Multi-criteria signal synthesis procedure for adapting cognitive radio systems to the influence of interfering factors in the Arctic

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Multi-criteria signal synthesis procedure for adapting cognitive radio systems to the influence of interfering factors in the Arctic

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Abstract. For trouble-free operation of robotic complexes in the Arctic, it is necessary to use reliable radio channels to transmit control commands and to receive data from the robot. During operation, the data radio channel influenced by intentional and unintentional interference. Radio signal synthesis procedure is proposed to ensure efficient operation of robotic systems in complex interference-signal environment adaptation using cognitive radio transmission of information under influence of interfering factors. For creating a radio synthesis procedure used generalized representation signals. The objective function of multi-criteria synthesis of radio signals is substantiated. This function uses a combined quality criterion, which includes particular criteria responsible for throughput and detuning from interference, noise immunity as well as spectral and energy efficiency of the signal formed.

The procedure of multi-criteria synthesis of radio signals includes the step of estimating the power spectral density of the interference, the formation of the objective function and optimization for finding the optimum of the objective function. Quasi-Newton methods with finite-difference approximation of derivatives are used for the optimization procedure, since the maximum speed of the algorithm is ensured. The proposed procedure was simulated on a computer. The model included a channel with additive white Gaussian noise and narrowband interference. The study showed that the synthesized radio signals at most unfavorable (among the considered) effects on radio channel by narrowband interference provide noise immunity at the QPSK-signal level when exposed only to additive white Gaussian noise.

1. Introduction

Currently, a variety of robotic systems (RS) are being increasingly and widespread used in the Arctic. To ensure the efficiency of such systems, as a rule, it is necessary to implement radio communication channels (in the interests of both controlling RS and provision of payload requirements). At the same time, radio control channel is of critical importance for entire complex functioning.

In connection with the widespread use of RS (included in the group), modern radio communication systems are experiencing acute shortage of frequency resources. Consequently, radio channel has a large amount of mutual interference resulting from the operation of other radio systems, amplitude-frequency characteristics of radio channel also varies; at the same time, spectral composition of interference changes over time.

Consequently, the task of developing efficient approaches for adapting radio communication systems to changes in interference environment becomes urgent. In this case, the object of adaptation is radio signals, as, firstly, it is possible to vary the parameters without changing hardware composition of receiving-transmitting devices, i.e. by means of software; secondly, quality signal
indexes have decisive influence on communication systems characteristics (noise immunity, energy efficiency, etc.) [1, 2].

In [3, 4], cognitive radio technology is proposed as a solution to a similar problem. This technology uses on a secondary basis the plots of spectrum that are not currently occupied by services assigned to these frequencies. However, the existing systems of cognitive radio usually adapt signals by changing carrier frequency, the power of radio transmitter and modulation type [4], i.e. use a class of standard signals. This approach does not allow to achieve multi-level interference immunity of radio channel, since known modulation types can be recognized for the purpose of generating imitative interference.

Thus, in the conditions of limited frequency resource or in the interests of further improvement of cognitive radio technology, it is advisable to produce radio signal synthesis to adapt cognitive radio systems (CRS) to interference environment, i.e. to use also the class of non-standard modulation types.

When optimizing a signal for one quality indicator, uncontrolled deterioration of other indicators is possible [5]-[7]. Therefore, it is advisable to produce multi-criteria signal synthesis, which also allows more efficient use of radio channel resources at appropriate quality criteria [7].

2. Generalized representation of radio signals

To solve this problem, it is necessary for signal representation to encompass both existing and unknown types of modulation. The analysis of existing CRS signals (satellite, personal communication systems, etc., see Table 1) showed that signals with different types of modulation can be represented in the form of:

$$A(t) = \sum_{i=0}^{N_s-1} s_{r(i)}(t - iT_s)$$

(1)

where $s_{r(i)}$ is the element of signal set, $r(i)$ is mapping procedure, $N_s$ is the number of information symbols, $T_s$ is symbol interval.

| No | Modulation Types | Canonical representation |
|----|------------------|-------------------------|
| 1  | PSK – phase shift keying | $\sum_{i=0}^{N_s-1} \exp(j\varphi_i) p(t - iT_s)$ |
| 2  | APSK – amplitude-phase shift keying | $\sum_{i=0}^{N_s-1} C_i \exp(j\varphi_i) p(t - iT_s)$ |
| 3  | QAM – quadrature amplitude modulation | $\sum_{i=0}^{N_s-1} [C_{iI} p(t - iT_s) + jC_{iQ} p(t - iT_s)]$ |
| 4  | FSK – frequency shift keying | $\sum_{i=0}^{N_s-1} \exp(j\Delta\omega_i t) p(t - iT_s)$ |

Here $p(t)$ is a real signal pulse; $C_i$, $\varphi_i$ are amplitude and phase, respectively; $C_{iI}$, $C_{iQ}$ are amplitudes in in-phase and quadrature channels, respectively; $\Delta\omega_i$ is the frequency deviation corresponding to the $i$-th symbol.
Also, [2, 8] show that perspective types of modulation can be represented in form (1), such as FQPSK (Feher-patented quadrature phase-shift keying), EFQPSK (Enhanced FQPSK), CEFQPSK (Constant envelope FQPSK).

Thus, the representation for signals in form (1) is common for a class of signals with both modern, promising, and non-standard modulation types. In addition, due to the generality of expression (1), it is possible to represent unknown radio signals, at least, as intermediate classes between standard types of modulation. The representation for a fairly wide variety of radio signals is necessary for effective adaptation of CRS to external conditions, including the action of narrow-band interference (NI).

3. **Justification of objective function for multi-criteria synthesis of radio signals**

For the rational use of radio channel resources, it is advisable to apply a combined quality criterion, which includes particular criteria responsible for throughput and interference detuning, noise immunity as well as spectral and energy efficiency of the formed signal.

3.1. **Maximum throughput criterion due to attenuation of interference action**

In [9] it was shown that in order to maximize throughput in the presence of “non-white” Gaussian noise, the following condition must be met:

\[
\frac{1}{N(f) + P(f)} + \lambda = 0, \quad \lambda = \text{const}, \quad \lambda < 0,
\]

where \( P(f) \) is total transmitter power distributed over spectrum; \( N(f) \) is power spectral density (PSD) of “non-white” Gaussian noise, i.e. at frequencies where interference power is low, signal power should be high and vice versa. Thus, for measured PSD interference \( N(f) \), it is required to calculate “reference” signal PSD:

\[
G_{opt}(f) = \max_{f \in [F_l, F_h]} [N(f)] - N(f)
\]

where \([F_l, F_h]\) is normalized frequency band reserved for the signal. With the limited energy of synthesized signal, it is necessary to normalize maximum \( G_{opt}(f) \) and maximum of signal set energy.

Consequently, for the detuning from actual interference, it is advisable to bring closer synthesized signal PSD \( G_S \) to \( G_{opt}(f) \), i.e. to solve the task:

\[
\min_{s \in \Theta} \{d_2(G_{opt}, G_s)\},
\]

where \( d_2(\cdot) \) is Euclidean metric distance, \( \Theta \) is function class within which the calculation of optimal signal set \( S \) occurs. Expression (3) defines the criterion for maximizing throughput of radio channel under interference action.

3.2. **Criterion of maximum noise immunity to the receiver own noise**

As it is well known from [1, 2], the receiver own noise of input stages can be described with sufficient accuracy for practical application using additive “white” Gaussian noise (AWGN).

In [1], it was shown that under AWGN conditions, the signals with the greatest noise immunity are those for which the distance between the elements of signal set is maximum in the sense of metric \( d_2(\cdot) \).

Therefore, at signal synthesis, in order to reduce the probability of bit error due to the effect of the receiver’s own noise, it is necessary to solve the problem:

\[
\max_{k,j \in \Theta} \left\{ < d_2(s_k, s_j) > \right\},
\]

where \( s_k \) and \( s_j \) are elements of signal set. Expression (4) defines the criterion for maximizing noise immunity of radio channel.
hence it is necessary to maximize the arithmetic mean of all possible pairwise distances between the elements of signal set \((s_i, s_j)\) measured in the Euclidean metric (here \(<\cdot\)> is the averaging operator over the ensemble, \(M\) is the number of elements in signal set). It is advisable to use exactly the arithmetic mean of the distances, since when using the minimum distance, the Chebyshev metric is present in expression (4), and hence difficulties arise while determining the global optimum [7].

3.3. Criterion of minimum out-of-band emission
To minimize out-of-band emission and the level of mutual interference for radio communication channels, it is advisable to use spectral-effective radio signals with a given bandwidth of occupied frequencies. Then this quality indicator can be set in the form:

\[
\min_S \left\{ h(10\log(G_s(f)) - G_{\log}(f)) \right\},
\]

where \(h(\cdot)\) is a “penalty” function, which increases sharply when the limit is violated; \(G_{\log}(f)\) is PSD "mask" on a logarithmic scale, setting limits on out-of-band emission.

3.4. Criterion for maximum energy efficiency
To increase the efficiency of most modern power amplifiers, radio transmitters operate in nonlinear mode. As [2] shows, in this mode, the use of signals with envelope fluctuations is energetically inefficient. For quantitative measurement of energy efficiency indicators, the peak-to-average power ratio (PAPR) is used. Hence, the problem of minimizing PAPR is equivalent to the following:

\[
\min_S \left( \max_t \left( \frac{P_p(t)}{M[P_p(t)]} \right) \right),
\]

where \(P_p(t)\) is instantaneous power of the complex envelope for radio signal, \(M[\cdot]\) is mathematical expectation operator (averaging over time implementation).

At the same time, expression (5) contains the Chebyshev metric, which is undesirable in optimization problems, as mentioned above. [10] proposed to use the square of the variation coefficient for instantaneous power to estimate energy efficiency:

\[
J = \frac{D[P_p(t)]}{(M[P_p(t)])^2},
\]

where \(D[\cdot]\) is a dispersion calculation operator.

When adapting the square of variation coefficient for instantaneous signal power, it is advisable to calculate only the elements of a signal set, i.e. instead \(J(S)\) to use \(J_1(S)\). To test energy efficiency assessment adequacy preliminary studies [10] by simulation were conducted. Analysis of the obtained results shows that the square of variation coefficient for instantaneous power, calculated from the elements of signal set \(J_1(S)\) has, at least on a kit of known signals (BPSK, QPSK, FSK-4, EFQPSK, QAM-16, QPSK, QPSK \((p_1(t)\)) ), a monotonic dependence with PAPR for corresponding radio signal and, therefore, can be used to characterize energy efficiency. Here QPSK-signal \((p_1(t))\) has the form of an elementary pulse:

\[
p_1(t) = \sin(\pi t / T_s), \quad 0 \leq t \leq T_s,
\]

and QPSK-signal \((p_2(t))\):

\[
p_2(t) = \sin^2(\pi t / T_s), \quad 0 \leq t \leq T_s.
\]

Thus, to improve signal energy efficiency, it is necessary to solve the problem:
3.5. Combined quality criterion

As it is shown in [5]-[7], the effective method for solving such multi-criteria problems is signal synthesis according to combined quality criterion with the objective function of the form:

\[
\min_{s \in \Theta} \{ J_i(S) \} \tag{6}
\]

\[
k_i(S) = c_i M_i d \left[ G_{sp}(f), G_s(f) \right] + c_i M_i h \left[ 10 \log G_s(f) - G_{thp}(f) \right] +
+ c_i M_i \left[ < d_i(s_i, s_i) > \right] + c_i M_i \left( D[P_p(S)] / (M[P_p(S)])^2 \right), \tag{7}
\]

\[
\sum_{i=1}^{4} c_i = 1; \quad M_i, c_i > 0; \quad M_i, c_i = \text{const}; \quad s_i, s_i \in S; \quad k, l = 1, M,
\]

where \( c_i \) are the parameters that determine the weight for each incoming quality indicator; \( M_i \) are the normalizing coefficients leading the separate terms to total dynamic range.

The synthesis results obtained using objective function (7) do not contain the “worst” signals, i.e. they do not require additional time for screening out non-optimal solutions, however, they may not contain all “non-worst” signals [7].

4. The procedure for multi-criteria synthesis of radio signals

Figure 1 shows a flow chart of the procedure for multi-criteria signal synthesis (in accordance with criterion (7)) for adapting CRS to changes in interference environment.

After receiving interference PSD, reference PSD of a signal is calculated according to expression (2) (block 2). Then (block 3), objective function is formed in accordance with expression (7).
In block 4, the algorithm for determining global optimum region is initialized: the minimum value of objective function is calculated from the kit of signal set synthesized in advance for various interference models.

In block 5, local optimum is determined in a global region, according to the decision rule:

$$\min_{S \in \Theta} k_p(S)$$  \hspace{1cm} (8)

Since signal synthesis is performed to adapt CRS, during which it is necessary to minimize objective function in real time, it is advisable to use optimization methods that have the highest convergence rate. It should be borne in mind that the calculation of first and especially second derivatives of objective function (7) is difficult because of certain nonlinear nature. The analysis of [11, 12] showed that with the abovementioned requirements, it is advisable to use quasi-Newton methods with a finite-difference approximation of derivatives.

In block 6, stop conditions are checked: first of all, time factor (adaptation should not last longer than a certain period of time), as well as standard stop criteria, such as [12]: achieving the required accuracy of solution; movement speed to the minimum has fallen so much that it makes no sense to continue optimization; the method either began to diverge or it looped. In block 7, an optimized signal set output is performed. The procedure of signal synthesis for adaptation CRS is performed with each reception of information about the change in interference PSD.

5. Experimental results

To study CRS performance when changing external parameters of interference, it is advisable to make a quantitative assessment of quality indicators for synthesized radio signals with signal-to-interference ratio variation. In addition, it is advisable to carry out a comparative analysis of synthesized and known four-position radio signals. As a model of interfering factors, it is interesting to consider NI that have significantly negative impact on radio communication systems.

Figure 2 shows the dependence of noise immunity threshold for synthesized and known radio signals on signal-to-interference ratio ($q$).

![Figure 2. Dependences of noise immunity threshold for synthesized and known radio signals on signal-to-interference ratio.](image)
Here $g$ is noise immunity threshold of signals, which was defined as a value equal to $E_b/N_0$ with the probability of bit error $P_e = 10^{-3}$ under the conditions of AWGN and NI. Normalized center frequency $f_N = f_T / M$, i.e. it corresponds to the carrier frequency of useful signal; width PSD of NI $\Delta f_N = 5\%$.

From the analysis of Figure 2 it follows that the synthesized radio signals at weighting factors $c_1 = 0.5$, $c_3 = 0.3$ and $c_1 = 0.25$, $c_3 = 0.3$ up to signal-to-interference ratio -7 and 2 dB, respectively, retain noise immunity at the level of QPSK-signal when exposed to only AWGN. At the same time, for the considered known types of modulation, the same value of index $g$ is achieved with a signal-to-interference ratio greater than 20 dB. Characteristics of the synthesized signal with values $c_1 = 0.25$, $c_3 = 0.3$ are given to illustrate noise immunity index while reducing the weighting factor $c_1$ for the criterion of interference action minimum.

It should be noted that synthesized radio signals with $c_1 = 0.5$, $c_3 = 0.3$ and $c_1 = 0.25$, $c_3 = 0.3$ although have large spectrum width at the level of -30 dB (due to the formation of dip in PSD), significantly benefit at the level of -60 dB (compared to spectral-effective signals: with QPSK $(p_1(t))$ - more than 1.2 and 1.3 times; and with QPSK $(p_2(t))$ - 2.9 and 3.2 times respectively). The value of PAPR is comparable for known signals QPSK $(p_2(t))$ and synthesized signals at $c_1 = 0.5$, $c_3 = 0.3$ as well as QPSK $(p_1(t))$ and synthesized at $c_1 = 0.25$, $c_3 = 0.3$.

6. Conclusion
The procedure for radio signal synthesis to adapt CRS in the Arctic to interfering factors was proposed, using a combined quality criterion, which includes particular criteria responsible for throughput and interference detuning, noise immunity to receiver noise, and both spectral and energy efficiency of the formed signal.

The simulation method has shown that the synthesized radio signals at most unfavorable (of the considered) effects on radio channel by NI $(f_N = 0 f_T; \Delta f_N = 5\%)$ provide noise immunity at QPSK-signal level when exposed only to AWGN, up to signal-to-interference ratio -7 dB, which is 27 dB better than this indicator for known types of modulations [QPSK, QPSK $(p_1(t))$ and QPSK $(p_2(t))$].

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