    | 1.23 0.78 0.47 0.43 | 0.435 0.867 0.144 |
| 6    | 3       | Time simple x | A3E – two-way amplitude telephony | 300…3000 UHF | 12.5    | 1.27 0.87 0.55 0.39 | 0.391 0.924 0.131 |

**Table 1.** Extended decision matrix.
We present the results of applying the system parameter control algorithm to the analog modes of the system. Table 1 shows the extended decision matrix, compiled on the basis of the parameter control algorithm in analog modes.

According to the table 1 in terms of minimax criterion $Z_{MM}$ you should select $E_5$ mode as the main mode; $Z_{BL}$ criterion suggests $E_4$ mode as the most optimal.

For $Z_s$ table 2 shows risks matrix $R$ non-optimal decision making for the decision matrix given in table 1.

**Table 2.** Non-optimal decision risk matrix.

| $q$ | $E_i$ | Deviation of $Y$ from max $Y$ for each $F_j$, units |
|-----|------|-----------------------------------------------|
|     |      | $F_1$ | $F_2$ | $F_3$ | $F_4$ |
| 0.4 | 1    | 0.115 | 0.202 | 0.297 | 0.000 |
| 0.3 | 2    | 0.037 | 0.118 | 0.168 | 0.093 |
| 0.2 | 3    | 0.049 | 0.065 | 0.090 | 0.175 |
| 0.1 | 4    | 0.004 | 0.000 | 0.000 | 0.209 |
| 0.043 | 5   | 0.098 | 0.144 | 0.086 |
| 0.000 | 6   | 0.004 | 0.064 | 0.131 |

According to the data in table 2, $Z_s$ offers the $E_6$ mode as the most optimal, which has the smallest maximum deviation from the best result under the influence of the considered factors $F_j$. Consider the application of the results of maximizing the efficiency indicator $Y$ as an example of digital data transfer modes (table 3). For each factor $F_j$, there is a better (risk-free) mode of operation (relative to other modes).

**Table 3.** Indicator of the efficiency of the system $Y$ in different situations when transmitting digital data.

| $E_i$ | Power, W | Speed, bit/sec | SCS modulation type | Frequency, MHz | Band, kHz | $Y$, units | $q$ |
|------|----------|---------------|-------------------|---------------|----------|------------|-----|
|      |          |               |                   |               |          | $F_1$ | $F_2$ | $F_3$ | $F_4$ |
| 1    | 1        | 75            | SSB               | 3…30 (HF)     | 3,1      | 1.135    | 1.188 | 0.966 | 0.264 |
|      | 10       | 200           | OFDM              | 3…30 (HF)     | 3,1      | 1.750    | 0.920 | 0.440 | 0.533 |
|      | 100      | 800           | SSB               | 3,1           | 3,1      | 1.647    | 0.923 | 0.460 | 0.346 |
|      | 2400     | QPSK          | 30…300 (VHF)     | 6,25/12,5     | 12,5     | 1.357    | 1.047 | 0.419 | 0.875 |
| 3    | 1        | 2400          | 4FSK              | 300…300 (UHF) | 6,25/12,5| 25/50/100/150 |
|      | 3        | 9600          | QPSK              | 25/50/100/150 | 12,5     | 25/50/100/150 |
Tables 4–7 show the results of processing the decision matrix in order to obtain the maximum indicator \( Y \) for the entire cycle of message transmission.

Consider the results of calculating the performance indicator \( Y \) (table 3, four right columns) by the simplex method in various modes of the system (table 4). We introduce the notation: PC – power control of the transceiver equipment; SC – control of the speed of reception and transmission; SCSC – control of the type of signal-code structures; CC – control of the carrier frequency; BC – band management.

**Table 4.** The results of calculating the efficiency indicator \( Y \) by the simplex method in E2 operating mode with a full battery charge.

| The coefficients of the goal function (1) | Need | Stock | Balance | –     |
|-----------------------------------------|------|-------|---------|-------|
| \( \begin{array}{ccccc}
   c_1 & c_2 & c_3 & c_4 & c_5 \\
   0.323 & 0.188 & 0.257 & 0.120 & 0.112 \\
\end{array} \) |      |       |         |       |
| PC | SC | SCSC | CC | BC | 0.591 | 0.149 | 0.119 | 0.062 | 0.079 | **0.901** | 1.000 | 0.099 |       |
|    |    |      |    |    | 0.057 | 0.362 | 0.328 | 0.058 | 0.194 | **0.848** | 1.000 | 0.152 |       |
|    |    |      |    |    | 0.190 | 0.374 | 0.291 | 0.069 | 0.076 | **1.000** | 1.000 | 0.000 |       |
|    |    |      |    |    | \( x_1 \) | \( x_2 \) | \( x_3 \) | \( x_4 \) | \( x_5 \) |   | \( Y \) |                  | 0.848 |       |
|    |    |      |    |    | 0.000 | 0.000 | 0.000 | **14.555** | 0.000 | 1.750 |       |

The system starts to work in the second (\( E_2 \)) mode as the most effective according to the efficiency indicator \( Y = 1.750 \) (see table 3, factor \( F_1 \)). In this mode, resources will be used to control the frequency.

When the charge level reaches about 50\%, the system remains in the second mode of operation (see table 3, factor \( F_2 \)). In this mode of operation, the resources will be used to control the speed of the type of signal-code structures and control the carrier frequency.

When a critical battery level is reached, the system switches to \( E_3 \) operation mode as having the highest efficiency indicator (table 3, factor \( F_3 \)). In this mode of operation, all resources will also be directed to the formation of signal-code constructions.

When the time allotted for the session comes to an end, the system should switch to the \( E_4 \) operating mode as the most effective one - having the highest value of the efficiency indicator (table 3, factor \( F_4 \)). In this mode of operation, all resources will be aimed at increasing the transmission power of messages.

**Table 5.** The results of calculating the consumption of battery capacity in a controlled mode of digital data transmission.

| \( t \), units | \( E_i \) | \( Y \), units | Energy stock, units | Energy consumption, units |
|----------------|---------|----------------|---------------------|--------------------------|
| 0              | 2       | 1.750          | 1.00                | 0.09                     |
| 0.1            | 2       | 1.750          | 0.91                | 0.09                     |
| 0.2            | 2       | 1.750          | 0.82                | 0.09                     |
| 0.3            | 2       | 1.750          | 0.73                | 0.09                     |
| 0.4            | 2       | 1.750          | 0.64                | 0.09                     |
It can be seen from tables 3 and 5, the system can function more efficiently (mode $E_w$) in various external situations $F_j$ when controlling the operating modes $E_i$. For comparison, we give the calculated values of the battery capacity for the remaining operating modes (table 6).

**Table 6.** Comparison of the results of calculating battery consumption digital data transmission modes $E_i$

| $t$, units | $Y$, units | Estimated energy reserve in the considered modes, units |
|------------|------------|--------------------------------------------------------|
|            |            | $E_0$ | $E_2$ | $E'_2$ | $E_3$ | $E_4$ |
| 0          | 1.75       | 1.00  | 1.00  | 1.19   | 1.42  | 0.44  |
| 0.1        | 1.75       | 0.91  | 0.91  | 1.07   | 1.27  | 0.40  |
| 0.2        | 1.75       | 0.82  | 0.82  | 0.95   | 1.12  | 0.36  |
| 0.3        | 1.75       | 0.73  | 0.73  | 0.83   | 0.97  | 0.32  |
| 0.4        | 1.75       | 0.64  | 0.64  | 0.70   | 0.82  | 0.27  |
| 0.5        | 1.75       | 0.55  | 0.55  | 0.58   | 0.67  | 0.23  |
| 0.6        | 1.03       | 0.46  | 0.46  | 0.46   | 0.52  | 0.19  |
| 0.7        | 1.03       | 0.34  | 0.37  | 0.34   | 0.37  | 0.15  |
| 0.8        | 0.46       | 0.22  | 0.28  | 0.22   | 0.22  | 0.11  |
| 0.9        | 0.49       | 0.06  | 0.19  | 0.09   | 0.06  | 0.06  |
| 1          | 0.49       | 0.02  | 0.10  | -0.03  | -0.09 | 0.02  |

$E'_2$ – is $E_2$ at half capacity of the energy source.

**Table 7.** Comparison of the results of calculating the rate of consumption of battery capacity of digital data transmission modes.

| $t$, units | Energy consumption in the considered modes, units |
|------------|--------------------------------------------------|
|            | $E_0$ | $E_2$ | $E'_2$ | $E_3$ | $E_4$ |
| 0          | 0.09  | 0.09  |        |       |       |
| 0.1        | 0.09  | 0.09  |        |       |       |
| 0.2        | 0.09  | 0.09  |        |       |       |
| 0.3        | 0.09  | 0.09  |        |       |       |
| 0.4        | 0.09  | 0.09  |        |       |       |
| 0.5        | 0.09  | 0.09  |        |       |       |
| 0.6        | 0.12  | 0.12  |        | 0.12  |       |
| 0.7        | 0.12  | 0.12  |        | 0.12  |       |
Conclusions
A developed algorithm for managing the parameters of the cognitive radio system is presented. The target functions of the efficiency of the radio system in the analog and digital modes of data voice transmission are determined. To increase the efficiency of the radio system, an assessment was made of the consumption of resources when transmitting information for a given criterion of the effectiveness of the radio system - reliable transmission of information.

For analog speech transmission modes (see table 1), the results of calculating the performance criteria obtained by the simplex method based on the objective function, as well as the minimax criterion, the Savage and Bayes – Laplace criteria are given. Each of them can be used to optimize the performance of the cognitive radio system in the respective scenarios. For Savage criterion, the calculation of the risk matrix for making a non-optimal decision on the choice of the operating mode is presented.

For digital data and speech transmission modes, an example of choosing the optimal operating mode based on the efficiency criterion obtained by the simplex method is presented. When transmitting information in digital data transfer modes, to achieve maximum efficiency of information transfer to the radio system when the battery is fully charged, work should begin in \( E_2 \) mode. When working in this mode (in fact, the mode without restrictions), it is possible to increase the transmission efficiency by controlling the frequency, since controlling the rest of the parameters will not give a significant improvement in radio exchange. When the battery is discharged by 50%, there is a limitation in the energy resource, so it is optimal to continue working in \( E_2 \) mode, however, to increase the efficiency of information exchange, it is necessary to manage signal-code constructions. This is due to the fact that more noise-resistant SCS will give a greater increase in efficiency than control of transmission frequencies. When the battery level is low, the radio needs to switch to \( E_3 \) mode. To increase the efficiency of information transfer in this mode, it is also advisable to continue the control of signal-code constructions. When continuing to work in time constraints, it is necessary to switch to the \( E_4 \) operating mode and direct the resources of the radio system to control the transmission power, thereby increasing efficiency by increasing the energy of the radio line. It should be noted that work under strong energy and time constraints leads to a sharp increase in the consumption of energy resources and a decrease in the efficiency of the system.

In general, considering the operation of the radio system in digital modes, it can be concluded that when energy and time constraints occur, the resource consumption rate decreases and the system performance decreases.

Considering the efficiency of the radio system in the modes of voice and data transmission, we can conclude that with the onset of time constraints, it is effective to control the transmitter power (increase the energy of the radio line).

Thus, on the example of the analysis of voice and data transmission in digital modes, the principle of choosing the optimal parameters of the radio system using the proposed parameter control algorithm is shown.

Acknowledgements
This work was supported by a grant BGA/20-28-09 of ISTU named after Kalashnikov.

References
[1] Principe F, Bacci G, Giannetti F, Luise M 2011 Software-Defined Radio Technologies for GNSS Receivers: A Tutorial Approach to a Simple Design and Implementation International
Journal of Navigation and Observation 2011 979815

[2] Rupali B P, Kulat K D, Gandhi A S 2018 SDR Based Energy Detection Spectrum Sensing in Cognitive Radio for Real Time Video Transmission Modelling and Simulation in Engineering 2018 2424305

[3] Halloush R, Musa A, Salameh H B, Halloush M, Almalkawi I 2018 A resource sharing platform for resource-constrained software defined cognitive radio networks Fifth Int. Conf. on Software Defined Systems (SDS) 2018 Barcelona 32-39

[4] Nguyen V, Villain F, Guilhou Y 2012 Cognitive Radio RF: Overview and Challenges VLSI Design 2012 716476

[5] Tanveer A, Khan Z U, Malik A N, Qureshi I M, Lee S 2018 Flexible Queuing Model for Number of Active Users in Cognitive Radio Network Environment Wireless Communications and Mobile Computing 2018 8349486

[6] Kopysov A N, Khvorenkov V V, Zykin A A, Markov M M, Bogdanov A A 2018 Using the Internet of Things technology to create automated systems for monitoring and testing radio systems Journal Achievements of Modern Radio electronics 12 71-6

[7] Khvorenkov V V, Baturin I S, Savel'ev A V 2017 Automated workplace of the chief designer of electronic equipment based on the theory of multi-agent systems Bulletin of Kalashnikov ISTU 4 77-81

[8] Rastrigin L A 1981 Adaptacija slozhnych system (Riga: Zinatne Publ.)

[9] Blagodatsky G A, Kopysov A N, Khvorenkov V V, Baturin I S 2018 Analysis of the hierarchical model of the automated control system of the parameters of the radio lines of the cognitive radio system H&ES Research 6 51-67

[10] Blagodatsky G A, Kopysov A N, Khvorenkov V V, Baturin I S 2019 Research and development of hierarchical models of automated control systems for the parameters of the radio line of the cognitive radiosystem Journal of Physics: Conference Series 1368 042001

[11] Kantorovich L V 2011 Matematiko-jekonomicheskie raboty (Novosibirsk: Nauka Publ)

[12] Dantzig G B and Thapa M N 2003 Linear programming (Springer)

[13] Muschik E, Muller P 1987 Entscheidungspraxis: Ziele, Verfahren, Konsequenzen (Springer)

[14] Triantaphyllou E 2000 Multi-criteria decision making methods: a comparative study Applied optimization (Springer)

[15] Brockmann Erich N, Anthony William P 2016 Tacit knowledge and strategic decision making Group & Organization Management 27 436-55

[16] Jonathan Rosenhead, Martin Elton, Shiv K. Gupta 1972 Robustness and Optimality as Criteria for Strategic Decisions Operational Research Quarterly 23 413-31

[17] Saaty Thomas L 2008 Relative Measurement and its Generalization in Decision Making: Why Pairwise Comparisons are Central in Mathematics for the Measurement of Intangible Factors - The Analytic Hierarchy/Network Process. Review of the Royal Academy of Exact, Physical and Natural Sciences, Series A: Mathematics (RACSAM) 2 251-318

[18] Liu Z, Huang M, Tang Z, Liu T 2000 Selection and Evaluation of Assembly Dimension Chain Based on Analytical Hierarchy Process Proc. of the Seventh Asia Int. Symposium on Mechatronics: Lecture Notes in Electrical Engineering 588 870-8

[19] Zhidyaev A, ZagidullinYu T, Kopysov A, Khvorenkov V, Klimov I 2016 Development of signal detection algorithm for multi-rate HF telecommunication system Proc. Int. Siberian Conf. on Control and Communications (SIBCON-2016) IEEE 866-9

[20] Kopysov A, Klimov I, Zagidullin Yu, Muravev V, Muraveva O 2014 The use of polarization characteristic of ionosphere for data communications Proc. Int. Conf. on Mechanical Engineering, Automation and Control Systems (MEACS) IEEE 1-2