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METOD FOR INCREASING THE SPECTRAL EFFICIENCY OF TROPOSCATTER COMMUNICATION BASED ON THE USE OF COMPOSITE SIGNALS IN THE WALSH BASIS

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Background. In modern telecommunications, troposcatter communication systems organize long-distance communication. These systems allow communication beyond the line of sight. An important factor that must be considered in these systems is multipath, due to the physical principle underlying the functioning of troposcatter systems. Diversity reception and broadband signals are used to overcome this factor's negative impact. However, broadband signals use an excessive frequency band and are characterized by a low spectral efficiency.

Objective. The purpose of the paper is to develop a method for overcoming the negative impact of multipath by using composite signals on the Walsh basis.

Methods. Parallel composite signals provide simultaneous packet transmission of a group of signals built based on a complete system of mutually orthogonal Walsh-Hadamard functions. Each signal transmits one bit of information, but the parallel transmission of a packet of mutually orthogonal signals avoids decreasing the system's information transmission rate. To counteract the effect of multipath, pilot signals are added to the composite signal, as individual Walsh-Hadamard functions with better auto- and cross-correlation properties are selected. The advantages of composite signals in the Walsh-Hadamard basis include their spectral efficiency, which significantly exceeds the spectral efficiency of broadband signals. The paper describes a method for forming a composite signal on a Walsh-Hadamard basis with pilot signals and a functional diagram of a receiving device that provides optimal pre-detector addition of signals from four independent diversity reception channels.

Results. The method of forming the composite signal with pilot signals based on the Walsh-Hadamard basis is presented as a functional diagram of a reception device that will ensure optimal detection of composite signals from several independent channels of a separated receiver. The spectral efficiency of the composite signals is shown on the size of the Walsh-Hadamard vicor basis. The introduction of the pilot signals makes it possible to ensure the synchronous composition of signals received from several independent receiving channels.

Conclusions. The proposed technical solutions using composite signals in the Walsh-Hadamar basis make it possible to create troposcatter communication systems that provide operation in multi-path conditions, and the spectral efficiency of which significantly exceeds this indicator for systems using M-sequence signals, which allows increasing in the information transmission rate at the same frequency bandwidth or increasing their noise immunity by using additional noise-resistant coding at a fixed information transmission rate.

Keywords: *Troposcatter communication; multipath propagation; spectral efficiency; diversity technique; broadband signal; orthogonal signals; pilot signals; Walsh basis; Walsh-Hadamard functions; M-sequence type signals; receiving device; information transmission rate; noise-eliminating coding.*

Introduction

In troposcatter communication, multipath propagation is an important factor that affects quality indicators, communication reliability, and system bandwidth. The nature of the multipath propagation consists in the principle of radio signal reradiation within the common scattering volume formed by the transmitting and receiving beams of the troposcatter link. To minimize the impact of the negative factor of multipath propagation in troposcatter communication systems and equipment, the methods of scattered reception and the use of signals with special characteristics are used [1-3, 9-12].

In the transmitting/receiving equipment of troposcatter communication, signal diversity in frequency and space is usually used. In order to increase the effectiveness of diversity reception in both cases, spread spectrum signals are used, in particular, signals built on the basis of M-sequences, shortened M-sequences and segments of M-sequences [4, 5, 9-12]. Implementing algorithms for correlation processing of signals coming from different diversity reception channels allows for improving the quality of reception by compensating for (or taking into account) the relative delay of reception that occurs in different channels. Despite the high efficiency of using this multi-path propagation compensation method, this approach has certain drawbacks. In particular, its low spectral efficiency is a disadvantage. This drawback is generally characteristic of most systems that use the principle of spread spectrum expanding with the use of spreading sequences. Therefore, increasing the efficiency of troposcatter communication by the method of forming composite signals in the Walsh basis in the conditions of existing frequency limitations and transmitter power limitations is an urgent task.

Main part

In the search for methods and means of ensuring the effectiveness of troposcatter communication and reception systems in conditions of multi-path, it is advisable to consider the possibility of using parallel complex signals built on the basis of orthogonal binary Walsh functions [6-8]. The Walsh orthogonal function system is used in radio communication systems and tools. In particular, in the mobile communication standard IS-95, introduced in Ukraine as CDMA cellular communication, signals built based on Walsh functions were used in the forward and reverse channels.

Walsh functions are binary functions that take the value −1 or +1. One of the advantages of Walsh functions is their orthogonality. To calculate the linear combination of Walsh functions, well-known and well-established discrete and fast transformation algorithms are used. Due to the binary nature of Walsh functions, only integer or real number operations are used in discrete and fast transformation algorithms. It is a well-known fact that performing a fast transformation operation with real numbers does not involve complex multiplication operations and requires four times fewer elementary multiplication operations compared to Fourier algorithms.

Using binary Walsh functions allows for parallel, i.e., simultaneous transmission of a binary symbols packet of length N. The dimension N determines the basis of the system of Walsh functions and usually takes the value $N = 2^n$. A packet of N information binary symbols enters the input of the parallel composite signal generator. Each information bit performs a binary modulation of one of the Walsh-Hadamard functions. All the modulated Walsh functions are added and thus a multi-level composite signal is formed, which transmits a packet of N information bits. The composite signal built in the basis of Walsh-Hadamard functions is defined as follows

$$S(t)=\sum_{i=0}^{N} c_i(t)\, w_i(t)$$

where $c_i(t)$ – binary symbols of the information package that modulates the Walsh-Hadamard functions; $w_i(t)$ are Walsh-Hadamard functions of dimension N.

To overcome the effect of multi-path, pilot signals are added to the information packet, as several Walsh-Hadamard functions $w_i(t)$ are chosen. The number of Walsh-Hadamard functions used as pilot signals n is determined by the dimension of the Walsh basis $N = 2^n$ and is an indicator of degree 2.

It is known that the Walsh functions and the signals built on their basis are orthogonal on the signal duration interval T. But each of these functions is inferior in its auto- and cross-correlation properties to M-sequences and their derivatives. When choosing Walsh functions to be used as pilot signals, special attention is paid to their periodic auto- and cross-correlation properties. Due to multi-path, these indicators affect the effectiveness of estimating the relative delay in troposcatter communication channels.

However, in Walsh's orthogonal functions, several functions have periodic auto and cross-correlation characteristics approach M-sequence characteristics. These functions and the signals corresponding to them can be used as pilot signals to synchronize the composite signals that come from different reception channels to the equipment in the troposcatter communication station.

The procedure for forming a composite signal built in the Walsh-Hadamard basis can be described using the operation of multiplying the column matrix containing the symbols of the information message by the Walsh-Hadamard square matrix H_N of dimension $N \times N$. Fig. 1 shows the procedure for forming a composite signal in the Walsh-Hadamard basis with pilot signals.

A packet of information symbols of length N-n is received at the input of the composite signal-forming device.

$$C=\{c_1, c_2, c_3, \ldots, c_{N-n}\}$$

For use as pilot signals on the Walsh basis, n Walsh-Hadamard functions that meet the minimum level side peak requirements of their periodic auto- and cross-correlation functions are selected.

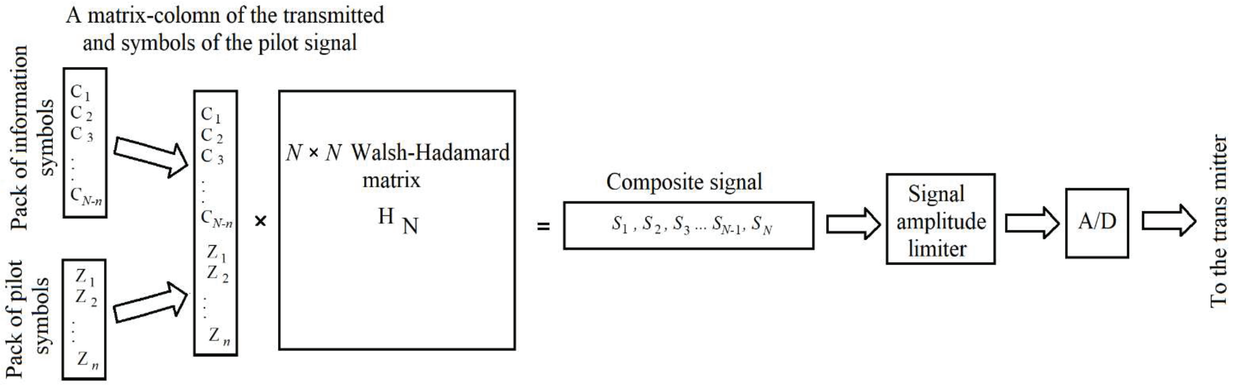

Fig. 1. The procedure for forming a composite signal in the Walsh-Hadamard basis.

The numbers of selected functions in the Walsh basis ordered using Hadamard matrices are included in a packet of pilot signal symbols of length *n*.

$$Z=\{z_1, z_2, \ldots, z_n\}$$

The values of the symbols z_j included in the package *Z* do not change. Conventionally, it can be assumed that the condition is fulfilled for symbols z_j

$$z_j=1, \quad j=\overline{1,n}$$

Packets of information symbols *C* and symbols of pilot signals *Z* form a 1 × *N* column matrix. It should be noted that the symbols of the pilot signals are located in the matrix-column structure by the numbers of the selected Walsh functions that will be used as pilot signals. The matrix-column formed in this way is the initial array for the formation of a composite signal (see Fig. 1). The column matrix is multiplied by the square matrix H_N of dimension $N \times N$. The matrix H_N is the Hadamard matrix ordering the system of Walsh functions of dimension *N*.

The algorithm of the Inverse Fast Transformation, based on the "Butterfly" operation, can be used to form a composite signal on the Walsh-Hadamard basis. The composite signal formed in this way is a row matrix of length *N*.

$$S=\{s_1, s_2, s_3, \ldots, s_k, \ldots, s_{N-1}, s_N\}$$

In the given form, each symbol of the row matrix s_i determines the amplitude of the composite signal *S* at the *k* time interval with a duration of Δt. In analogue form, the generated composite signal has the form

$$S(t)=\sum_{i=1}^{N} s_i(t)w_i(t)=\sum_{i=1}^{N-n} c_i(t)w_i(t)+\sum_{j=1}^{n} z_j w_j(t)$$

The composite signal $S(t)$ is the sum of two components: a group of signals transmitting information symbols $c_i(t)w_i(t)$ and a group of pilot signals $z_j w_j(t)$. The absence of the symbol of the pilot signal z_j of the time parameter *t* in the designation means that these symbols are unchanged.

The composite signal $S(t)$ is a random process with discrete values described by a binomial distribution with zero mean, or mathematical expectation. The features of Walsh's functions include the equality of the number of time intervals, or beats, where the function takes the value +1 of the number of time intervals where the function takes the value −1. Therefore, the average or mathematical expectation of each individual function and their aggregate is equal to 0. The standard deviation for a random variable distributed according to the binomial distribution with an equally probable value of +1 and −1 for each component process is determined by the formula

$$\sigma_N=0.5\sqrt{N}$$

Thus, the composite signals are characterized by a large value of the peak factor, which is

$$K_{pf}=\frac{N}{\sigma_N}=2\sqrt{N}$$

To reduce the peak factor of the composite signal $S(t)$, a limiter is used in the scheme of forming the composite signal (see Fig. 1). As a result of the two-way limitation of the signal amplitude at the output of the limiter, we have the following mixture of three random processes

$$S(t)=\sum_{i=1}^{N-n} c_i(t)w_i(t)+\sum_{j=1}^{n} z_j w_j(t)+\xi(t)$$

In the given expression, the process $\xi(t)$ represents disturbances describing the violation of orthogonality between the Walsh functions, which occurs as a result of the amplitude limitation of the component signal.

From the output of the limiter, the signal is fed to the transmitter of the troposcatter radio link. Radio signals are transmitted in dual-frequency mode at frequencies f_{c1} and f_{c2}.

On the receiving side of the troposcatter link, to overcome multi-path, a traditional spread reception scheme is used: with two spread antennas at two frequencies. As a result, a fourfold difference is achieved. Fig. 2 shows the functional scheme of the troposcatter communication receiving device, which uses composite signals on the Walsh-Hadamard basis with pilot signals.

High-frequency radio signals are received by two antennas and fed to the inputs of two low-noise amplifiers (LNA). From the output of the LNA, the signals are fed to the inputs of two mixers. Signals of frequencies f_1 and f_2 from the generator of reference frequencies are received at the reference inputs of the mixers. To increase the stability of the reference frequencies, the shaper input is connected to the output of a highly stable quartz oscillator, which is a source of highly stable oscillations and synchronization marks for the entire troposcatter communication station. The frequencies at the output of the reference frequency shaper are calculated in such a way as to form signals at the output at the intermediate frequency f_{if}, which is the same for all signal processing channels in the receiving device.

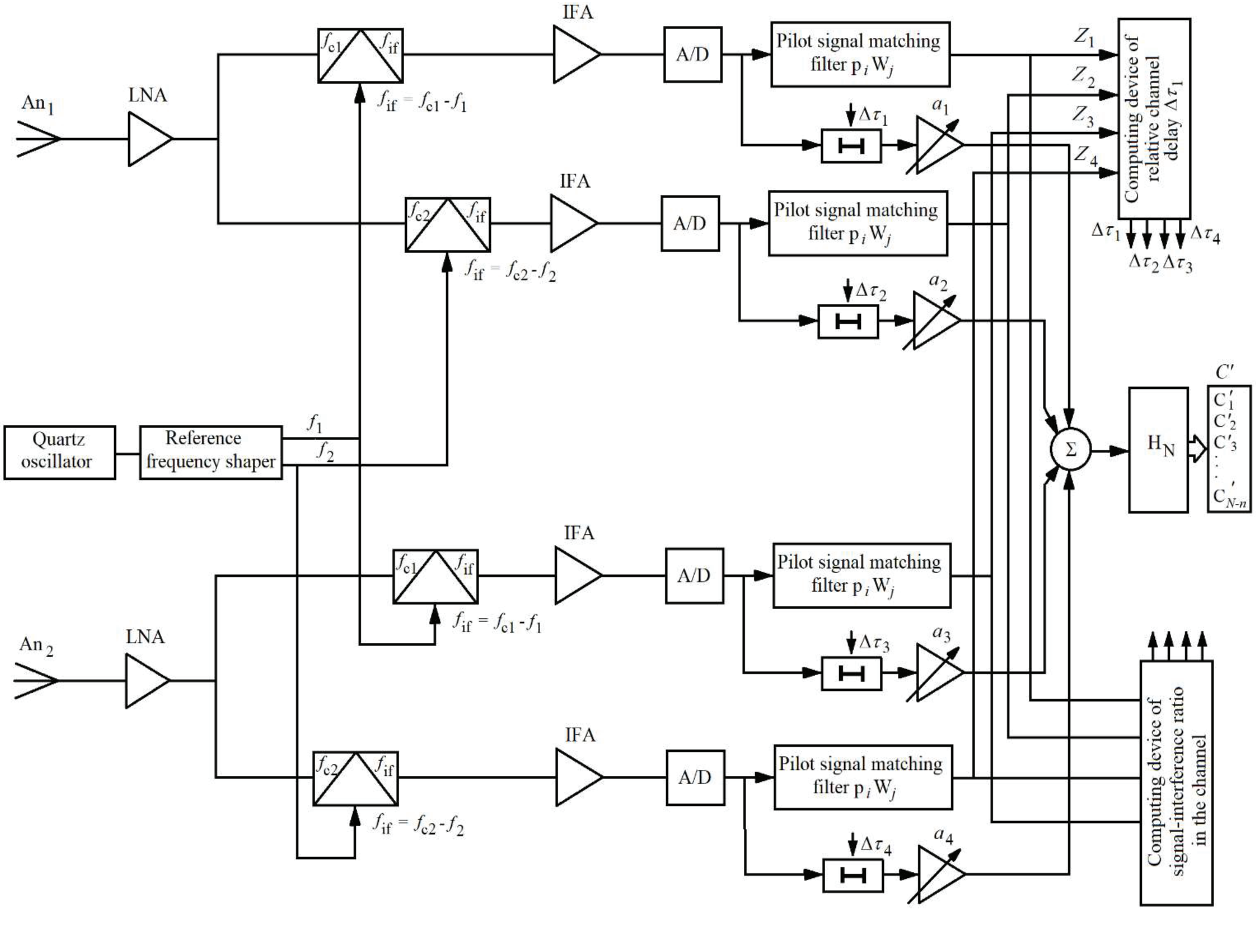

Fig. 2. Functional diagram of the receiving device of a tropospheric communication station using composite signals in the Walsh-Hadamard basis with pilot signals

$$f_{if} = f_{c1} - f_1 = f_{c2} - f_2$$

The intermediate frequency amplifier (IFA) amplifies the signal and transmits it to the input of the analogue-to-digital converter (A/D).

The A/D input receives a mixture of the received composite signal, orthogonality disturbance, and noise

$$S'(t) = \sum_{i=1}^{N-n} c_i'(t) w_i(t+\tau_l) + \sum_{j=1}^{n} z_i' w_j(t+\tau_l) + \\ + \xi'(t+\tau_l) + n(t)$$

In the above expression, c_i' and z_j' are the adopted information symbols and pilot symbols, ξ' is the adopted implementation of the orthogonality violation interference, and $n(t)$ is the thermal noise. All components of the mixture received from the tropospheric radio link transmitter, except for thermal noise, have the same delay τ_l, which is common to the selected reception channel and includes the multipath delay. The index l determines the channel number and in the case of four-channel reception $l=\overline{1,4}$.

From the A/D output, a mixture of the composite signal, interference, and thermal noise is fed to the input of a matched filter and a controlled delay line. The impulse response of the matched filter $h(t)$ is configured to simultaneously receive n pilot signals included in the composite signal. In analogue form, the reception of a composite signal in a matched filter can be written in the following form:

$$Z_l=\int_0^T S'_l(t)h(t-\Delta t)\,dt=\int_0^T\left(\sum_{i=1}^{N-n}c'(t)w_i(t+\tau_l)+\right.$$
$$\left.+\sum_{j=1}^{n}z'_i\,w_j(t+\tau_l)+\xi'(t+\tau_l)+n(t)\right)h(t-\Delta t)\,dt$$

The above expression can be broken down into components as follows:

$$Z_l=\sum_{i=1}^{N-n}\int_0^T c'_i(t)w_i(t+\tau_l)\cdot h(t-\Delta t)\,dt+$$
$$+\sum_{j=1}^{n}\int_0^T z'_i\,w_j(t+\tau_l)\cdot h(t-\Delta t)\,dt+$$
$$+\int_0^T \xi'(t+\tau_l)\cdot h(t-\Delta t)\,dt+\int_0^T n(t)\cdot h(t-\Delta t)\,dt$$

Provided that cyclic synchronization of the reception of the component signal is ensured, the first component in the above expression determines the cross-correlation function between the Walsh functions transmitting information symbols and the Walsh functions that are pilot signals. Given that the Walsh-Hadamard basis is constructed by orthogonal Walsh functions, this component takes on a zero value on intervals of the component signal duration T. The third and fourth components determine the influence of orthogonality violation interference and thermal noise. The second component is of interest. It can be represented as follows:

$$Z'_l=\sum_{j=1}^{n}\int_0^T z'_i\,w_j(t+\tau_l)\cdot h(t-\Delta t)=\sum_{j=1}^{n}Z'_{l,j}(\tau_l)$$

The function $Z'_{l,j}(\tau_l)$ is the response at the output of the matched filter in the lth reception channel to the j pilot signal, as which the Walsh function is used.

Estimates from the outputs of matched filters of pilot signals, which are formed in the case of detecting responses for all n pilot signals at once, are transmitted to the input of the Computing Device of the relative channel delay $\Delta\tau_i$. The computing device has four inputs for four receive channels. The computing device calculates the relative delay of the arrival of the estimate for each channel separately, taking the moment of arrival of the first estimate as the reference point. Based on the determined relative delays $\Delta\tau_i$, control signals are formed for the controlled delay lines that are part of each reception channel.

In parallel, the estimates Z_l are fed to the inputs of the signal-to-noise ratio computing device (see Fig. 2). This device generates estimates of the signal-to-interference ratio for each reception channel. As a result of the evaluation, the device generates four signals a_l, which determine the weighting coefficients and are transmitted to the control inputs of the channel amplifiers.

As a result of obtaining estimates of relative delays and weighting coefficients, a final received component signal is formed at the output of the adder

$$S'(t)=\sum_{l=1}^{4}a_l S'_l(t-\Delta\tau_l)$$

The formed received component signal $S'(t)$ is fed to the input of the Hadamard matrix, which performs the direct Walsh-Hadamard transformation to determine the received combination of information symbols C'

$$C'=\{c'_1,c'_2,c'_3,\ldots,c'_{N-n-1},c'_{N-n}\}.$$

An important indicator of the efficiency of tropospheric communication systems is spectral efficiency. Spectral efficiency is defined as the ratio of the number of information symbols (bits) to a unit of frequency spectrum width of 1 Hz. For troposcatter communication systems in which M-sequence signals or their segments are used to counteract multipath, the spectral efficiency is estimated by the expression

$$\eta_M=\frac{R_{\text{bit}}}{\Delta F_M}=\frac{R_{\text{bit}}}{m\Delta F_{\text{bit}}}=\frac{1}{m}[\text{bit/Hz}].$$

In the above expression, R_{bit} is the information transmission rate [bit/s], ΔFM is the bandwidth required for transmitting signals of the M-sequence type [Hz], m is the length of the M-sequence, ΔF_{bit} is the bandwidth required for transmitting an information stream at a rate of R_{bit} without using an expanding M-sequence.

When using composite signals, each bit is transmitted for the entire duration of the composite signal $T = N \cdot \Delta t$, where T is the dimension of the Walsh-Hadamard orthogonal basis, $N = 2^n$, Δt is the duration of one symbol of the Walsh function, $\Delta t = 1/R_{\text{bit}}$. The frequency band required to transmit a composite signal with an information rate of R_{bit} is

$$\Delta F_{\text{cs}} = \frac{1}{\Delta t} = R_{\text{bit}} \left[\text{Hz}\right].$$

Accordingly, the spectral efficiency of the composite signals is

$$\eta_{\text{cs}} = \frac{R_{\text{bit}}}{\Delta F_{\text{bit}}} = 1.$$

This rate is significantly higher than that for systems using signals of the M-sequence type. On the other hand, systems with M-sequences provide better signal-to-noise ratios. The resulting gain in spectral efficiency allows you to increase the information transmission rate at the same frequency band, or to use additional noise-resistant coding at a fixed information transmission rate.

Conclusions

The method proposed by the authors for forming a composite signal, which is built in the Walsh-Hadamard basis with pilot signals using the operation of multiplying the row matrix containing the symbols of the information message by a square Walsh-Hadamard matrix of dimension $N \times N$, can be taken as a basis for minimizing the impact of the negative factor of multipath when creating modern tropospheric lines and new generation communication networks.

A functional diagram of a receiving device of a troposcatter communication station using a traditional diversity reception scheme has been developed and described: with two diversity antennas at two frequencies, which uses composite signals in the Walsh-Hadamard basis with pilot signals, and provides multipath avoidance at four-fold frequency separation.

The proposed technical solutions using the method of forming composite signals in the Walsh basis make it possible to create troposcatter communication systems in the future, the spectral efficiency of which significantly exceeds this indicator for systems using M-sequence signals, which allows increasing the information transmission rate at the same frequency band, or increasing their noise immunity by using additional noise-resistant coding at a fixed information transmission rate.

References

1. Sposib troposfernoho zv″yazku [Tropospheric communication method]. Patent of Ukraine for a utility model No. 108632, publication date 07/15/2016, Bull. No. 14 with priority from 01/29/2016. Ilchenko M.Yu., Narytnyk T.M., Slyusar V.I.

2. Recommendation ITU-R P.617-3 (09/2013). Propagation prediction techniques and data required for the design of trans-horizon radio-relay systems. P Series. Radiowave propagation/© ITU 2013.

3. Wave Propagation Models in the Troposphere for Long-Range UHF/SHF Radio Connections. [Online]. Retrieved from: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.diva-portal.org/smash/get/diva2:1473256/FULLTEXT02.pdf

4. Tsyfrovi radioreleyni ta troposferni liniyi zv'yazku (osnovy rozrakhunku) [Digital radio relay and tropospheric communication lines (calculation basics)] / Narytnyk T. M., Pochernyayev V. M., Povkhlib V. S.; O. S. Popov Odesa National Acad. of Communications named after. - Odesa: O. S. Popov ONAZ, 2019. - 163 p. : fig., table. - Bibliography: pp. 160-163. - 300 notes - ISBN 978-617-582-066-7

5. T.N. Narytnyk, V.V. Volkov, YU.V. Utkin. Radioreleyni i troposferni systemy peredachi [Radio relay and tropospheric transmission systems]: Tutorial – 2008.– 349 p.

6. Numerical Methods. Using MATLAB. Book • Fourth Edition • 2019 8.4 The Walsh Transforms. Retrieved from: https://www.sciencedirect.com/book/9780128122563/numerical-methods

7. Vykorystannya funktsiy Uolsha dlya pidvyshchennya enerhetychnoyi prykhovanosti tsyfrovoyi radioliniyi [Using Walsh functions to increase the energy secrecy of a digital radio line]/ Andreyev O.V., Dubyna O.F., Nikitchuk T.M., Tsyporenko V.V. // Bulletin of NTUU "KPI". Radio engineering, radio equipment manufacturing: collection of scientific works. – 2021. – Issue 85. – pp. 27-32. – Bibliography: 17 titles. URI https://ela.kpi.ua/handle/123456789/56058, DOI https://doi.org/10.20535/RADAP.2021.85.27-32.

8. Koduvannya syhnaliv v elektronnykh systemakh. Chastyna 3. Sposoby koduvannya syhnaliv: Tom 1. Natural′ni, efektyvni ta liniyni kody [Signal Coding in Electronic Systems. Part 3. Signal Coding Methods: Volume 1. Natural, Effective and Linear Codes [Online]: Textbook for Students of Specialty 171 “Electronics”, Educational Program “Electronic Devices and Equipment” / S.V. Denbnovetsky, I.V. Melnyk, L.D. Pisarenko; Igor Sikorsky Kyiv Polytechnic Institute. – Electronic Text Data (1 File: 6.32 MB). – Kyiv: Igor Sikorsky Kyiv Polytechnic Institute. Igor Sikorsky, 2021.

9. Ilchenko M.Yu., Narytnyk T.M., Slyusar V.I. Directions Napryamky stvorennya troposfernykh stantsiy novoho pokolinnya [Directions for the creation of new generation

tropospheric stations]// Digital technologies .-2014.-Issue 16.- pp.8-18

10. Narytnyk T.M., Vetoshko I.P., Semeriy S.I., Sayko V.H., Sarapulov S.V. Analitychnyy ohlyad suchasnykh tekhnolohiy troposfernoho ta radioreleynoho zv'yazku [Analytical review of modern technologies of tropospheric and radio relay communication] // Bulletin of the University "Ukraine". Series - Informatics, computing, cybernetics, 2019. - No. 2 (23). – pp. 105-120.

11. Slyusar V.I., Masesov M.O. Ideolohiya pobudovy perspektyvnykh troposfernykh (radioreleynykh) stantsiy spetsial'noho pryznachennya [Ideology of construction of promising tropospheric (radio relay) stations of special purpose]// Collection of scientific works of Military Institute of Telecommunications and Information Technology of NTUU “KPI”. – 2010. – Issue 2. - pp. 114 -120.

12. Narytnyk T.M. Analiz elektromahnitnoyi bezpeky suchasnykh troposfernykh radioreleynykh stantsiy [Analysis of electromagnetic safety of modern tropospheric radio relay stations]. Proceedings of the 2nd International Scientific and Technical Conference “Problems of electromagnetic compatibility of promising wireless communication networks EMC 2016” - pp. 61-63, Kharkiv.

Капштик С.В, Наритник Т.М.

Метод підвищення спектральної ефективності тропосферного зв’язку на основі використання складених сигналів в базисі Уолша

Проблематика. В сучасних телекомунікаціях для організації зв’язку на далекі відстані використовуються системи тропосферного зв’язку. Ці системи дозволяють організувати зв’язок за межами прямої видимості. Важливим фактором, який необхідно враховувати в цих системах, є багатопроменевість, яка зумовлена фізичним принципом, що покладений в основу функціонування тропосферних систем. Для подолання негативного впливу цього фактору застосовуються рознесений прийом та широкосмугові сигнали. Але широкосмугові сигнали використовують надмірну смугу частот і характеризуються низьким значенням спектральної ефективності.

Мета досліджень. Розробка методу подолання негативного впливу багатопроменевості за рахунок застосування складених сигналів в базисі Уолша.

Методика реалізації. Паралельні складені сигнали забезпечують пакетну передачі одночасно групи сигналів, що побудовані на основі повної системи взаємно ортогональних функцій Уолша-Адамара. Кожен сигнал передає один біт інформації, але паралельна передача пакету взаємно ортогональних сигналів дозволяє уникнути зниженню швидкості передачі інформації в системі. Для протидії впливу багатопроменевості до складеного сигналу додаються пілот-сигнали, в якості яких обрані окремі функції Уолша-Адамара із кращими авто- та взаємно кореляційними властивостями. До переваг складених сигналів в базисі Уолша-Адамара відноситься їх спектральна ефективність, що значно перевищує спектральну ефективність широкосмугових сигналів. У статті описано метод формування складеного сигналу за принципом Уолша-Адамара з пілот-сигналами та функціональна схема приймального пристрою, що забезпечує оптимальне переддетекторне додавання сигналів чотирьох незалежних рознесених каналів прийому.

Результати досліджень. В роботі описаний метод формування складеного сигналу в базисі Уолша-Адамара із пілот-сигналами та приведена функціональна схема приймального пристрою, що забезпечує оптимальне додетекторне складення сигналів з чотирьох незалежних каналів рознесеного прийому. Визначено залежність спектральної ефективності складених сигналів від розмірності використаного базису Уолша-Адамара. Застосування пілот-сигналів дозволяє забезпечити синхронне складення сигналів, прийнятих із чотирьох незалежних рознесених каналів прийому.

Висновки. Запропоновані технічні рішення з використанням складених сигналів в базисі Уолша дають можливість створення систем тропосферного зв’язку, що забезпечують роботу в умовах багатопорменевості, та спектральна ефективність яких значно перевищує цей показник для систем, що використовують сигнали типу М-послідовності, що дозволяє збільшити швидкість передачі інформації при однаковій смузі частот, або підвищити їх завадостійкість, використовуючи додатково завадостійке кодування при фіксованій швидкості передачі інформації.

Ключові слова: *Тропосферний радіозв’язок; багатопроменевість; спектральна ефективність; методи рознесеного прийому; широкосмуговий сигнал; ортогональні сигнали; пілот-сигнали; базис Уолша; функції Уолша-Адамара; сигнали типу М-послідовності; приймальний пристрій; швидкість передачі інформації; завадостійке кодування.*