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RESEARCH ARTICLE

Use of a spatially distributed in-phase antenna to increase the noise immunity of signal reception

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Abstract
Objectives. Radio-technical information transmission systems are widely used in various sectors of our life, not only for telecommunications and associated domestic needs, but also for the functioning of various special services, such as emergency response units, which increasingly use robotic complexes in the course of their work. In the event of an emergency, robot devices can be used to get in under rubble, in concrete pipes or other municipal facilities, which typically result in a sharp deterioration of the necessary conditions for the propagation of radio waves. In this regard, the problem of ensuring reliable communication with the robotic complex becomes rather acute. The aim of the present work is to reduce the effect of multipath propagation of radio waves in the communication channel under complex interference conditions.
Methods. The methods of statistical radio engineering and mathematical modeling are used according to optimal signal reception theory.
Results. The presented model for a multi-element, spatially-distributed, in-phase receiving antenna of various configurations, featuring an electronically adjustable radiation pattern, is designed to ameliorate the multipath nature of signal propagation. A simulation of a multipath communication channel was carried out in the presence of one main and three reflected beams of radio wave propagation, as well as with harmonic interference at two angles of its arrival and different frequency detuning relative to the frequency of the useful signal. The probability of a bit error when receiving discrete information using the proposed antenna is estimated.
Conclusions. The proposed signal processing algorithm on the receiving side can be used to partially compensate for the influence of the multipath effect. As a result, the noise immunity of information reception in comparison with reception on an omnidirectional antenna with one antenna element increases: for a bit error probability of 10^{-3}, the energy gain ranges from 2 dB for two beams to 7–10 dB for three or four beams. In the presence of concentrated harmonic interference in the radio channel, its simultaneous spatial (by the antenna) and spectral (by the demodulator) filtering is also observed, the effectiveness of which depends on the direction of arrival and the frequency detuning of the interference, which also leads to a significant decrease in the error probability.

Keywords: spatially distributed in-phase antenna, electronic beam control, multipath propagation of radio waves, harmonic interference, noise immunity, bit error rate

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НАУЧНАЯ СТАТЬЯ

Использование пространственно-распределенной синфазной антенны для повышения помехоустойчивости приема сигналов

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Резюме

Цели. Радиотехнические системы передачи информации находят широкое применение в различных отраслях нашей жизни не только для обеспечения телекоммуникаций и бытовых потребностей человека, но и для функционирования различных спецслужб, например, служб МЧС, которые в своей работе применяют роботизированные комплексы. В случае чрезвычайного происшествия возможно попадание такого робота под завал, в железобетонные трубы или другие коммунальные объекты, в результате чего условия распространения радиоволн резко ухудшаются. В этой связи остро стоит вопрос обеспечения надежной связи с роботизированным комплексом. Цель работы – снижение влияния эффекта многолучевого распространения радиоволн в канале связи в сложных помеховых условиях.

Методы. Использованы методы статистической радиотехники, теории оптимального приема сигналов и математического моделирования.

Результаты. Приведена модель приемной многоэлементной пространственно-распределенной синфазной антенны разных конфигураций с электронно-регулируемой диаграммой направленности, предназначенной для борьбы с многолучевым характером распространения сигнала. Проведено моделирование многолучевого канала связи при наличии одного основного и трех отраженных лучей распространения радиоволн, а также с гармонической помехой при двух углах ее прихода и разной частотной расстройкой относительно частоты полезного сигнала. Оценена вероятность битовой ошибки при приеме дискретной информации с применением предложенной антенны.

Выводы. Применение предложенного алгоритма обработки сигналов на приемной стороне позволяет частично скомпенсировать влияние эффекта многолучевости. В результате помехоустойчивость приема информации по сравнению с приемом на всенаправленную антенну с одним антенным элементом повышается: для вероятности битовой ошибки 10^{-3} энергетический выигрыш составляет от 2 дБ при 2 лучах до 7–10 дБ при 3–4 лучах. При наличии в радиоканале сосредоточенной гармонической помехи также наблюдается ее одновременная пространственная (с использованием антенны) и спектральная (с использованием демодулятора) фильтрация, эффективность которой зависит от направления прихода и частотной расстройки помехи, что также приводит к существенному снижению вероятности ошибки.

Ключевые слова: пространственно-распределенная синфазная антенна, электронное регулирование диаграммы направленности, многолучевое распространение радиоволн, гармоническая помеха, помехоустойчивость, вероятность битовой ошибки

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INTRODUCTION

Radio-technical information transmission systems are widely used in various sectors of our life, not only for telecommunications and associated domestic needs, but also for the functioning of various special services, such as emergency response units, which increasingly use robotic complexes in the course of their work. In the event of an emergency, robot devices can be used to get in under rubble, in concrete pipes or other municipal facilities, which typically result in a sharp deterioration of the necessary conditions for the propagation of radio waves. In this regard, the problem of ensuring reliable communication with the robotic complex becomes rather acute.

Radio signals are significantly affected by the radio propagation environment though which they pass. In addition to additive noise interference, concentrated interference from other radio facilities and retranslated interference caused by multipath propagation of radio waves in their reflection from obstacles and refraction are observed in the communication channel [1–3]. The formation of such a multipath communication channel causes distortion of the useful radio signal parameters; such changes to its amplitude, phase, and angle of arrival (AoA) result in the essential decrease of noise immunity of receiving information [4–10].

There are various methods for counteracting multipath propagation in the communication channel. These include the use of channel equalizers, radiation pattern (RP) control, increasing the intervals in the transmitted pulse sequence, and using the dispersed reception systems. One such approach is the Multiple-Input Multiple-Output (MIMO) [11] system widely used in wireless local area networks of different standards, as well as in wireless mobile communication systems.

Another effective way to counteract multipath in communication channels involves the use of beam antennas and antenna systems to spatially filter received signals. When using such antennas, RPs are formed either by design methods or by special methods of the received signals processing [12].

One complex beam antenna system is represented by an in-phase antenna array, comprising separate near-omnidirectional antennas, which are arranged in such a way that the phases of the signals induced in them are the same, allowing the signals from each antenna to be added up in phase.

This eventually results in the increasing signal level at the output of the antenna system, a narrowing of the RP, and, finally, increasing the gain factor as compared to that of a single antenna included in the array.

MODEL OF THE IN-PHASE ANTENNA WITH ELECTRONICALLY ADJUSTABLE RP

A spatially distributed antenna system containing N = 2 up to 8 antenna elements may be used under complex interference conditions for reducing the effect of multipath radio wave propagation in the communication channel with a robotic system [13].

Such an in-phase antenna system (Fig. 1) consists of resonator antenna elements *1–8*, electronically adjustable delay elements *9–16*, and am in-phase adder *17*. The resonator antenna elements are arranged uniformly with an angular step of $2\pi/N$ in a circle of diameter equal to half the wavelength of the received signal $\lambda/2$. The signals from antenna elements come through adjustable delay elements to the in-phase adder to form the resulting signal S_{out}. The purpose of the adjustable delay elements consists in ensuring the in-phase condition of the received oscillations and forming the summarized antenna pattern.

Time delays of the received oscillations from antenna elements to the in-phase adder with allowance for the required angle φ of the RP rotation are determined as follows:

$$\tau_i = \frac{T}{4}\left\{1 + \sin\left[\left(\frac{\pi}{2} - \frac{i\pi}{4}\right) + \varphi\right]\right\}, \qquad (1)$$

where $i = \overline{1,8}$ is the antenna element number of the system while T is the wave period of the received signal.

In [14, 15], RPs of the in-phase antenna under consideration are calculated for three cases: nominal frequency of the received signal, reduced frequency, or increased frequency. It is shown how the RP width and

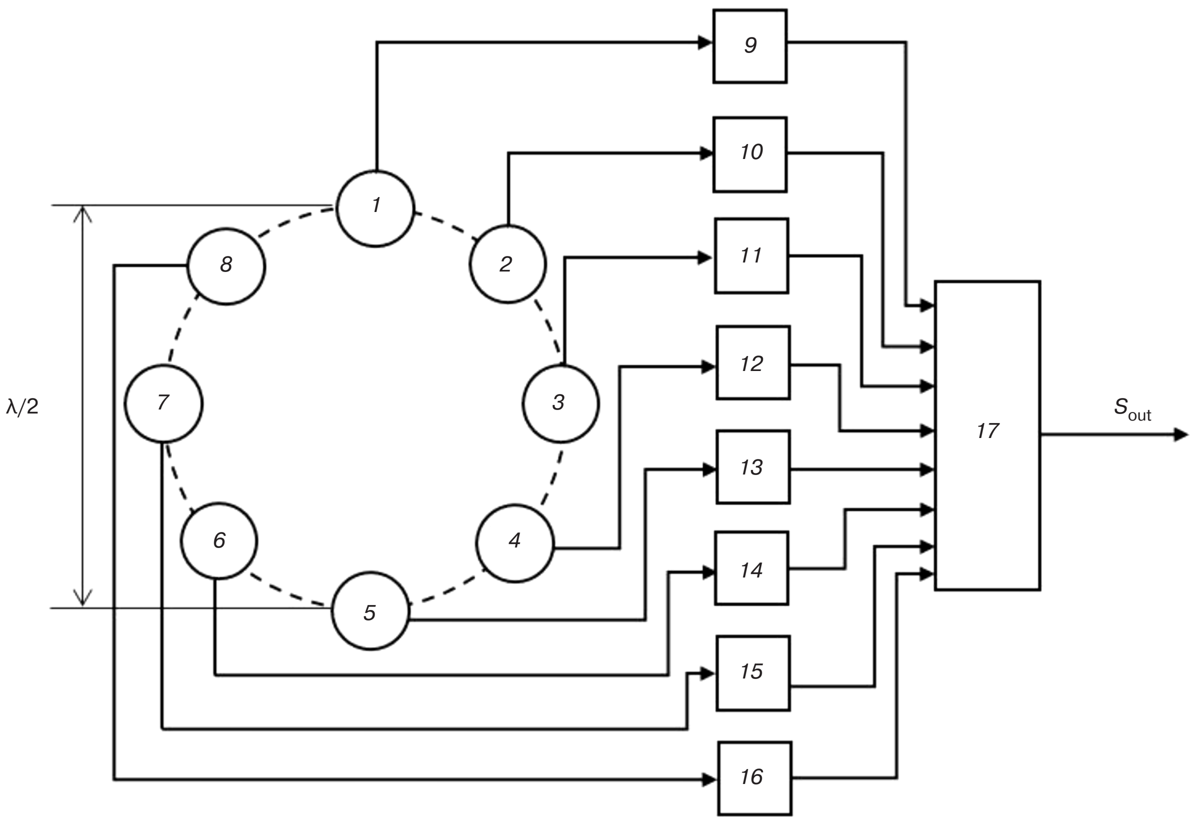

Fig. 1. Schematic diagram of the in-phase antenna array with electronically adjustable RP control

sidelobe level change with frequency. The plots show that structurally simple two-element antennas have quite wide RP and very high sidelobe levels. Four- and eight-element antennas, which have good, very close indices, can be used for spatial filtering in channels with multipath wave propagation. Here, it may be noted that the selective properties of these antennas remain normal when the signal frequency deviates from the nominal frequency even by as much as 10%.

The possibility of adjusting the antenna RP electronically is illustrated in Fig. 2 showing the directional characteristics at various angles φ set in delay elements (1). It is worth noting that at different angles of rotation, the pattern shape itself, and hence the selective properties, remain unchanged.

MODELING RESULTS

In order to assess immunity to interference of the communication system with the proposed in-phase antenna on the receiving side under difficult interference conditions, mathematical modeling was carried out.

A. Signal and disturbance models. A signal with binary phase-shift keying $s(t) = A_0\cos(\omega_0 + C_k\pi)$ is used

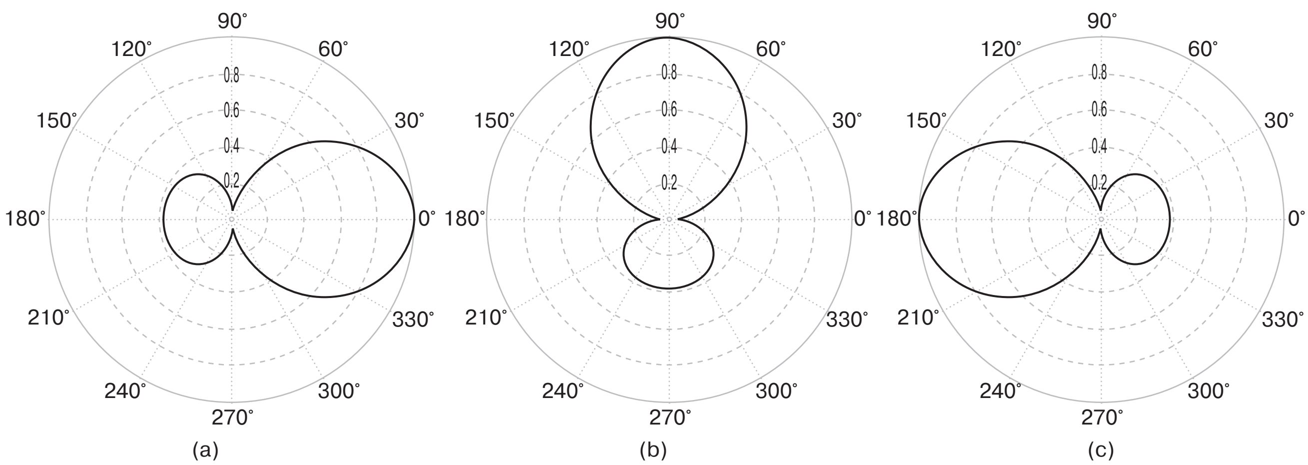

Fig. 2. RPs of the in-phase antenna: (a) φ = 0, (b) φ = π/2, and (c) φ = π

as a test signal. Here, $A_0 = \sqrt{2E/T_s}$ is its amplitude, ω_0 is carrier frequency, t is time, $C_k = \pm 1$ is information symbol, E is signal energy, and T_s is signal duration. A coherent demodulator is used. Gaussian noise with uniform spectral density N_0 is used as fluctuation noise. The communication channel has been assumed to be multipath with one main beam and several ($M = 1, 2, 3$) retransmitted beams

$$s_r(t) = \mu_r s(t - \tau_r)$$

with different relative intensity μ_r, time delay τ_r, and AoA θ_r.

In addition, harmonic oscillation $s_h(t) = \mu_h A_0 \cos(\omega_h t + \varphi_h)$ with random phase φ_h, relative intensity μ_h, frequency ω_h close to the useful signal frequency, and different AoAs θ_h have been used as a concentrated disturbance.

B. Multipath communication channel. For modeling the multipath communication channel, one main beam (AoA $\theta_r = 0$) and three reflected beams are used: $\theta_r = \pi/4$, $\mu_r = 0.5$, and $\tau_r = 0.5T_s$ for the first reflected beam; $\theta_r = \pi/3$, $\mu_r = 0.3$, and $\tau_r = 0.1T_s$ for the second reflected beam; and $\theta_r = \pi/5$, $\mu_r = 0.4$, $\tau_r = 0.7T_s$ for the third reflected beam. The signal-to-noise ratio E/N_0 varies within the range from 1 to 13 dB.

Figure 3 shows the obtained dependencies of the bit error probability P_e on the signal-to-noise ratio (SNR) for different numbers of received beams including the main one. Curves *1* corresponds to the in-phase antenna with four antenna elements, curves *2* correspond to the one with eight antenna elements, curves *3* corresponds to the simple omnidirectional antenna with one antenna element, while curves *4* correspond to the simple omnidirectional antenna with one antenna element and one main received beam (the classical case is given for comparison). Although the presence of reflected beams during reception can be seen to significantly increase the bit error probability compared to the classical case, the proposed in-phase antenna can be used to partially compensate their influence. As a result, the noise immunity of receiving information is improved as compared to the omnidirectional antenna reception with a single antenna element. For error probability $P_e = 10^{-3}$, the energy gain ranges from 1.5–2 dB for 2 beams to 7–10 dB for 3–4 beams; it is noticeable that the difference for the 4-element and 8-element antennas is small, which indicates the possibility of simplifying its design.

C. Communication channel with harmonic interference. The following harmonic interference parameters are used in the communication channel modeling: relative intensity $\mu_h = 0.5$; random initial phase φ_h is uniformly distributed on the interval $(-\pi, \pi]$; reduced frequency deviation $\Delta\omega T_s = (\omega_h - \omega_0)T_s$ is in the interval $(-12, +12)$. The in-phase antenna contains 8 antenna elements.

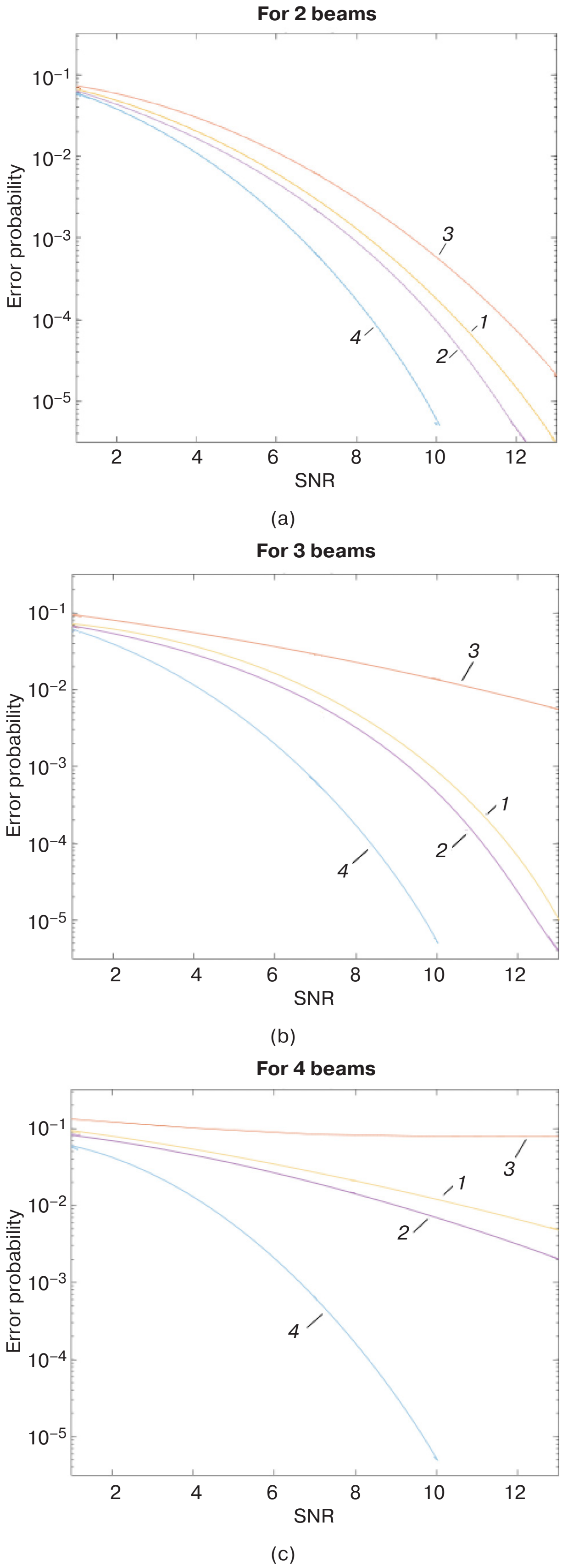

Fig. 3. Dependencies of bit error probability on SNR for: (a) two-beam communication channel, (b) three-beam communication channel, (c) four-beam communication channel

Figure 4 shows the dependencies of the bit error probability P_e on the interference detuning $\Delta\omega T_s$ at E/N_0 = 7 dB and at two AoAs: θ_h = 0 (direction of the RP maximum) and π/3. A simultaneous spatial (using antenna) and spectral (using demodulator) filtering of interference is observed, resulting in a significant decrease in error probability, i.e., to be more ordered at θ_h = 0. It may be assumed that the impact of such harmonic interference may be neglected at $\Delta\omega T_s \geq 5$.

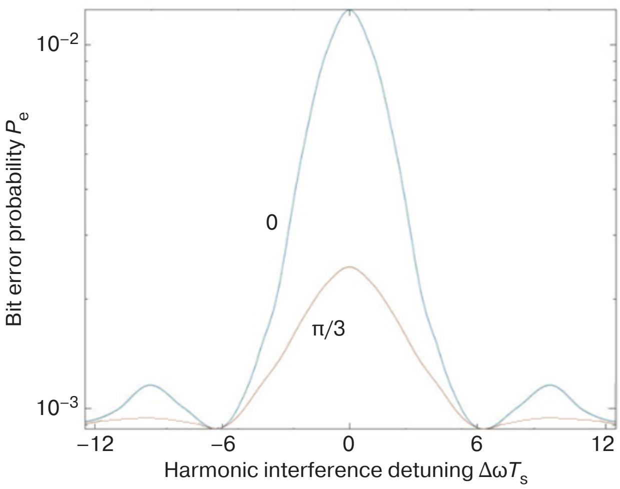

Fig. 4. Dependencies of bit error probability on harmonic interference detuning

CONCLUSIONS

In the present work, a mathematical model for a multi-element, spatially-distributed, in-phase antenna, whose design is aimed at counteracting the multipath nature of signal propagation, is constructed. The principal possibility of electronically adjusting the RP is demonstrated.

By applying the proposed signal processing algorithm on the receiving side, the impact of the multipath effect can be partially compensated. As a result, the noise immunity of receiving information is increased compared to the omnidirectional antenna reception with one antenna element; for error probability $P_e = 10^{-3}$, the energy gain ranges from 2 dB for 2 beams up to 7–10 dB for 3–4 beams.

When concentrated harmonic interference is present in the radio channel, there is also simultaneous spatial (using antenna) and spectral (using demodulator) filtering whose efficiency depends on the arrival direction and frequency detuning of the interference, which also results in a significant reduction in error probability.

Authors' contributions

G.V. Kulikov—the research idea, consultations on the issues of conducting all stages of the study.

Yu.A. Polevoda—computer simulation, processing of results.

M.S. Kostin—development of an antenna model.

REFERENCES

1. Perfilov O.Yu. *Radiopomekhi* (*Radio Interference*). Moscow: Goryachaya Liniya – Telekom; 2017. 110 p. (in Russ.). ISBN 978-5-9912-0491-0
2. Polyakov P.F. *Priem signalov v mnogoluchevykh kanalakh* (*Signal Reception in Multipath Channels*). Moscow: Radio i svyaz'; 1986. 248 p. (in Russ.).
3. Yakovlev O.I., Yakubov V.P., Uryadov V.P., Pavel'ev A.G. *Rasprostranenie radiovoln* (*Radio-Wave Propagation*). Moscow: LENAND; 2009. 486 p. (in Russ.). ISBN 978-5-9710-0183-6
4. Kulikov G.V., Lelyukh A.A., Grachenko E.N. Noise immunity of coherent signal receiver with quadrature amplitude modulation in the presence of relayed interference. *J. Commun. Technol. Electron*. 2020;65(8):934–938. https://doi.org/10.1134/S1064226920070074
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СПИСОК ЛИТЕРАТУРЫ

1. Перфилов О.Ю. *Радиопомехи*. М.: Горячая линия – Телеком; 2017. 110 с. ISBN 978-5-9912-0491-0
2. Поляков П.Ф. *Прием сигналов в многолучевых каналах*. М.: Радио и связь; 1986. 248 с.
3. Яковлев О.И., Якубов В.П., Урядов В.П., Павельев А.Г. *Распространение радиоволн*. М.: ЛЕНАНД; 2009. 486 с. ISBN 978-5-9710-0183-6
4. Куликов Г.В., Лелюх А.А., Граченко Е.Н. Помехоустойчивость когерентного приемника сигналов с квадратурной амплитудной манипуляцией при наличии ретранслированной помехи. *Радиотехника и электроника*. 2020;65(8):804–808. https://doi.org/10.31857/S0033849420070074
5. Куликов Г.В., Данг С.Х. Помехоустойчивость приема сигналов с амплитудно-фазовой манипуляцией в двухлучевом канале связи. *Вопросы радиоэлектроники. Серия: Техника телевидения*. 2022;2:43–49.
6. Нгуен В.З. Помехоустойчивость корреляционного приемника сигналов с многопозиционной фазовой манипуляцией при наличии ретранслированной помехи. *Журнал радиоэлектроники.* 2019;3. https://doi.org/10.30898/1684-1719.2019.3.4

5. Kulikov G.V., Dang X.H. Noise immunity of reception of signal with amplitude-phase shift keying in a two-path communication channel. *Voprosy radioelektroniki. Seriya: Tekhnika televideniya = Questions of Radio Electronics. Series: TV Technique*. 2022;2:43–49 (in Russ.).
6. Nguyen V.D. Noise immunity of correlation receiver of signal with multi-position phase shift keying in the presence of retransmitted interference. *Zhurnal radioelektroniki = J. Radio Electronics*. 2019;3 (in Russ.). https://doi.org/10.30898/1684-1719.2019.3.4
7. Zelenevskii V.V., Popov A.V., Zelenevskii Yu.V., Nakonechnyi A.B. Statistical quality assessment Rice radio channel of meter band. *Izvestiya Instituta Inzhenernoi Fiziki*. 2023;1(67):56–58 (in Russ.). Available from URL: https://iifrf.ru/wp-content/uploads/2023/01/izvestiyaiif-67.pdf
8. Krasnoselsky I.N., Kanev S.A. Analyzing DVB-T system's interference immunity in a multipath fading channel as a model. *Elektrosvyaz' = Telecommunications and Radio Engineering.* 2010;7:28–30 (in Russ.).
9. Sidelnikov G.M., Ognev D.V. Noise stability of diversity system for signals PSK and DPSK in multipath channels. *Omskii nauchnyi vestnik = Omsk Scientific Bulletin.* 2018;2(158):104–109 (in Russ.). https://doi.org/10.25206/1813-8225-2018-158-104-109
10. Sidelnikov G.M., Sinyavskaya A.S. Intersymbol interference of signal PSK and DPSK for discrete channels. *Omskii nauchnyi vestnik = Omsk Scientific Bulletin*. 2014;1(127):205–210 (in Russ.).
11. Bakulin M.G., Varukina L.A., Kreindelin V.B. *Tekhnologiya MIMO: printsipy i algoritmy* (*MIMO Technology: Principles and Algorithms*). Moscow: Goryachaya Liniya – Telekom; 2022. 242 p. (in Russ.). ISBN 978-5-9912-0457-6
12. Goncharenko I.V. *Antenny KV i UKV. Napravlennye KV antenny. Sinfaznye i prodol'nogo izlucheniya* (*Antennas of SW and VHF. Directional SW Antennas. In-phase and Longitudinal Radiation*). Moscow: RadioSoft: Radio; 2010. 256 p. (in Russ.). ISBN 5-93037-144-X
13. Kulikov G.V., Kostin M.S., Zamuruev S.N., Yarlykov A.D., Polevoda Yu.A. *In-phase antenna array with an electronically adjustable directional pattern*: RF Pat. RU 217728 U1. Publ. 14.04.2023 (in Russ.).
14. Polevoda Yu.A., Kulikov G.V., Konyashkin G.V., Kuzelenkov P.I. Research of the directional pattern of the spatially distributed receiving antenna. In: *Fundamental, Exploratory, Applied Research and Innovation Projects: Proceedings of the National Scientific and Practical Conference.* Moscow: RTU MIREA; 2022. P. 272–277 (in Russ.).
15. Kulikov G.V., Kuzelenkov P.I. Mathematical Modelling of Antenna System for Combating Multi-Beam Character of Signal Propagation in Hydroacoustic Communication Channel. In: *Actual Problems and Prospects of Development of Radio Engineering and Infocommunication Systems* (*RADIOINFOCOM 2022*)*: Proceedings VI International Conference.* Moscow: RTU MIREA; 2022. P. 164–167 (in Russ.).

7. Зеленевский В.В., Попов А.В., Зеленевский Ю.В., Наконечный А.Б. Статистическая оценка качества райсовского радиоканала метрового диапазона. *Известия Института инженерной физики.* 2023;1(67): 56–58. URL: https://iifrf.ru/wp-content/uploads/2023/01/izvestiyaiif-67.pdf
8. Красносельский И.Н., Канев С.А. Исследование помехоустойчивости системы DVB-T на модели канала с многолучевым распространением. *Электросвязь*. 2010;7:28–30.
9. Сидельников Г.М., Огнев Д.В. Помехоустойчивость разнесенного приема сигналов с фазовой и относительной фазовой модуляцией в каналах с многолучевостью. *Омский научный вестник*. 2018;2(158):104–109. https://doi.org/10.25206/1813-8225-2018-158-104-109
10. Сидельников Г.М., Синявская А.С. Межсимвольная интерференция сигналов с ФРМ и ФМ в каналах с дискретной многолучевостью. *Омский научный вестник.* 2014;1(127):205–210.
11. Бакулин М.Г., Варукина Л.А., Крейнделин В.Б. *Технология MIMO: принципы и алгоритмы.* М.: Горячая линия – Телеком; 2022. 242 с. ISBN 978-5-9912-0457-6
12. Гончаренко И.В. *Антенны КВ и УКВ. Направленные КВ антенны. Синфазные и продольного излучения.* М.: РадиоСофт: Радио; 2010. 256 с. ISBN 5-93037-144-X
13. Куликов Г.В., Костин М.С., Замуруев С.Н., Ярлыков А.Д., Полевода Ю.А. *Синфазная антенная решетка с электронно-регулируемой диаграммой направленности*: пат. RU 217728 U1. Заявка № RU 2023 102 773 U; заявл. 07.02.2023; опубл. 14.04.2023.
14. Полевода Ю.А., Куликов Г.В., Коняшкин Г.В., Кузеленков П.И. Исследование диаграммы направленности пространственно-распределенной приемной антенны. В сб.: *Фундаментальные, поисковые, прикладные исследования и инновационные проекты: сборник трудов Национальной научно-практической конференции;* под ред. С.У. Увайсова. М.: РТУ МИРЭА; 2022. С. 272–277.
15. Куликов Г.В., Кузеленков П.И. Математическое моделирование системы антенн для борьбы с многолучевым характером распространения сигнала в гидроакустическом канале связи. В сб.: *VI Международная НПК «Актуальные проблемы и перспективы развития радиотехнических и инфокоммуникационных систем»* (*РАДИОИНФОКОМ – 2022*). М.: РТУ МИРЭА; 2022. С. 164–167.

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