ALGORITHM FOR APPLICATION OF INFORMATION FOR MANAGEMENT OF USERS SPATIAL DISPOSITION IN THE PROCESS OF AUTOMATED SOFTWARE-DEFINED RADIO COMMUNICATION NETWORK IMPLEMENTED BY ORTHOGONAL FREQUENCY DIVISION AND MULTIPLEXING

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Abstract: *A software-defined radio (SDR) system is a radio communication system which uses software for the modulation and demodulation of radio signals. An SDR performs significant amounts of signal processing in a general purpose computer, or a reconfigurable piece of digital electronics. SDR can talk and listen to multiple channels at the same time, also it can be quickly and easily upgraded with enhanced features. In fact, the upgrade could be delivered over-the-air In the long run, SDR is expected to become the dominant technology in radio communications.*

Keywords: *software-defined radio, communication system, signal processing, management of users, communication network.*

1. INTRODUCTION

In this research, an algorithm for building radio communication networks (RCN) implementing the concept of SDR through OFDM is proposed.

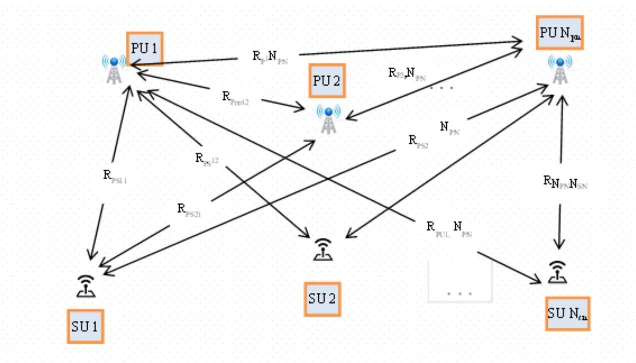

FIG. 1 General geometric structure of the positions of the users of the primary and the secondary SDR - RCN

The users (primary users) of the existing PNs (primary networks - PN) are $PU\ 1, PU\ 2, \dots, PU\ N_{PN}$, and the users (secondary users) of SDR PNs (secondary network - SN) implemented in the physical layer using OFDM technology, are $SU\ 1, SU\ 2, \dots, SU\ N_{SN}$(Fig. 1).

Also, considering the frequency resource tracking and detection technologies in SDR - RCN and the basic principles of OFDM - RCN the following assumptions can be made.

A1) The frequency band ∆F of the secondary SDR- RCN covers the frequency bands of all primary RCNs (Fig. 2a).

A2) The frequency band ∆F of the secondary SDR - RCN, implemented at the physical level using OFDM technology, is divided into N frequency subchannels of width $\Delta f = 1/\mathrm{T_c}$, where $\mathrm{T_c}$ is the duration of the symbol interval. Therefore, $\Delta F = N\Delta f = N/\mathrm{T_c}$ (Fig. 2b).

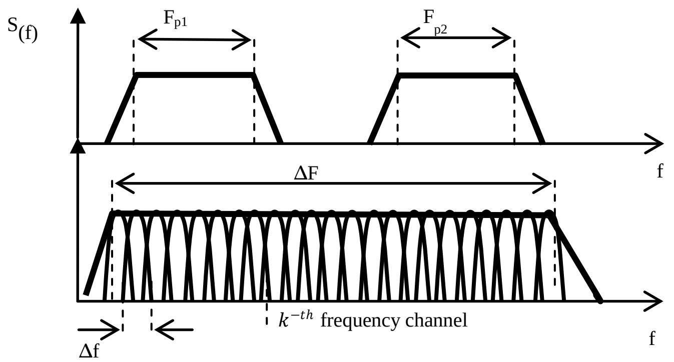

FIG. 2 Frequency bands of the primary (a) and the secondary SDR - RCN implemented at the physical level using OFDM technology (b)

A3) In the current time frame, using specialized measuring equipment and artificial intelligence methods for information processing, the following parameters have been measured and/or determined with sufficient accuracy:

P1) Geographical location of each of the users $PU\,1, PU\,2, \ldots, PU\,N_P$ and $SU\,1, SU\,2, \ldots, SU\,N_S$ of the primary and secondary RCN;

P2) Power of the signals $P_{Pi,k}\ [W], i = 1, 2, \ldots, N_P, k = 1, 2, \ldots, N$, emitted by the transmitter of the user $PU\ i, i = 1, 2, \ldots, N_P$ in the kth frequency subband (k^{-th} channel), $k = 1, 2, \ldots, N$, of the secondary SDR PCN;

P3) Information reception rate $Ir(k)_i\ \left[\frac{b}{s}\right]$ by the user $PU\ i, i = 1, 2, \ldots, N_P$ in the k^{-th} frequency subband (k^{-th} channel $k = 1, 2, \ldots, N$, of the secondary SDR - RCN;

P4) Spectral density $P(k)_{n_0}\ [\frac{W}{Hz}]$ of the noises in the kth frequency subband (k^{-th} channel), $k = 1, 2, \ldots, N$, of the secondary SDR - RCN.

Regarding the determination of the parameters P2 and P3, it is necessary to make the following clarification: The power of the used signals $P_{PU}\ [W]$ and the information transmission rate $I_{r_{PU}}\ \left[\frac{b}{s}\right]$ are known from the technical documentation of the corresponding primary RCN. Most often, however, the frequency band F_P used by the primary RCN spans several frequency subbands (frequency channels) of the secondary OFDM - RCN, whose width $\Delta f = 1/T_s$ is determined by the duration of the symbol interval T_s. That is why in the most general situation it is fulfilled:

$$\frac{F_P}{\Delta f} = K_{ol} > 1 \tag{1}$$

It follows from (1) that the parameters P2 and P3 should be calculated using the formulas:

$$P(k)_{Pi} = \begin{cases} \frac{P_P}{K_{ol}}, \; i = 1,2,\dots,N_P, k = 1,2,\dots,N \\ 0, \end{cases} \quad (2)$$

$$Ir(k)_i = \begin{cases} \frac{I_{r_P}}{K_{ol}}, \; i = 1,2,\dots,N_P, k = 1,2,\dots,N \\ 0, \end{cases} \quad (3)$$

In (2) and (3), the values $P(k)_{Pi} = 0$ и $Ir(k)_i = 0$ refer to the cases when the user $PU\, i$ does not transmit and/or does not receive signals via primary RCN on k^{-th} frequency subband (k^{-th} channel) of the secondary SDR - RCN.

It should be especially noted that the operation of the SDR - RCN management server is divided into the following two stages:

Stage 1: Determination of the restrictions on the use of the radio frequency spectrum in SDR - RCNs, which must be observed in order not to disrupt the normal operation of the primary RCNs;

Stage 2: Allocation of frequency channels among the users of the secondary SDR - RCN, maximizing the criterion of efficiency of the operation of the secondary SDR - RCN, subject to the restrictions established in the previous stage.

According the upper conclusion the SDR - RCN construction approach using the user's spatial location information should be further developed to be applicable to the general case where the primary and secondary RCN users are more of two and are located at random positions on the site (fig. 1). As a result, the following general algorithm for operation of the SDR - RCN management server can be formulated.

2. ALGORITHM FOR MANAGING A SOFTWARE-DEFINED RADIO COMMUNICATION NETWORK IMPLEMENTED AT THE PHYSICAL LEVEL USING OFDM TECHNOLOGY

Stage 1: Determining the limitations of using a software-defined radio communication network implemented at the physical level using OFDM technology.

Step 1: Splitting the set of primary SDR users into subsets depending on the used frequency subband (frequency channel) of the secondary SDR - RCN and the distances between them:

$$\begin{gathered} Cp_1 = \left\{R(1)_{pi_1i_2}, R(1)_{pi_1i_3}, \dots, R(1)_{pi_{N_{p1}-1}i_{N_{p1}}}\right\}, \\ Cp_2 = \left\{R(2)_{pi_1i_2}, R(2)_{pi_1i_3}, \dots, R(2)_{pi_{N_{p2}-1}i_{N_{p2}}}\right\}, \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots, \\ Cp_k = \left\{R(k)_{pi_1i_2}, R(k)_{pi_1i_3}, \dots, R(k)_{pi_li_m}, \dots, R(k)_{pi_{N_{pk}-1}i_{N_{pk}}}\right\}, \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots, \\ Cp_N = \left\{R(N)_{pi_1i_2}, R(N)_{pi_1i_3}, \dots, R(N)_{pi_{N_{pN}-1}i_{N_{pN}}}\right\}. \end{gathered} \quad (4)$$

In (4) the following notations are used:

− $Cp_k, k = 1,2,\dots,N$ is the set of distances between users of primary PCNs using the k^{-th} subband (k^{-th} channel), $k = 1,2,\dots,N$;

− $R(k)_{pi_li_m}$ is the distance between the lth and mth users of the set $Cp_k, k = 1,2,\dots,N$;

− N_{pk} is the number of primary RCN users using the k^{-th} subband (k^{-th} channel), $k = 1,2,\dots,N$ (if $N_{pu} = 0$ then a set Cp_u is empty).

Obviously:

$$N_P \geq N_{p1}, N_{p2}, \dots, N_{pk}, \dots, N_{pN} \tag{5}$$

Step 2: Determining the distances between users of the primary RCN and users of the secondary SDR – RCN.

The geographic location information of each user $PU\ 1, PU\ 2, \dots, PU\ N_P$ and $SU\ 1, SU\ 2, \dots, SU\ N_S$ of the primary and secondary RCN (P1) makes it possible to calculate the elements of the following sets:

2.1) Multiple distances between users of the secondary SDR - RCN:

$$Cs = \{R_{s11}, R_{s12}, \dots, R_{slm}, \dots, R_{sN_s-1N_s}\} \tag{6}$$

2.2) Multiplicity of distances between the users of the secondary SDR - RCN and the users of the primary RCN:

$$Csp = \{R_{11}, R_{12}, \dots, R_{lm}, \dots, R_{N_sN_P}\} \tag{7}$$

In (7) R_{lm} is the distance between the 1^{-th} user $SU\ l$ of the secondary SDR - RCN $l = 1, 2, \dots, N_S$ and the m^{-th} user $PU\ m$ of the primary RCMs $m = 1, 2, \dots, N_P$.

Step 3: Calculation of the additional noise powers created by the operation of the transmitters of the users of the secondary SDR - RCN at the inputs of the receivers of the users of the primary RCN.

As is known, when non-directional antennas are used, the maximum powers of the signals from the k^{-th} subband (k^{-th} frequency channel) of the users of the secondary SDR - RCN at the inputs of the receivers of the users of the primary RCN are:

$$Psp(k)_{lm} = \begin{cases} \dfrac{Ps(k)_l}{4\pi R_{lm}^2}, \\ 0, \end{cases} \tag{8}$$

$k = 1,2, \dots, N,\ \ l = 1,2, \dots, N_S,\ \ m = 1,2, \dots, N_P,\ \ l \neq m.$

In (8) the following notations are used:

$-\ Psp(k)_{lm}$ is the signal power of the user $SU\ l, l = 1, 2, \dots, N_s$ in the k^{-th} frequency subband (k^{-th} channel) received at the input of the user's receiver $PU\ m, m = 1, 2, \dots, N_P$;

$-\ Ps(k)_l$ is the user's transmitter power $SU\ l, l = 1, 2, \dots, N_s$ in the k^{-th} frequency subband (k^{-th} channel) which is determined at stage 2, Step 6 of the operation of the SDR PCN management server (i.e. at the stage of frequency OFDM channel allocation among users of the secondary SDR - RCN);

$-\ R_{lm}$ is the distance between the user determined in Step 2 $SU\ l, l = 1, 2, \dots, N_s$ and user $PU\ m, m = 1, 2, \dots, N_P$;

The values $Psp(k)_{lm} = 0$ refer to the cases when in the current time frame (time frame) the user $PU\ m$ does not receive signals via primary RCN in the k^{-th} frequency subband (k^{-th} channel).

Step 4: Calculation of the signal powers of the inputs of the receivers of the users of the primary RCNs.

Analogously to (5), the maximum powers of the signals from the k^{-th} subband (k^{-th} frequency channel) at the inputs of the receivers of the users of the primary RCNs are:

$$Pp(k)_{uv} = \begin{cases} \dfrac{Pp(k)_u}{4\pi R(k)_{puv}^2}, \\ 0, \end{cases} \tag{9}$$

$k = 1,2, \dots, N,\ \ u = 1,2, \dots, N_P,\ \ v = 1,2, \dots, N_P,\ \ u \neq v.$

In (9) the following notations are used:

$-\ Pp(k)_{uv}$ is the signal power of the user $PU\ u, u = 1, 2, \dots, N_P$ in the k^{-th} frequency subband (k-th channel) received at the input of the user's receiver $PU\ v, v = 1, 2, \dots, N_P$;

$-\ Pp(k)_u$ is the user's transmitter power $PU\ u, u = 1, 2, \dots, N_P$ in the k^{-th} frequency subband (k^{-th} channel), which is calculated according to (2);

$-\ R(k)_{puv}$ is the distance between users determined in Step 1 $PU\ u, u = 1, 2, \dots, N_P$ and $PU\ v, v = 1, 2, \dots, N_P$, using the kth frequency subband (k^{-th} channel) (i.e. $R(k)_{puv} \in Cp_k$);

the values $Pp(k)_{uv} = 0$ refer to the cases when in the current time frame (time frame) the user PUv does not receive signals via primary RCN in the k^{-th} frequency subband (k^{-th} channel) from the user PUu (i.e. user PUu does not emit signals or its signals are shielded by hills or buildings).

Step 5: Calculation of the maximum permissible signal powers of the transmitters of the users of the secondary SDR – RCN.

According to the Shannon-Hartley Theorem [1], and [2], the possible maximum rate of information transmission on the k^{-th} frequency subband from the user PUu to the user PUm (i.e. the capacity $Imax(k)_m$ of the k^{-th} frequency channel, evaluated from the point of view of the user PUm) is determined by the formula:

$$Imax(k)_{um} = \Delta f \log_2\left(1 + \frac{Pp(k)_{um}}{\Delta f P(k)_{n_0}}\right) \tag{10}$$

In (10) $\Delta f P(k)_{n_0}$ is the noise power in the kth frequency channel.

If $Imax(k)_{um} > Ir(k)_m > 0$ (i.e. if the possible maximum speed of information transmission on the k^{-th} frequency channel to the user PUm is greater than the actually used speed), then the users of the secondary SDR - RCN can use the k^{-th} frequency channel without interfering of the user PUm if the powers of their signals $Psp(k)_{lm}$ ensure the fulfillment of equality:

$$Imax(k)_{um} = \Delta f \log_2\left(1 + \frac{Pp(k)_{um}}{\Delta f P(k)_{n_0}}\right) \tag{11}$$

Accordingly:

$$\begin{aligned}
&Ir(k)_m = \Delta f \log_2\left(1 + \frac{Pp(k)_{um}}{\Delta f P(k)_{n_0} + Ps(k)_{lm}}\right) \Rightarrow \\
&\Rightarrow \frac{Ir(k)_m}{\Delta f} = \log_2\left(1 + \frac{Pp(k)_{um}}{\Delta f P(k)_{n_0} + Ps(k)_{lm}}\right) \Rightarrow \\
&\Rightarrow 2^{\frac{Ir(k)_m}{\Delta f}} = 1 + \frac{Pp(k)_{um}}{\Delta f P(k)_{n_0} + Ps(k)_{lm}} \Rightarrow \\
&\Rightarrow \Delta f P(k)_{n_0} + Ps(k)_{lm} = \frac{Pp(k)_{um}}{2^{\frac{Ir(k)_m}{\Delta f}} - 1} \Rightarrow \\
&\Rightarrow Ps(k)_{lm} = \frac{Pp(k)_{um}}{2^{\frac{Ir(k)_m}{\Delta f}} - 1} - \Delta f P(k)_{n_0}.
\end{aligned} \tag{12}$$

Once accounted for (12) in (7) it's found that in the k^{-th} frequency channel the permissible powers of the signals of the users of the secondary SDR - RCN (i.e. the powers at which the rate of transmission of information to the user $PU\ m$ does not falls below the nominal speed as a result of the simultaneous use of the k^{-th} frequency channel and by the user $PU\ l$), are:

$$Ps(k)_l = \left(\frac{Pp(k)_{um}}{2^{\frac{Ir(k)_m}{\Delta f}} - 1} - \Delta f P(k)_{n_0} \right) 4\pi R_{lm}^2, \tag{13}$$
$$k = 1,2, \dots, N, \;\; l = 1,2, \dots, N_S, \;\; m = 1,2, \dots, N_P.$$

If $Ir(k)_m = 0$ (i.e. if no information is transmitted on the k^{-th} frequency channel to the user $PU\ m$), then the users of the secondary SDR - RCN can use the k^{-th} frequency channel without interfering with the user $PU\ m$, even if the powers of their signals $Psp(k)_{lm}$ are maximally possible, according to the technical characteristics of the secondary SDR - RCN, i.e.:

$$Ps(k)_l = P_{max}\, s(k)_l, \tag{14}$$
$$k = 1,2, \dots, N, \;\; l = 1,2, \dots, N_S.$$

Stage 2: Allocation of OFDM channels among users of the secondary SDR - RCN, maximizing the rate of information transmission in the secondary SDR - RCN subject to the constraints established in the previous stage.

Step 6: Calculation of the maximum possible rates of information transmission by users of the secondary SDR – RCN.

Based on the set Cs (step 2, formula (6)) of the distances between the users of the secondary SDR - RCN and the set of maximum permissible signal powers of their transmitters (calculated at step 5, formulas (8) and (9)), the power of the signals at the inputs of the receivers of the users of the secondary SDR - RCN is calculated by the formula:

$$Ps(k)_{lw} = \frac{Ps(k)_l}{4\pi {R_{Slw}}^2}, \tag{15}$$
$$k = 1,2, \dots, N, \;\; l = 1,2, \dots, N_S, \quad w = 1,2, \dots, N_S, \;\; l \neq w.$$

In (15) the following notations are used:

$-\ Ps(k)_{lw}$ is the signal power of the user $SU\ l, l = 1, 2, \dots, N_S$ in the k^{-th} frequency subband (k^{-th} channel) received at the input of the user's receiver $SU\ w, w = 1, 2, \dots, N_S$;

$-\ Ps(k)_l$ is the user's transmitter power $SU\ l, l = 1, 2, \dots, N_S$ in the k^{-th} frequency subband (k^{-th} channel), which was calculated in the previous step according to (8) or (9);

$-\ R(k)_{slw}$ is the distance between users determined in Step 2 $U\ l, l = 1, 2, \dots, N_S$ и $SU\ w, w = 1, 2, \dots, N_S$, when using the k^{-th} frequency subband (k^{-th} channel).

Analogous to (11), the information transmission rates that can be achieved by the users of the secondary SDR - RCN at the current moment in time are calculated by the formula:

$$Ir(k)_{lw/u} = \Delta f \log_2 \left(1 + \frac{Ps(k)_{lw}}{\Delta f P(k)_{n_0} + Pps(k)_{uw}} \right), \tag{16}$$
$$k = 1,2, \dots, N, \quad l, w = 1,2, \dots, N_S, \quad m, u = 1,2, \dots, N_P, \quad l \neq w, \quad u \neq m.$$

In (16) the following notations are used:

$-\ Ir(k)_{lw/u}$ is the maximum possible speed of transmission of information by the user $SU\ l$ to user $SU\ w$ to $SU\ w$ on k^{-th} the frequency subband (k^{-th} channel) when using (by the user $SU\ l$) signals with permissible power;

$-\ Ps(k)_{lw}$ is the signal power of the user $SU\ l, l = 1, 2, \dots, N_S$ in the k^{-th} frequency subband (k^{-th} channel) available at the user's receiver input $SU\ w, w = 1, 2, \dots, N_S$ according (15);

– $\Delta f P(k)_{n_0}$ is the noise power in the k^{-th} frequency channel;

– $Pps(k)_{uw}$ is the power of the signal of the user $PU\,u, u = 1, 2, \dots, N_P$ in k^{-th} frequency subband (k^{-th} channel) available at the user's receiver input $SU\,w, w = 1, 2, \dots, N_S$ which is calculated analogously to (8) by the formula:

$$Pps(k)_{uw} = \frac{Pp(k)_u}{4\pi R_{uw}^2} \tag{17}$$

$k = 1,2, \dots, N,\ \ u = 1,2, \dots, N_P,\ \ w = 1,2, \dots, N_S.$

In (17) the following notations are used:

– $Pp(k)_u$ is the user's transmitter power $PU\,u, u = 1, 2, \dots, N_P$ in the k^{-th} frequency subband (k^{-th} channel), which is calculated according to (8);

– $R(k)_{lw}$ is determined by step 2 and this is the distance between the users $PU\,u, u = 1, 2, \dots, N_P$ и $SU\,w, w = 1, 2, \dots, N_S$.

Step 7: Allocation of OFDM channels among users of the secondary SDR - RCN, maximizing the information transmission rate in the secondary SDR – RCN.

The purpose of this step is to find the one-way communication links (lines) “passing information from the user $SU\,l, l = 1, 2, \dots, N_S$ receiving information from the user $SU\,w, w = 1, 2, \dots, N_S$ for which the information transmission rate is maximum for each frequency channel. To achieve this goal, $N \times N_S$ number of two-dimensional arrays are constructed, each of which can be represented by a table of the following type.

Table 1 Maximum possible speeds of information transmission by a user SU l to user SU $w, w = 1, 2, \dots, N_S$ on the k^{-th} frequency channel in case of interference by a user PU $u, u = 1, 2, \dots, N_P$

		User $SU\,w$					
		1	2	…	w	…	N_S
User $PU\,u$	1	$Ir(k)_{l1/1}$	$Ir(k)_{l2/1}$	…	$Ir(k)_{lw/1}$	…	$Ir(k)_{lN_S/1}$
	2	$Ir(k)_{l1/2}$	$Ir(k)_{l2/2}$	…	$Ir(k)_{lw/2}$	…	$Ir(k)_{lN_S/2}$
	…	…	…	…	…	…	…
	u	$Ir(k)_{l1/u}$	$Ir(k)_{l2/u}$	…	$Ir(k)_{lw/u}$	…	$Ir(k)_{lN_S/u}$
	…	…	…	…	…	…	…
	N_P	$Ir(k)_{l1/N_P}$	$Ir(k)_{l2/N_P}$	…	$Ir(k)_{lw/N_P}$	…	$Ir(k)_{lN_S/N_P}$
Min. element in the column		$Ir(k)_{l1}$	$Ir(k)_{l2}$		$Ir(k)_{lw}$		$Ir(k)_{lN_S}$

The analysis of the w^{-th} of the table. 1 shows that if on the k^{-th} frequency channel information is transmitted from user $SU\,l$ to user $SU\,w$, then the speed of information transmission is determined by the user $SU\,u$, which disturbs the indicated connection to the greatest extent. For this reason, the rate of transmission of information from user $SU\,l$ to user $SU\,w, w = 1, 2, \dots, N_S$ to k^{-th} frequency channel is:

$$Ir(k)_{lw} = \min_{u = 1, 2, \dots, N_P} \{Ir(k)_{lw/1}, Ir(k)_{lw/2}, \dots, Ir(k)_{lw/N_P}\} \tag{18}$$

The rates of information transmission for all w determined by (18) are presented in the last row of the table. 1.

Since, in principle, a user $SU\,l$ can transmit information to any user, $SU\,w, w = 1, 2, \dots, N_S$, the rate of information transmission is maximal for that user $SU\,w_0$ for which:

$$\mathrm{Ir(k)_{lw_0}} = \max_{\mathrm{w = 1, 2, \dots, N_S}} \{\mathrm{Ir(k)_{l1}, Ir(k)_{l2}, \dots, Ir(k)_{lN_s}}\} \tag{19}$$

According (19), it can be summarized that the communication connection "transmission of information from the user $SU\ l$ - reception of information from the user $SU\ SU\ w_0$, in which the speed of information transmission on the k^{-th} frequency channel is the highest, is determined by the maximum element in the last row of the table 1.

After applying the described procedure for each user $SU\ l, l = 1, 2, \dots, N_S$ and for each frequency channel, the one-way communication connections (lines) "transmission of information from the user $SU\ l, l = 1, 2, \dots, N_S$ - receiving information from the user SU $SU\ w, w = 1, 2, \dots, N_S$, maximizing the speed of information transmission in the secondary SDR - RCN.

3. CONCLUSIONS

In conclusion of this paper, it is necessary to note the following circumstances in particular:

- First, the criterion "maximum information transmission rate" for allocation of OFDM channels among users of the secondary SDR - RCN is suitable for many cases, but it is not universal. Therefore, in situations where there are specific requirements for the operation of the secondary SDR - RCN, then some combination of the approaches should be used at the stage of allocation of OFDM channels between users.

- Second, in cases where the secondary SDR - RCN is used for the needs of the police, army, civil defense, etc., the main problem of ensuring maximally noise-protected and secure communication comes to the fore.

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