ANNOTATION

for the dissertation work towards the degree of Doctor of Philosophy (PhD) in the educational program "8D06201 – Radio Engineering, Electronics, and Telecommunications."

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Hardware Implementation of Information-Entropy Signal Analysis

At present, the rapid development of information technologies and telecommunication systems places new demands on signal processing and analysis. The increase in channel capacity, data complexity, and quality requirements necessitates the improvement of data processing methods. Effective signal analysis and classification systems not only improve transmission quality but also ensure reliability, stability, and noise resistance of communication systems.

Traditional approaches describe signals in terms of amplitude, frequency, or phase parameters. However, these methods often fail to capture hidden structures within the signal. Therefore, in recent years, methods based on informational entropy have gained special attention.

Information entropy is a key mathematical measure characterizing the degree of uncertainty and order within a signal structure. The concept of entropy, introduced by C. Shannon, became the foundation of information theory, allowing quantitative evaluation of the complexity and information content of various processes. Consequently, entropy-based analysis methods have become effective tools in signal recognition, filtering, and classification.

The main idea of this work is to implement information-entropy analysis methods for signal processing at the hardware level, that is, to create a system capable of calculating and processing entropy-based signal features in real time.

Relevance of the research

The main trend in the development of information systems is to increase processing speed and reliability. Modern telecommunication, radar, and security systems operate with large amounts of data, where software-level processing is often insufficient due to high computational costs and latency.

An effective solution is to implement entropy methods on hardware platforms such as FPGA, DSP, or SoC. These devices provide high-speed parallel processing with low energy consumption. Advantages of entropy analysis include:

- Describing structural characteristics of signals;
- High resistance to noise and multipath propagation;
- Ability to distinguish chaotic and ordered processes;
- Quantitative evaluation of signal statistics.

Therefore, entropy-based approaches are widely applied in telecommunications, radiomonitoring, connection quality control, IoT devices, and cybersecurity systems. This research is not only relevant but also practical, aiming to create an autonomous, real-time intelligent signal analysis system. Such systems can be used in radiomonitoring centers, military and industrial communication networks.

Research objectives and tasks

The purpose of this research is to develop methods for signal analysis using informational entropy and to design a hardware prototype for its implementation. To achieve this goal, the following tasks were defined:

1. Develop algorithms and numerical methods for robust classification of PSK signals based on informational entropy analysis.
2. Implement a hardware model of informational entropy analysis based on FPGA, ensuring high performance and energy efficiency.
3. Build a theoretical model of informational entropy analysis for neural networks, considering the signal dynamics and its entropy characteristics.
4. Conduct experimental research and testing of the developed system on real data, including tasks related to the classification of digital modulation signals.

Scientific basis and content of the work

The novelty of this research lies in adapting the entropy method for hardware implementation capable of real-time operation. Entropy analysis is based on the probabilistic distribution of signals, allowing the identification of ordered and random components.

In the FPGA-based system, the entropy computation block includes several functional modules:

- Pre-filtering;
- Discretization and normalization;
- Entropy calculation;
- Data classification and visualization.

Fast Fourier Transform (FFT) is used during signal processing to evaluate frequency-domain characteristics. Parallel architecture allows multiple operations to be performed simultaneously, minimizing processing time and maximizing throughput.

Key findings

1. The results of the computational experiment confirmed that, when classifying PSK modulations using the HisarMod2019.1 dataset, Shannon entropy is the most informative feature, providing higher recognition accuracy compared to Rényi, Tsallis, and exponential entropies.
2. The optimized hardware implementation of the radio module on Xilinx Zynq-7000, utilizing 18.2% of DSP and 25.7% of BRAM resources, performs a 4096-point FFT with a 128 μs latency, demonstrating high real-time signal processing efficiency.

3. The convolutional neural network (CNN) classifies PSK modulation data obtained from the NI PXIe-1065 with 99.9% accuracy, except for QPSK modulation, for which the accuracy drops to 94.9% at SNR = 6 dB.

4. Automatic PSK modulation classification based on machine learning methods, including constellation diagrams, probability distribution functions, higher-order cumulants (HOCs), and a newly introduced filtering and regeneration technique, achieves 95% accuracy at SNR = 9 dB.

Scientific Novelty

1. It has been demonstrated that Shannon entropy is the most informative feature for the classification of PSK modulations compared to Rényi, Tsallis, and exponential entropies, which is confirmed by experiments conducted on the HisarMod2019.1 dataset.

2. A new energy-efficient radio module based on the Xilinx Zynq-7000 FPGA has been developed. It performs a 4096-point FFT with a delay of 128 μs while using minimal hardware resources (18–19% DSP and 25–26% BRAM), providing a significant acceleration in signal processing compared to software implementations.

3. For the first time, the architecture of a deep convolutional neural network (CNN) optimized for PSK signal classification based on entropy features has been developed and experimentally validated. The proposed architecture achieves up to 99.9% accuracy on data collected using the NI PXIe-1065 platform and maintains high robustness even at SNR = 6 dB.

4. A hybrid digital modulation classification architecture has been proposed and justified. It integrates statistical distribution functions, higher-order cumulants, and machine learning models, achieving recognition accuracy of up to 95% at SNR = 9 dB and higher.

Practical significance

The developed system has wide practical potential and can be used in:

1. Radiomonitoring systems - spectrum control, unauthorized transmitter detection, and frequency analysis;
2. Military and defense communications - rapid signal recognition under interference conditions;
3. SDR systems - automatic receiver adaptation and energy optimization;
4. IoT and 5G devices - embedded low-power autonomous analysis modules;

The main advantages are adaptability, reliability, and scalability.

Conclusion

The conducted research on information-entropic signal processing has demonstrated that the use of entropy-based features significantly enhances the efficiency of digital modulation analysis. The examination of the HisarMod2019.1 dataset showed that among the evaluated entropy measures — Rényi, Tsallis, and exponential — Shannon entropy exhibits the highest informativeness for PSK signal classification, providing more stable and distinguishable features even under low signal-to-noise ratio conditions.

The developed optimized hardware radio module based on the Xilinx Zynq-7000 platform confirmed the effectiveness of hardware-implemented entropic analysis. The module performs a 4096-point FFT with a delay of approximately 128 μs, while using minimal FPGA resources (18.2% DSP and 25.7% BRAM). This demonstrates the system's capability for real-time signal processing and its suitability for embedded and autonomous telecommunication complexes.

Additional experiments conducted using the NI PXIe-1065 data acquisition platform showed that the proposed convolutional neural network (CNN) achieves up to 99.9% accuracy in PSK classification, confirming the high suitability of the architecture for analyzing complex signals. For QPSK modulation, the accuracy at SNR = 6 dB is 94.9%, indicating the method's sensitivity to transitional processes and phase-shift characteristics.

Furthermore, the proposed method for automatic classification of digital modulations, which integrates entropic features with optimized processing algorithms, demonstrates high noise robustness and strong performance at low SNR levels. The method achieves 95% accuracy at SNR = 9 dB, while requiring fewer computational resources than classical approaches. This makes it a universal and practical solution suitable for various modulation types, including PSK, QAM, and others.

Approbation of the dissertation

The results of the dissertation research have been published in the following sources. Articles published in journals indexed in international scientific databases such as Thomson Reuters and Scopus:

1. Ibraimov M.K., Kozhagulov E.T., Zheksebai D.M., Sarmanbetov S.A. Implementation of functional block radio unit based on system-on-chip // Eurasian Physical Technical Journal. – 2023. – Vol. 20, № 4(46). – C. 74–80. – DOI: 10.31489/2023No4/74-80. Quartile Q3.
2. **Sarmanbetov S.,** Nurgaliyev M., Zholamanov B., Kopbay K., Saymbetov A., Bolatbek A., Kuttybay N., Orynbassar S., Yershov E. Novel filtering and regeneration technique with statistical feature extraction and machine learning for automatic modulation classification // Digital Signal Processing. – 2024. – Vol. 155. – P. 104744. – DOI: 10.1016/j.dsp.2024.104744. Quartile Q2.

Scientific articles published in journals recommended by the Committee for quality assurance in the field of education and science of the Ministry of Science and Higher Education:

1. Кожагулов Е.Т., Жексебай Д.М., **Сарманбетов С.А.**, Максутова А.А. Классификатор изображений микросхем при помощи сверточной нейронной сети // News of the National Academy of Sciences of the Republic of Kazakhstan. Physico-Mathematical Series. – 2021. – Vol. 6, № 340. – С. 59–65. – ISSN 1991-346X. – DOI: 10.32014/2020.2518-1726.102.
2. Kozhagulov Y.T., Zhexebay D.M., **Sarmanbetov S.A.**, Sagatbayeva A.A., Zholdas D. Comparative analysis of object detection processing speed on the basis of neuroprocessors and neuroaccelerators // News of the National Academy of Sciences of

the Republic of Kazakhstan. Physico-Mathematical Series. – 2020. – Vol. 4, № 332. – pp. 61–67. – ISSN 1991-346X. – DOI: 10.32014/2020.2518-1726.66.

3. **Сарманбетов С.А.**, Сагидолда Е., Кожагулов Е.Т., Жексебай Д.М. Классификация модулированных радиосигналов на основе сверточных нейронных сетей // Engineering Journal of Satbayev University. – 2021. – Vol. 143, № 2. – С. 98–105. – DOI: 10.51301/vest.su.2021.i2.13.

4. Kozhagulov Y.T., Zhexebay D.M., **Sarmanbetov S.A.**, Ussipov N.M., Kopbay K.T. Identification of digital modulation based on informational entropy // Academic Journal of Physical and Chemical Sciences. – 2024. – № 2. – pp. 73–83. – DOI: 10.32014/2024.2518-1483.279.

5. Кожагулов Е.Т., Жексебай Д.М., Намазбаев А.Т., **Сарманбетов С.А.** Эффективная классификация цифровой модуляции с использованием сверточных нейронных сетей // Bulletin of Abai KazNPU. Series of Physical and Mathematical Sciences. – 2024. – № 2 (86). – С. 201–210. – DOI: 10.51889/2959-5894.2024.86.2.019

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Zhanabaev Z. Z., Kozhagulov E. T., Zhexebay D. M., Sarmanbetov S. A. Determination of the analytical analogue of the signal-to-noise ratio (IER) based on informational entropy analysis. Republic of Kazakhstan, "National Institute of Intellectual Property," copyright certificate No. 3008. 2019.