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EVALUATING THE IMPACT OF CROSS-CORRELATION PROPERTIES OF COMPLEX SIGNALS ON THE CHARACTERISTICS OF SMART RADIO SYSTEMS

Introduction

In modern cognitive radio systems, assessing the impact of cross-correlation properties of complex signals on the characteristics of smart radio systems is crucial, necessary, and highly relevant for several reasons. Cognitive radio systems operate in dynamic and congested radio frequency environments. Evaluating cross-correlation properties helps in understanding how different signals interact in the spectrum. This knowledge is essential for efficient spectrum access, enabling cognitive radios to dynamically adapt to changing conditions and utilize available frequency bands more effectively. Understanding the cross-correlation among signals is crucial for managing interference in cognitive radio networks. By assessing these properties, one can develop interference mitigation techniques to enhance the overall performance of the system. This is particularly important in scenarios where multiple radios share the spectrum, and interference management becomes a critical factor.

The evaluation of cross-correlation properties contributes to improving signal detection and classification capabilities in cognitive radio systems. By analyzing how signals correlate with each other, it becomes possible to develop advanced algorithms for signal identification, enhancing the system's ability to recognize and adapt to diverse signal types.

Efficient resource allocation is a key objective in cognitive radio networks. Understanding cross-correlation properties helps in optimizing the allocation of resources such as frequency bands, power levels, and time slots. This optimization leads to enhanced spectral efficiency and improved overall performance of the cognitive radio system.

Cognitive radio systems aim to be adaptive and intelligent in utilizing available resources. Assessing cross-correlation properties enables the system to make informed decisions based on the correlation between signals, allowing for more intelligent and context-aware operation. This adaptability is crucial in meeting the dynamic demands of wireless communication.

In summary, evaluating the impact of cross-correlation properties of complex signals in cognitive radio systems is fundamental for effective spectrum utilization, interference management, signal detection, resource allocation, and overall intelligent operation in dynamic and challenging radio frequency environments.

Analysis of recent research and publications

The «smart radio» system efficiently utilizes the radio frequency spectrum through the use of complex signals, which encompass signals with multiple components, including code modulation signals, frequency modulation signals, phase modulation signals, and more. The ensemble size of complex signals refers to the number of signals within this ensemble. Ensemble size is crucial as it impacts robustness, data transmission efficiency, and spectral efficiency. The «smart radio» system can increase the ensemble size of complex signals in several ways.

1. Low-Sidelobe Pseudo-Random Sequences. By employing pseudo-random sequences with low sidelobe levels in the cross-correlation function, the system avoids interference, enhances reliability in data transmission, and facilitates the formation of code modulation signal ensembles with improved interference-resistant properties.

2. Advanced Signal Generation Algorithms (Artificial Intelligence). Utilizing new algorithms for generating complex signals through artificial intelligence contributes to enlarging the ensemble size without compromising interference resistance.

3. Innovative Coding Methods. New coding methods allow for an increase in the ensemble size of signals without sacrificing data transmission efficiency.

The choice of a specific approach to increase the ensemble size of complex signals depends on the specific requirements of the cognitive telecommunications system. For instance, in conditions with significant interference, different strategies for creating new complex signals may be necessary to enhance interference resistance. In scenarios with limited spectral resources, methods for improving the efficiency of complex signal utilization through ensemble size become crucial for enhancing data transmission efficiency.

A Cognitive channel coding system enables subscribers to use different code sequences to form their signals, facilitating the separation of signals from various subscribers and enhancing the efficiency of radio frequency spectrum utilization. Different subscribers utilize distinct code sequences, making their signals significantly different in form. This allows receivers to effectively distinguish signals from different subscribers, ensuring efficient information transmission [1-9].

Problem statement

To design a Cognitive Telecommunication System (CTS) capable of serving a large number of subscribers, signals are chosen that enable effective utilization of limited spectral resources. Broadband signals (BSS) are employed in cognitive telecommunication systems to ensure high throughput.

Broadband signals offer several advantages over narrowband signals, including more efficient spectral resource utilization and increased system interference resistance. The number of signals that can simultaneously operate in a telecommunication system is limited by the total number of signals in the system (L). Various types of signal systems are distinguished [1; 2; 7]:

– Small signal systems with the condition $L \le B$;
– Normal signal systems with the condition $L \approx B$;
– Large signal systems with the condition $L \gg B$.

Certainly, delving into the intricacies of forming complex signals with temporal separation through the application of neural networks is an imperative undertaking, primarily because this realm remains relatively underexplored. To comprehend the gravity of this pursuit, it is crucial to outline a comprehensive rationale for research in this domain.

First and foremost, the landscape of telecommunications is in a perpetual state of evolution. The continuous demand for faster, more reliable, and adaptable communication technologies necessitates innovation and novel approaches. In this context, the utilization of neural networks to craft ensembles of signals with temporal separation emerges as a compelling frontier that can be instrumental in optimizing telecommunications systems to meet modern requirements.

Modern telecommunications signals are characterized by their complexity and dynamic nature. These signals are not static entities; they undergo variations over time, which can present formidable challenges. Investigating and deciphering such signals, encompassing the intricacies of their encoding and ensemble formation, mandates the development of new methodologies and approaches. This facet of research is particularly significant as it has the potential to substantially enhance the performance and reliability of telecommunications systems. Ensuring uninterrupted and seamless communication is of paramount importance in our digitally connected world.

Furthermore, the implications of advancements in signal ensemble formation techniques extend beyond the realm of telecommunications. These innovations can reverberate throughout various domains, including wireless networks, medical technologies, data analysis, and more. Consequently, research in this field is not limited to its immediate applications but holds the promise of catalyzing broader technological advancements and innovations.

In essence, the pursuit of understanding and perfecting the formation of complex signal-code ensembles with temporal separation through the medium of neural networks is an imperative task. It represents an exciting avenue that not only addresses the current challenges in telecommunications but also offers new possibilities for innovation and progress in a continuously evolving technological landscape. As technologies perpetually advance, research in this domain is a catalyst for staying at the forefront of these transformations and ensuring that telecommunications systems remain agile, reliable, and adaptable to the ever-changing demands of our digital age.

The purpose of the article

The primary objective of the article, which delves into the intricacies of shaping intricate signals characterized by temporal separation through the utilization of neural networks, is to embark on a comprehensive exploration of the methodologies employed in the creation of these complex signals. This endeavor involves a multifaceted inquiry into various facets, including algorithms, approaches, and the architectural underpinnings of neural networks deployed for the generation of such signals. Additionally, it entails a meticulous scrutiny of the utilization of temporal separation and the profound ramifications it bears on the process of signal formation. Of paramount significance is the exploration of the role neural networks play in optimizing this intricate process.

In essence, this article serves as a beacon guiding us through the labyrinth of complexities inherent in the formation of signals that span a temporal dimension. It encapsulates a multifaceted research journey that encompasses not only the mechanics of neural networks but also the intricate choreography required to mold signals into sophisticated, time-varying constructs. This exploration shines a spotlight on the synergy between temporal separation and neural networks, shedding light on the potential for achieving unprecedented levels of optimization within this domain. As we delve into the inner workings of signal formation and the role of neural networks, we unlock a treasure trove of insights that promises to reshape the landscape of signal processing and pave the way for new horizons in the field.

Summary of the main material

Most well-known signal systems allow for the utilization of only a limited number of subscribers, meaning they are small or normal in size. To support a large number of subscribers in modern telecommunication systems, signal systems are required that can generate an exponentially increasing number of signals, expressed by the formula where: (β, α) constants, (B) – is the signal base, and [1–4]:

$$L = \beta \cdot \exp(\alpha B).$$

An important parameter for exponentially growing signal systems is the constant – (α). It determines the rate at which the number of signals increases with an increase in the base – (B). The larger the constant (α), the faster the number of signals increases. Modern exponentially growing signal systems include Code Division Multiple Access (CDMA) signal systems, Orthogonal Frequency Division Multiplexing (OFDM) signal systems, and systems with Pseudo-Random Sequences (PN).

For effectively increasing the system's capacity, it is necessary to implement an exponential law. If this is not possible, alternative methods such as utilizing systems with a power-law growth, where: ((β, n) – constants, and it is essential to satisfy the condition ($n > 1$), can be employed [1–4].

$$L = \beta B^n.$$

Signal Basis (ΔBW – bandwidth) – a parameter defining the relationship between the signal's bandwidth and its duration. In the context of signal processing and telecommunications, the signal basis is a crucial metric determining how effectively a signal can be represented in the frequency or time domain. Simply put, the signal basis indicates how quickly a signal can change in time or frequency. It establishes how «short-time» or «short-frequency» a signal is.

A smaller signal basis allows the transmission of more details within a limited time or frequency range. Additionally, the signal basis can be utilized to assess data transmission efficiency and spectral efficiency in telecommunication systems. Employing signals with an optimal basis can enhance system performance and ensure optimal information transmission. Expressed by the formula:

$$B = \Delta BW \cdot T_s,$$

where: T_s – **(**timespan) – the duration (time) of the signal.

Taking into account the signal amplitude, the formula for the Signal Basis (ΔBW) will have the following form:

$$B = \frac{1}{T_s} \int_0^T |s(t)|^2 \, dt,$$

where: $|s(t)|^2$ – square of the signal magnitude in time; dt – time element.

In a «smart radio» system, signals should be designed in a way to minimize mutual interference between them. This is achieved by reducing the maximum values of the cross-correlation function ($R_{\max}$) between signals [7].

$$R_{\max} = \frac{\beta}{\sqrt{B}}, \quad (1)$$

where: β (bandwidth expansion factor) – spectrum spreading factor, most commonly equal to 1/5, depends on the method of code sequence generation.

Contemporary requirements in wireless networks necessitate the exploration of novel methodologies for constructing Spread Spectrum Systems (SSS) that exhibit superior cross-correlation properties. The algorithms governing these systems must be deterministic, ensuring that receivers can uniquely identify signals. Table 1 provides an overview of the key signal classes' characteristics in cognitive wireless networks employing channel coding.

Table 1

Characteristics of the main signal classes in cognitive wireless networks

Signal Class	Characteristics
Pseudo-Random Sequence (PRS) Signals	They exhibit a low level of mutual correlation, enabling them to efficiently utilize the limited radio frequency spectrum. The spectral power density of the signal S(f) is the ratio of the energy of one bit of the signal (Eb) to the number of bits in the signal. N_s: $$S(f)=\frac{E_b}{N_s}\cdot\sin c^2\left(\frac{fT_c}{2}\right)$$
Code Division Multiple Access (CDMA) Signals	Used for channel separation among different users in 5G, the probability of error (*Pe*) during the demodulation of (CDMA) signals depends on the energy of the coded symbol (*Eb*) and the power of the noise. *No*: $$P_e=Q\left(sqrt\left(2\cdot\frac{E_b}{N_0}\right)\right),$$ where: $Q(x)$ – Gaussian distribution function
Adaptive Modulation (AM) Signals	Adaptive Modulation (AM) techniques adjust the modulation type based on environmental conditions. AM enables increased efficiency in utilizing the radio frequency spectrum in cognitive networks. The average power of the signal $R_e=\frac{E_b}{2\cdot N_0}$.
Phase-Shift Keying (PSK) Modulated Signals	They vary the phase and width of their carrier pulses according to changes in the modulating signal. (N) represents the number of pulses in the sequence. $$T_i=\frac{T_s}{N};\ \Delta BW=\frac{1}{T_i}=\frac{N}{T_s}.$$
Frequency-Shift Keying (FSK) Modulated Signals	They change the frequency and width of their carrier pulses according to changes in the modulating signal. This category includes pulse frequency modulation (PFM): $T_i=\frac{T_s}{f_s};\ \Delta BW=\frac{1}{T_i}=\frac{f_s}{T_s}$, where: f_s – sampling frequency; – interference-like pulse frequency modulation (IPFM) signals. If the [sampling frequency] is sufficiently large, then the interference is white noise, and in this case – $\Delta BW=f_s$. If (f_s) is not large, then $\Delta BW=f_s\frac{1}{1-2h}$, where: *h* – interference coefficient
Pulse Width Modulation (PWM) Signals	It has a spectrum width equal to the bandwidth of the Pulse Width Modulation (PWM) filter. The frequency range of the PWM signal is determined by the difference between the carrier frequency and the upper frequency of the PWM. $D=\frac{T_{on}}{T_{period}}$, where: *D* – duty cycle, T_{on} – duration of the on state, T_{period} – pulse period

If the signals in the ensemble do not overlap, i.e., do not share common components, then they can be efficiently separated. This is possible only if the signals $s_i(t)$ $s_j(t)$ in the ensemble are orthogonal. After integrating over time and applying the Heine-Kornegay theorem – the integral over time of the product of two signals equals the scalar product of these signals, we obtain the expression $\int s_i(t)s_j(t)dt =$ $=< s_i(t)s_j(t) >$, taking into account the energies of signals E_i and *Ej*, will have the form [1; 4]:

$$\frac{1}{E_i \cdot E_j}\int_0^T s_j(t)s_i(t)dt = 0,\ i \neq j.$$

In the case of using complex signals and asynchronous operation, satisfying the orthogonality condition is practically impossible. This leads to the appearance of side lobes in the time-frequency domain, the level of which is determined by the ratio according to the formula (1) [2; 4; 7].

Complex signals used in various systems are typically formed from sequences of pulse patterns generated by a specific algorithm. Among the most widely used sequences are Galois sequences, M-sequences, Hamming-Woo sequences, Gold sequences, McClellan sequences, Kasami sequences, quasi-random noise sequences, pseudorandom noise sequences, sequences with unique bit density [1–9].

The structure of subscriber signals affects the level and nature of internal interference, as well as system characteristics such as resistance to interference, efficient use of the frequency spectrum, and $L_{ак\max}$ – the maximum number of subscribers that can simultaneously use the system [1; 2]. Frequency overlap of signals can be utilized to implement data transmission systems if individual subscriber signals are used as information carriers.

In information transmission systems where mutual interference is present, the characteristics of subscriber service quality and information reliability form a unified set of requirements. The reliability of information transmission in a system with mutual interference depends on factors such as the number of subscribers, their activity, and the power of emitted signals. To enhance the interference resistance of the system, it is necessary to reduce the load on the channel created by subscribers. This can be achieved by reducing the number of simultaneously operating subscribers or by employing adaptive channel state control algorithms, such as the «sliding window» algorithm, which optimize channel usage for efficient system operation [3; 4].

Another way to improve service quality is to use signals with better mutual correlation, which is evaluated using the indicator of maximum side lobe outliers in the cross-correlation function (CCF). These outliers depend on the number of signals in the sequences. Table 2 presents the research results for five sequences: pseudo-random noise, Galois sequences, Gold sequences, Kiosaki sequences, and nonlinear sequences. For each type of sequence, the maximum correlation resistance $R_{\max}$ was measured for various sequence lengths (N).

Table 2

R_{max} side lobe of the cross-correlation function for the defined sequences

N is the number of elements in the sequences	$R_{\max}$			
	Sequences			
	Galois	Gold	Nonlinear	Kiosaki
40	0,0051	0,00323	0,00148	0,00225
100	0,0033	0,00212	0,00091	0,00145
256	0,0025	0,00145	0,00073	0,00982
512	0,0017	0,00098	0,00067	0,00728

The correlation function for a Galois sequence at point (k) is computed as the average value of the products of corresponding elements of two sequences, divided by the length of the sequence [5]:

$$R_{\max}(k) = \frac{\sum_{n=0}^{N=1} x(n)\cdot x(n-k)}{N}.$$

Here, $x(n)$ and $y(n)$ are the corresponding elements of the two sequences, and N is the length of the sequence.

For Gold sequences, the correlation function is also computed as the average value of the products of corresponding elements of two sequences, divided by the length of the sequence N. However, the formula also includes an additional element that takes into account the total energy of the sequence [5]:

$$R_{\max}(k) = \frac{\sum_{n=0}^{N=1} x(n)\cdot x(n-k)}{N} - \frac{2}{N}\sum_{n=0}^{N=1} x(n).$$

The correlation function for two sequences X and Y is calculated using the correlation coefficient formula [5]:

$$R_{XY}(k) = \frac{\sum_{i=1}^{N-k}\left(x_i - \overline{x}\right)\left(y_{i+k} - \overline{y}\right)}{\sqrt{\sum_{i=1}^{N-k}\left(x_i - \overline{x}\right)^2 \cdot \left(y_{i+k} - \overline{y}\right)^2}},$$

where: $\overline{x}, \overline{y}$ – is the mean value of sequence X та Y.

For all four sequences, the maximum value of the cross-correlation function decreases with an increase in the sequence length.

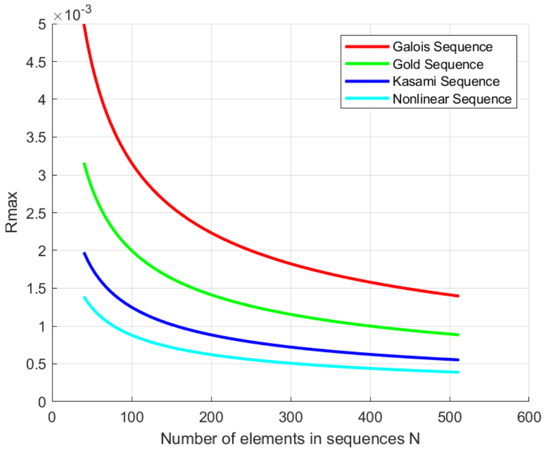

Fig. 2. R_{max} with respect to the number of elements in various sequences

This can be explained by the fact that increasing the sequence length leads to a reduction in the sequence's dispersion, thereby reducing the probability that the sequence values will deviate from the mean.

The Kiosaki sequence has the highest maximum correlation stability. This can be explained by the fact that the Kiosaki sequence possesses two main characteristics that make it more resistant to interference.

1. It is generated using a non-linear function, which results in a more even distribution of sequence values, reducing the periodicity of the sequence and its correlation stability.

2. It has high inertial memory, meaning that its current state is significantly dependent on its previous state. This also reduces the periodicity of the sequence and, hence, its correlation stability.

The non-linear sequence has the lowest maximum correlation stability. This can be explained by the fact that the non-linear function used to generate this sequence is not as effective as the non-linear functions used to generate the Kiosaki sequence.

The Galua and Gold sequences have correlation stability that falls between the correlation stability of the Kiosaki sequence and the correlation stability of the non-linear sequence.

Understanding and effectively managing the correlation between signals within a cognitive network is crucial for mitigating interference-related challenges. The correlation properties play a pivotal role in determining the network's ability to discern between different signals, thereby influencing overall performance. The development of novel signal generation methods with heightened interference resilience is imperative to address the complexities introduced by multiple access interference. Such advancements can significantly contribute to the efficient operation of cognitive networks, ensuring optimal signal quality even in scenarios involving the simultaneous transmission of multiple signals.

Conclusions

Cognitive radio systems use complex signals for efficient utilization of the radio frequency spectrum. The ensemble size of complex signals is an important metric that influences system characteristics such as interference resistance, data transmission efficiency, and spectral efficiency. To increase the ensemble size of complex signals, various methods can be employed, including the use of pseudo-random sequences with low side lobe levels in the cross-correlation function, new algorithms for generating complex signals (e.g., based on artificial intelligence), and novel coding methods that allow enlarging the ensemble size without compromising data transmission efficiency.

The choice of a specific approach to increase the ensemble size of complex signals depends on the specific requirements of the cognitive telecommunications system. A crucial task is the development of new methods for generating complex signals with high interference-resistant properties, enabling an increase in the ensemble size without sacrificing service quality. This task is essential for the advancement of next-generation "smart radio" systems.

The article calculates the maximum correlation immunity for different lengths of sequences and gives the results of research for five sequences: pseudorandom noise, nonlinear sequence, Galois sequence, Gold sequence, and Kiyosaki sequence. This information can be used to select the optimal sequence taking into account the specific requirements of "smart radio" systems. The conclusions of the article can make a valuable contribution to the development of effective and productive telecommunication systems for future generations of "smart radio".

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Козловська Д., Комар О. М., Чирва Д. П., Сорокун А. Д.

ОЦІНКА ВПЛИВУ КРОС-КОРЕЛЯЦІЙНИХ ВЛАСТИВОСТЕЙ СКЛАДНИХ СИГНАЛІВ НА ХАРАКТЕРИСТИКИ ІНТЕЛЕКТУАЛЬНИХ РАДІОСИСТЕМ

У статті розглянуто сучасні проблеми та перспективи розвитку систем «розумного радіо» з використанням складних сигналів для ефективного використання радіочастотного спектра. Когнітивні радіосистеми використовують складні сигнали для ефективного використання радіочастотного спектру. Підкреслено, що розмір ансамблю складних сигналів є ключовим фактором, який впливає на різні характеристики системи, такі як завадостійкість, ефективність передачі даних та спектральна ефективність. Для збільшення розміру ансамблю складних сигналів можна використовувати різні методи, включаючи використання псевдовипадкових послідовностей з низькими рівнями бічних пелюсток у крос-кореляційній функції, нові алгоритми генерації складних сигналів (наприклад, на основі штучного інтелекту), і нові методи кодування, які дозволяють збільшити розмір ансамблю без шкоди для ефективності передачі даних.

Вибір конкретного підходу до збільшення розміру ансамблю складних сигналів залежить від конкретних вимог когнітивної телекомунікаційної системи. Важливим завданням є розробка нових методів генерації складних сигналів з високими перешкодостійкими властивостями, що дозволяють збільшити розмір ансамблю без шкоди для якості обслуговування. Це завдання має важливе значення для розвитку систем «розумного радіо» наступного покоління.

Представлено аналіз різних методів збільшення розміру ансамблю складних сигналів. Розраховано максимальну кореляційну завадостійкість для різних довжин послідовностей і наведено результати досліджень для п'яти послідовностей: псевдовипадкового шуму, нелінійної послідовності, послідовності Галуа, послідовності Голда і послідовності Кіосакі. Ця інформація може бути використана для вибору оптимальної послідовності з урахуванням специфічних вимог систем "розумного радіо". Висновки статті можуть внести цінний вклад у розробку ефективних і продуктивних телекомунікаційних систем для майбутніх поколінь "розумного радіо".

Ключові слова: інтелектуальне радіо, складні сигнали, псевдовипадкові послідовності, послідовності Голда, послідовності Галуа, послідовності Кіосакі, кореляція, завади, спектральна ефективність.

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EVALUATING THE IMPACT OF CROSS-CORRELATION PROPERTIES OF COMPLEX SIGNALS ON THE CHARACTERISTICS OF SMART RADIO SYSTEMS

The article discusses modern problems and prospects for the development of "smart radio" systems using complex signals for effective use of the radio frequency spectrum. Cognitive radio systems use complex signals to efficiently use the radio frequency spectrum. It is emphasized that the ensemble size of complex signals is a key factor that affects various system characteristics such as immunity, data transmission *efficiency, and spectral efficiency. Various methods can be used to increase the ensemble size of complex signals, including the use of pseudo-random sequences with low levels of sidelobes in the cross-correlation function, new complex signal generation algorithms (e.g., based on artificial intelligence), and new coding techniques that allow for increased ensemble size. without compromising data transmission efficiency.*

The choice of a specific approach to increasing the size of the ensemble of complex signals depends on the specific requirements of the cognitive telecommunication system. An important task is the development of new methods of generating complex signals with high interference-resistant properties, which allow to increase the size of the ensemble without compromising the quality of service. This task is important for the development of next-generation "smart radio" systems.

The analysis of various methods of increasing the size of the ensemble of complex signals is presented. The maximum correlation immunity is calculated for different lengths of sequences and the results of research for five sequences are given: pseudorandom noise, nonlinear sequence, Galois sequence, Gold sequence and Kiyosaki sequence. This information can be used to select the optimal sequence taking into account the specific requirements of "smart radio" systems. The conclusions of the article can make a valuable contribution to the development of effective and productive telecommunication systems for future generations of "smart radio".

Keywords: smart radio, complex signals, pseudorandom sequences, Gold sequences, Galois sequences, Kiosaki sequence, correlation, interference, spectral efficiency.

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