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Andrey Popov

ADVANCED ELECTRONIC COUNTER-COUNTER-MEASURES TECHNOLOGIES UNDER EXTREME INTERFERENCE ENVIRONMENT

Defence forces rely on electromagnetic dominance for command, control, intelligence, surveillance, reconnaissance, and related applications that utilize the electromagnetic spectrum. Severe pressure on available spectrum from all spectrum users creates a situation demanding significant adaptivity and flexibility of communications systems to communicate successfully and achieve mission goals. Communications receivers operating in the presence of high power jammers or interference are operating "in the blind". "In the blind" operations occur when the received jamming-to-signal ratio and/or received jamming power are high enough that either the radiofrequency interface is overloaded.

A wide variety of reported techniques use signal processing to separate interference from desired communication signals.

Recently, new techniques have been proposed, each of which reduce interference to desired signals or improve the ability to correctly demodulate desired signals in the presence of interference. High levels of interference interacting with the dynamic range of the receiver result in the receiver being desensitized or even blocked by large numbers of intermodulation distortion signal components.

In September 2010 the Defence Advanced Research Projects Agency decided to collect its research efforts through the Broad Agency Announcement (BAA) process and started "The Communication Under Extreme RF Spectrum Conditions" (CommEx) program [1].

According to BAA, CommEx program is interested in those technologies and techniques that address successful mission communications in the presence of four types of interference: 1) high power jamming resulting in the receiver being blinded by intermodulation distortion, 2) traditional types of jamming, 3) adaptive jamming and 4) distributed interference from multiple sources.

As claimed, CommEx's technical objective is to develop innovative adaptive technologies for adaptive interference suppression, and examples of such techniques may include: awareness of affiliated systems interference source properties and behaviors; frequency and time agility; smart antenna techniques; advanced circuit/component design and novel receiver architectures; linear, adaptive, and non-linear signal processing techniques; adaptive modulation and error control waveform properties; adaptive networking, network topology, multi-link, and multi-networking.

Is supposed, this task advances the ability to suppress extreme power interference sources, develops technology to respond to novel or previously unknown interference behaviors, and determines how to integrate multiple interference suppression techniques. Also, this task should address sequencing multiple techniques in response to extreme, known and unknown interference behaviors and multiple interference sources.

Signal processing theory plays an increasingly central role in the development of modern telecommunication and information processing systems, and has a wide range of applications. The observable signals in interference environment are always distorted, incomplete and noisy. Hence, jam/noise reduction and the removal of channel distortion is an important part of a signal processing system. The purpose of this article is to provide a short and structured state of the art review of methods of signal processing under interference environment.

Modern communications systems rely on advanced signal processing methods for fast, efficient, reliable and low-cost communications. The signal processing functions in recent communications system characterized by the following features [2; 3].

Source coders compress signals at the transmitter by removing the correlation and redundancies from the signals; *source decoders* decompress and reconstruct the signals at the receiver. Source coding methods can greatly reduce (often by a factor of 10—20) the required bit rate and bandwidth and hence increase the capacity and speed of data transmission.

The purpose of *channel coding* is to reduce transmission errors due to noise, fading and loss of data packets. Channel coding involves the use of convolution and block coders for the addition of error-control bits to the source data in order to improve the error detection and error correction capability of communication systems.

Multiple access — this, as the name implies, provides simultaneous access to multiple users on the same shared bandwidth resource. Multiple access systems are based on division of time, frequency, code or space among different users, leading to time division multiple access (TDMA), frequency division multiple access (FDMA), code division multiple access (CDMA) and space division multiple access (SDMA) methods, respectively.

Rake receivers advantageously use the effect of the multipath propagation by combining the reflections of a signal received from different propagation paths. This can reduce fading and add to the strength of the received signal.

Channel equalization is used to remove the distortions and time-dispersion of signals that result from the nonideal characteristics of radio channels. Channel equalization reduces the symbol overlaps and bit error rate at the receiver.

Smart antennas are used for a variety of purposes from increasing the signal-jam/noise ratio to space division multiple access. Smart antennas are arrays of phased antennas whose beam direction and gain are controlled by adaptive signal processing methods so that the transmitted electromagnetic power is more efficiently beamed and selectively directed towards the mobile users [4].

Space-time signal processing refers to the signal processing methods that utilize the transmission and/or reception of several signals across time and space using multiple transmitter/receiver antennas [5; 6].

Space, polarization, angle, time, frequency diversity schemes deal with the transmission/reception of the replicas of a signal, or a combination of several signals, transmitted via several independent routes, namely time slots, frequency channels, multipath reflections, spatial directions or polarizations. The success of diversity schemes depends on the degree to which the noise and fading on the different diversity branches are uncorrelated and how the information from different routes and channels is processed and combined. Diversity schemes can help to overcome jam/noise and fading in wireless communications channels and increase the channel capacity [2; 7].

The Cognitive Radio Technology is based on Software Defined Radios (SDR) [8]: all functions, modes and applications can be configured and reconfigured by software, i. e. all modulation, cryptography, protocols, and source coding (voice, data, imagery) are established using software; many types of modulation can be accomplished over a broad range of frequencies; SDR can identify then use empty spectrum to communicate more efficiently.

Modern radioelectronic systems and sets functioning is implemented under parametric and nonparametric prior uncertainty conditions [9—11]. So while developing ECCM technologies on extreme jam environment, there is a problem of possible ways of prior uncertainty overcoming selection. The last ones determine the corresponding signal processing algorithms.

Some authors [10—13] emphasize three main groups of prior uncertainty overcoming methods: parametric and adaptive methods; nonparametric statistical methods and robust methods.

Parametric methods are meant for algorithms synthesis under parametric prior uncertainty conditions. Bayesian methods rank an important place among this methods [14; 10; 11]. On strictly Bayesian problem statement the transition is accomplished from conditional probability densities

$$p=(x/\lambda,\theta=1),\ p=(x/\mu,\theta=0),$$

under signal presence $(\theta=1)$ or its absence $(\theta=0)$ to a posteriori probability densities

$$p(x/\theta=1),\ p(x/\theta=0),$$

which are independent of unknown parameters λ, μ. As a result, prior uncertainty is removed. On partly Bayesian problem statement one should use the postulate, according to which prior probability densities have been consider uniform:

$$p_0(\lambda)=\text{const},\ p_0(\mu)=\text{const},$$

then, integrating on , accomplish a transition to a posteriori probability densities.

Asymptotic invariance property of Bayesian algorithms quality index with respect to prior distributions is important for Bayesian method substantiation [10; 11; 13].

Under observation period increasing, Bayesian algorithm, synthesized on parametric prior uncertainty conditions, regardless of prior distribution, usually converge to the algorithm, synthesized on full prior information. This convergence can be interpreted as an algorithm adaptation to unknown distribution parameters. Due to mentioned Bayesian algorithm property, prior distributions can be chosen more or less arbitrarily.

Parametric methods of synthesis, considered above, lead to algorithms, adapting to unknown parameters, or adaptive algorithms [15; 16].

In the cases, when unknown or variable parameter is easy controlled signal or jam/noise parameter, one can overcome prior uncertainty as a result of adjustment (adaptation) of signal processing (SP) set while observing. SP set adaptation considerably gets more complicated, when a few parameters or distribution densities $p = (x / \lambda, \theta = 1)$, $p = (x / \mu, \theta = 0)$, are unknown. So these algorithms could be found very complicated and unfeasible for functioning in real time scale [15].

Another way of prior uncertainty overcoming is based on development of algorithms, that are insensitive or weakly sensitive to signals and jams/noises statistical characteristics. In the case, when distributions of jam/noise and signal and jam/noise composition are unknown, this way leads to nonparametric algorithms, in another case - when distributions of jam/noise and signal and jam/noise composition are close to some standard distribution class, this leads to robust algorithms [17; 18].

Robust methods allow to synthesize algorithms, which are near-effective to optimal ones and worsen an efficiency while data distribution deflect from initial models in small ranges. Robust methods hold intermediate place between parametric and nonparametric ones, and don't require that rather large prior information quantity, parametric methods need of, and in the same time utilize more of prior information quantity, than nonparametric methods. Consequently robust algorithms are more effective than nonparametric, but this result is obtained of the cost of narrowing of possible distribution class, algorithm robustness remains in.

Recently more often nonparametric methods attract attention in SP problems. Statistical method is called nonparametric, if its use don't suppose the knowledge of data distribution. SP set is called nonparametric, if its decision statistics is independent of jam/noise distribution under signal absence and jam/noise presence [10; 13]. This means, that such a SP set provide quality indexes, which doesn't depend of jam/noise statistic characteristics [13; 19; 20].

The most known papers consider problems of processing of signals against interferences (noises) in terms of linear signal space LS; where interaction result x of signal s and noise n is described by commutative group additive operation [11; 14; 21]:

$$x = s + n.$$

But a number of authors assume general formulation for signal processing problem with regard to signal and interference (noise) interaction [12]:

$$x = s \oplus n,$$

where $\oplus$ — some binary operation of a group [13; 22; 9].

Algebraic lattices are widely known, researched and described in many papers. As a signal space we consider distributive lattice $L(\vee, \wedge)$ with operations of upper and lower bounds respectively [23; 24]:

$$a \vee b = \sup_L \{a,b\},$$
$$a \wedge b = \inf_L \{a,b\}.$$

In this case, elements a, b of lattice $L(\vee, \wedge)$ can be both elements of n-dimensional vector space ($a = [a_1, a_2, \ldots, a_n]$, $b = [b_1, b_2, \ldots, b_n]$), and functions (deterministic or stochastic), defined on some set T ($a = a(t), b = b(t), t \in T$).

The signal $s_i(t)$ with completely defined parameters from the ensemble

$$\{s_k(t)\} \equiv \{s_k\} \ (k = 0, 1, \ldots, K)$$

is represented as

$$s_i(t) = s_i(t, \lambda_i, \mu_i) = s_i(t, \mu_i),$$

where λ_i is informational parameters vector;

μ_i is non-informational parameters vector; meanwhile informational parameters are absent ($\lambda_i \equiv 0$), and there are no unknown and random parameters among non-informational parameters μ_i.

Application area for such signals is restricted by theoretical analysis, which results can be applied for comparison with the other algorithms of signal processing. Model of interaction of signal s_i from ensemble $\{s_k\}$ (k=0,1,...,K) and noise n in signal space with algebraic lattice properties is described by relation:

$$x = s_i \vee n, \tag{1}$$

where s_0=**O**, **O** is zero element of the lattice $L(\vee, \wedge)$.

Structure-forming function for optimal signal processing algorithm in this case is

$$y = \hat{s} \wedge x, \tag{2}$$

where signal estimate $\hat{s}$ is

$$\hat{s} = \begin{cases} s_i, \ i \neq 0; \\ s_0 \equiv \mathbf{O}, \ i=0. \end{cases} \tag{2.a}$$

According to lattice absorption property [23; 24], the result of optimal signal processing (2) is identical to received signal with completely known parameters:

$$y = s_i \wedge (s_i \vee n) = s_i \tag{3}$$

Formula (3) implies that optimal processing device output uniquely produce the received signal s_i.

Function (2) corresponds to optimal processing of signals from ensemble $\{s_k\}$ against interferences (noises) n in the case of their interaction (1) in signal space with algebraic lattice properties. Fact γ_i of multiple-alternative detection of signal s_i (or its nondetection fact γ_0) is registered by the rule:

$$y = \hat{s} \wedge x = \begin{cases} s_i \Rightarrow \gamma_i; \\ s_0 \equiv \mathbf{O} \Rightarrow \gamma_0, \end{cases} \quad (4)$$

where signal estimate $\hat{s}$ is defined by relation (2a).

Therefore, optimal processing algorithm (4) for signals with completely defined parameters against interferences (noises) in the case of their interaction in signal space with algebraic lattice properties is characterized by absolute values of signals multiple-alternative detection quality factors: conditional probabilities of correct multiple-alternative detection D_i of signal s_i are equal to one: $D_i = 1$, meanwhile conditional probabilities of false alarm F and erroneous multiple-alternative detection D_{err} are equal to zero: $F = 0$, $D_{err} = 0$.

The comparison of optimal detector, which implements algorithm (4) with classical optimal detector [14] of signals with completely known parameters allows to do following conclusions:

1. The efficiency of optimal processing device, which implements algorithm (4) is invariant with respect to parametrical prior uncertainty conditions.
2. The efficiency of optimal processing device, which implements algorithm (4) is invariant relatively to non-parametric prior uncertainty conditions. Meanwhile the stability of signals multiple-alternative detection quality factors values D_i and F, D_{err} is provided under arbitrary interference (noise) distribution laws:

$$D_i=1;\ F=0,\ D_{err}=0; \text{ while } p_n(x)=\text{var};$$

where $p_n(x)$ is noise probability density in receiving channel.

3. The efficiency of optimal multichannel processing device of group signal $s = \bigvee_{k=1}^{K} s_k$ formed by signals $\{s_k\}$ (k=0,1,...,K) with completely known parameters against interferences (noises) in signal space with algebraic lattice is invariant to the division multiple access method, the number K of processing channels and the applied shape of signals s_i.

Actually, at signal s_i extraction in i-th processing channel from grouped signal $s = \bigvee_{k=1}^{K} s_k$ against a background of interferences (noises) n, signal y_i at the output of i-th processing channel is defined by the following expression:

$$y_i = s(\bigvee_{k=1}^{K} s_k \vee n)\Big|_{s=s_i} = s_i \wedge (s_i \vee [\bigvee_{k\neq 1}^{K} s_k]n) = s_i.$$

Obtained relation implies efficiency of multichannel processing of signals with known parameters, which solves a problem of multiple-alternative detection and extraction of signals against interferences (noises) from the set $\{s_k\}$ is independent of listed above factors.

All mentioned differences between classical signal detector [14] and detector, which realize algorithm (4) are explained by fundamental differences between linear space LS and signal space with algebraic lattice properties $L(\vee, \wedge)$. In linear space the interaction of desired and interfering signals is always go with loss (or distortion) of contained information. On the contrary, lattice absorption property $s \wedge (s \vee n) = s$ allows to consider practically "ideal" interaction of desired and interfering signals in a space with algebraic lattice properties. The invariance of SP quality indexes in the signal space with algebraic lattice properties while solving unknown non-random parameters estimation problem, detection-discrimination and filtration problems is shown in articles [25—27] respectively.

Thus, in this signal space there is a principal possibility of processing of desired signals under interferences (noises) background of with comparatively small information loss, regardless of parametric and nonparametric prior uncertainty conditions. The last circumstance makes the application of SP in a space with algebraic lattice properties quite attractive for solving electronic counter-counter-measures (ECCM) problem on extreme interference environment.

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Розглянуті основні напрямки досліджень в рамках програми Агентства провідних оборонних дослідницьких проектів (Defense Advanced Research Projects Agency) "Передача інформації в умовах екстремального використання радіочастотного спектра". Зроблено стислий огляд відомих та перспективних методів захисту радіоелектронних систем в умовах впливу інтенсивних завад. Відмічено перспективність використання методів обробки сигналів в просторі сигналів із властивостями алгебраїчної решітки для вирішення проблеми захисту радіоелектронних систем в умовах впливу інтенсивних перешкод.

Ключові слова: радіоелектронний захист радіоелектронних систем, завадова обстановка, активна завада, апріорна невизначеність, обробка сигналів, простір сигналів із властивостями алгебраїчної решітки.

Рассмотрены основные направления исследований в рамках программы Агентства передовых оборонных исследовательских проектов (Defense Advanced Research Projects Agency) "Передача информации в условиях экстремального использования радиочастотного спектра". Сделан краткий обзор известных и перспективных методов защиты радиоэлектронных систем в условиях воздействия интенсивных помех. Отмечается перспективность применения методов обработки сигналов в пространстве сигналов со свойствами алгебраической решетки для решения проблемы защиты радиоэлектронных систем в условиях воздействия интенсивных помех.

Ключевые слова: радиоэлектронная защита радиоэлектронных систем, помеховая обстановка, активная помеха, априорная неопределенность, обработка сигналов, пространство сигналов со свойствами алгебраической решетки.