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IDENTIFICATION OF SPACECRAFT AT CLOSE RANGE USING DEPTH MAPS

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Abstract. The article addresses the problem of automatic detection, segmentation, and classification of spacecraft using depth maps. The study was based on synthesized semi-natural data, which made it possible to simulate various orbital imaging conditions and to provide accurate ground-truth annotations for the quantitative evaluation of algorithms. Due to the instability of texture and color features under real space conditions, the geometric structure of objects is proposed as a key invariant feature. To solve the detection problem, a multi-stage algorithm has been developed, which includes adaptive histogram equalization, local threshold segmentation, morphological processing, and filtering of false contours based on geometric criteria. To classify spacecraft, deep neural networks of the ResNet family were used in two configurations: based on optical images alone and based on combined data (image + depth map). Experiments on a synthetic dataset of 19440 images showed that the proposed algorithm significantly outperforms the SAM 3 model in terms of detection accuracy (Precision 0.917 vs 0.171), ensuring a low level of false positives. The multimodal approach to classification achieved an accuracy of 99.9% (ResNet-152 model), confirming the effectiveness of using depth maps for reliable recognition of spacecraft under near-real space imaging conditions.

Keywords: spacecraft, synthetic data, object detection, computer vision, depth maps

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ИДЕНТИФИКАЦИЯ КОСМИЧЕСКИХ АППАРАТОВ НА БЛИЖНЕЙ ДИСТАНЦИИ С ИСПОЛЬЗОВАНИЕМ КАРТ ГЛУБИНЫ

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Аннотация. В статье рассматривается задача автоматического обнаружения, сегментации и классификации космических аппаратов с использованием карт глубины. Исследование проведено на основе синтезированных полунатурных данных, что позволило смоделировать различные условия орбитальной съемки и обеспечить точную эталонную разметку для количественной оценки алгоритмов. В связи с нестабильностью текстурных и цветовых признаков в реальных условиях космоса предлагается использовать геометрическую структуру объектов как ключевой инвариантный признак. Для решения задачи обнаружения разработан многоэтапный алгоритм, включающий адаптивную эквализацию гистограммы, локальную пороговую сегментацию, морфологическую обработку и фильтрацию ложных контуров по геометрическим критериям. Для классификации космических аппаратов использовались глубокие нейронные сети семейства ResNet в двух конфигурациях: на основе только оптических изображений и на основе комбинированных данных (изображение + карта глубины). Эксперименты на синтезированной выборке из 19440 изображений показали, что предложенный алгоритм значительно превосходит модель SAM 3 по точности обнаружения (Precision 0,917 против 0,171), обеспечивая низкий уровень ложных срабатываний. Мультимодальный подход к классификации позволил достичь точности 99,9% (модель ResNet-152), что подтверждает эффективность использования карт глубины для надежного распознавания космических аппаратов в условиях космической съемки, приближенной к реальной.

Ключевые слова: космические аппараты, синтетические данные, обнаружение объектов, компьютерное зрение, карты глубины

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Introduction

Spacecraft rendezvous control is a critical task due to the complexity of space missions. The growing number of programs for servicing stations, assembling structures in orbit, and exploring the Moon requires more precise rendezvous and docking methods. This is essential for the safety of crews in manned missions and for the success of automated missions [1].

In 1962, a method of multi-stage spacecraft rendezvous was proposed, which was a significant event in the history of space exploration. This process involved guidance based on data from Earth, semi-automatic control using radar, automatic docking at a distance of 100 to 200 meters, and final manual docking [2]. Once docking technology had been developed, television systems were used to monitor the

process. This equipment allowed the distance between the spacecraft and their relative position to be determined throughout the rendezvous phase.

In [3], an adaptive approach to spacecraft rendezvous control is proposed, which adjusts the camera's resolution and frame rate according to distance. At long distances, high resolution and low frame rate are used; at short distances, the opposite is true due to pixel grouping. This optimizes the balance between static and dynamic errors. To further optimize the system, an information function is also proposed that takes into account data loss, transmission speed, and encoder complexity. In the same work [3], a method for adapting the frame rate for monitoring spacecraft is proposed that optimizes the signal accumulation time depending on the distance to and brightness of the object. The algorithm is based on a criterion that minimizes the decision delay and the risk of error due to noise. The developed algorithm automatically controls the frame rate, which improves the efficiency of spacecraft observation and control systems.

In [4], an approach to creating a space-based video system that operates with limited *a priori* data is explored. It is based on the relationship between illumination and image dynamics, which allows the observed distance range to be expanded by adapting the frame rate.

Currently, due to the large number of spacecraft and variations in their configurations [5], an important area of research is the integration of artificial intelligence-based computer vision into onboard television systems [6].

In [7], the integration of computer vision into onboard systems for adaptive spacecraft rendezvous control is described. It is proposed to adapt the image processing and encoding parameters depending on the approach stage. This, combined with object recognition and tracking algorithms, improves control accuracy and reduces computational load.

In [8], a method is proposed for assessing the accuracy of distance and spatial orientation measurements based on the method of proportions, applicable to a single-camera matrix television system when the object type is known. When a spacecraft approaches an object under conditions of *a priori* uncertainty of the object class, the use of spatial information about the object, formed on the basis of depth maps, becomes key.

The aim of this study is to develop and evaluate a comprehensive approach for the automatic detection, segmentation, and classification of spacecraft at close range using depth maps and multimodal data to ensure reliable identification under varying orbital imaging conditions.

To achieve this aim, the following research tasks were addressed:

- 1) compiling a representative synthetic dataset of spacecraft 3D models with generated depth maps and precise ground-truth annotations;
- 2) developing a multi-stage algorithm for spacecraft detection and segmentation based on depth map analysis;
- 3) quantitatively evaluating the proposed detection algorithm against modern neural network baselines;
- 4) investigating the effectiveness of a multimodal approach to spacecraft classification by combining optical images with depth maps using ResNet architectures.

Materials and methods

In this study, 90 3D spacecraft models were selected for the experiments. The models were obtained from the “3D Resources” open database of the National Aeronautics and Space Administration (NASA)¹.

The dataset was compiled based on the principles of representativeness, technological diversity, and operational significance. The key criterion was to cover all major types of space missions. The sample includes scientific observatories for astrophysical research (such as “Hubble Space Telescope”, “Chandra X-ray Observatory”, “James Webb Space Telescope”, and others), specialized spacecraft for Earth

¹ 3D Resources – NASA Science. [online] Available at: <https://science.nasa.gov/3d-resources/> (Accessed 14.09.2026).

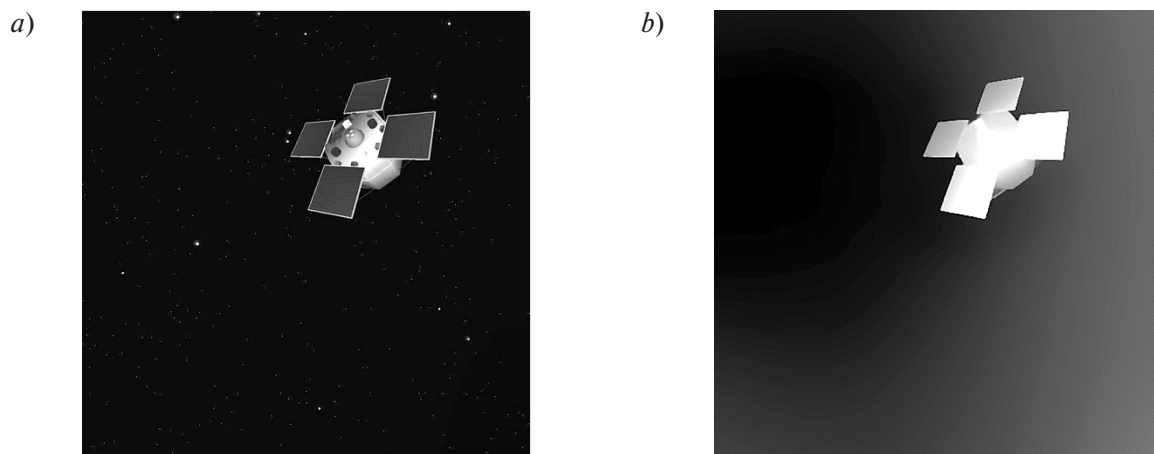


Fig. 1. Data visualization: original image of the spacecraft (a); depth map (b)

and solar observations (such as “Aqua”, “Terra”, “Solar Dynamics Observatory”, and others), and planetary and interplanetary stations (such as “Cassini-Huygens”, “Voyager”, “Dawn”, and others). To ensure the completeness of the analysis of structural forms, the set includes standardized models of small spacecraft, such as several CubeSat configurations (1RU, 2RU, ICECube etc.), which allows for comparing the unique geometric solutions of flagship missions with typical platforms. The dataset also provides historical retrospective – from early missions (“Pioneer 10”, “Skylab” etc.) to the most recent projects (“Parker Solar Probe”, “OSIRIS-Rex” etc.). In addition, it includes critical elements of space infrastructure, such as Tracking and Data Relay Satellites, which are essential for operational monitoring of near-Earth space.

Based on automatically centered 3D models, images were generated with a 60° rotation step around the Y, X, and Z axes, ensuring full coverage of all angles (216 images per class). Each image was saved on a transparent background. The objects were then placed on a realistic starry background with random scaling (from 50 to 150%) and position. The images were converted to grayscale to emphasize structural features, which is consistent with the conditions of practical space observation. For each image, a depth map was generated using Depth Anything V2 MDE model [9], which provides a relative distance to different parts of the device, preserving important 3D geometric information. These maps allow for the separation of objects from the background and the training of a classifier model based not only on visual textures but also on spatial features of the shape. Additionally, an annotation file was created for each image, containing the coordinates of the rectangle, polygon, class name, and image metadata.

Figure 1 shows a generated image of the ACRIMSAT solar observatory (Fig. 1, a) and a depth map (Fig. 1, b) obtained using Depth Anything V2 model.

Detection and segmentation of spacecraft based on depth

To solve the problem of extracting spacecraft from depth maps, an algorithm was proposed that avoids the drawbacks of neural network methods. The main criteria for development were maximum speed and autonomy: the algorithm does not require pre-training, reference databases, or the use of motion features. The key informative parameter is the depth feature, which allows for reliable segmentation of objects regardless of their dynamics. The proposed algorithm for detecting and selecting spacecraft implements a multi-stage processing of depth maps. The method is based on a step-by-step processing that includes adaptive contrast enhancement, nonlinear segmentation, morphological post-processing, and geometric filtering of false detections.

In the first stage, the depth image is pre-processed using Contrast Limited Adaptive Histogram Equalization (CLAHE) [10]. The CLAHE algorithm splits the image into a regular grid of 8×8 pixel

blocks and performs histogram equalization in each block independently, limiting the contrast gain factor to C_{Limit} . Mathematically, the operation is described as:

$$I_e(x, y) = CLAHE(I_{depth}(x, y), S_{grid}, C_{Limit}),$$

where I_{depth} is the original depth map.

Adaptive thresholding binarization [11] is used for object segmentation, which calculates a local threshold $T(x, y)$ for each pixel based on the average intensity value in a 11×11 pixel neighborhood:

$$B(x, y) = \begin{cases} 255, & I_e(x, y) > \mu_{local}(x, y) - K \\ 0, & \text{else} \end{cases},$$

where μ_{local} is the local mean in the Gaussian window, and K is the offset that provides sensitivity to low-contrast depth gradients.

The binary mask often contains noise and discontinuities. To eliminate them, the morphological closing operation is used:

$$M_{closed} = (B \oplus S) \ominus S,$$

where $\oplus$ and $\ominus$ are dilation and erosion operations, respectively, and S is a 5×5 structural element (kernel). This procedure eliminates small holes inside objects and connects closely spaced fragments. A subsequent dilation step compensates for gaps in the contours of elongated structures, such as solar panels and satellite antennas.

Contour detection is implemented using the algorithm described in [12], which builds a hierarchy of contours using boundary topology analysis. To eliminate object fragmentation, a heuristic algorithm is used to merge nearby contours based on the distance between their centers of mass. The center of mass of a contour C is calculated using the moments:

$$c_x = \frac{M_{10}}{M_{00}}, \quad c_y = \frac{M_{01}}{M_{00}},$$

where M_{00} is the zero moment (area), and M_{10} and M_{01} are the first moments.

False detection filtering is based on geometric shape invariants. Each contour is estimated by its area A , perimeter P , and circularity coefficient:

$$C = \frac{4\pi A}{P^2}.$$

The remaining contours are sorted by area in descending order, and no more than two largest objects are retained. For each object, a bounding rectangle R is constructed and projected onto the original image for visualization.

Standard metrics based on the intersection of predicted and true bounding boxes were used to quantify the effectiveness of the detection algorithm [13]. The basic formulas for calculating key indicators are presented below.

Intersection over Union (IoU) is a measure that determines the degree of overlap between the predicted B_p and the true B_{gt} rectangle:

$$\text{IoU}(B_p, B_{gt}) = \frac{\text{Area}(B_p \cap B_{gt})}{\text{Area}(B_p \cup B_{gt})}.$$

The IoU threshold (usually denoted as θ) is used to classify a prediction as either a true positive (TP) or a false positive (FP).

Precision is the proportion of correct detections among all predicted detections:

$$\text{Precision} = \frac{TP}{TP + FP}.$$

Recall is the proportion of true objects detected among all objects in the sample:

$$\text{Recall} = \frac{TP}{TP + FN},$$

where FN (False Negative) is the number of undetected true objects.

F1-score is the harmonic mean between Precision and Recall:

$$\text{F1-score} = 2 \times \frac{\text{Recall} \times \text{Precision}}{\text{Recall} + \text{Precision}}.$$

To evaluate the quality of semantic image segmentation, the Dice coefficient is used, which measures the degree of intersection between the predicted M_p mask and the M_{gt} reference:

$$\text{Dice}(M_p, M_{gt}) = \frac{2 \times |M_p \cap M_{gt}|}{|M_p| + |M_{gt}|},$$

where $|M_p \cap M_{gt}|$ is the number of common pixels in both masks (intersection), $|M_p| + |M_{gt}|$ is the total number of pixels in the predicted and reference masks, respectively.

The Segment Anything Model 3 (SAM 3) [14] was chosen as the modern baseline approach for comparison, due to its ability to operate in “zero-shot” mode without requiring pre-training or fine-tuning on target data. Table 1 presents the test results on a sample of 19440 images (90 classes $\times$ 216 images per class).

Table 1

Testing results of the proposed algorithm and SAM 3 on a test sample

Method	Precision	Recall	F1-score	IoU	Dice
Proposed	0.917	0.968	0.942	0.877	0.853
SAM 3	0.171	0.342	0.228	0.841	0.909

Figure 2 shows an example of detecting (a) and segmenting (b) the ACRIMSAT spacecraft using depth maps.

As can be seen from the Table 1, the proposed algorithm significantly outperforms the baseline SAM 3 in terms of the main detection metrics. The Precision of the proposed method is 0.917, which is more than five times higher than the corresponding value of SAM 3 (0.171). This indicates an extremely low

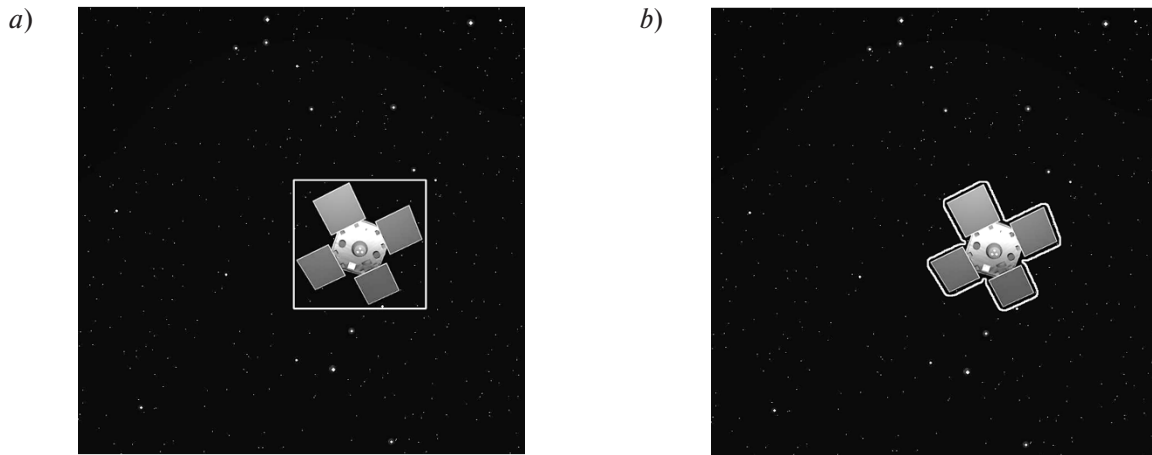


Fig. 2. Example of detection (a) and segmentation (b) of the spacecraft

level of false positives: there were only 1705 false positives compared to 32177 for SAM 3. The high Recall value (0.968 vs 0.342) confirms the reliability of object detection: the algorithm successfully identified 18824 out of 19440 objects (96.83%), missing only 616 (false negative).

Despite the fact that the SAM 3 demonstrates segmentation quality indicators comparable to those of a specialized algorithm (Dice 0.909 and Mask IoU 0.841), its practical application for the task of spacecraft detection is ineffective due to the extremely high level of false positives. The low Precision value of SAM 3 is due to its architecture, which is designed for the segmentation of arbitrary objects, which in the context of specific data leads to numerous false detections against the background of stars, noise, or the spacecraft's own structural elements. The proposed algorithm, due to the use of depth features and multi-stage geometric filtering, provides high detection accuracy.

A quantitative assessment of the segmentation quality of the proposed algorithm (average Dice = 0.853, average IoU = 0.877) confirms that the generated masks are well aligned with the true object boundaries. The slightly lower Dice value compared to SAM 3 is compensated by higher localization accuracy and the absence of training requirements. Therefore, the developed method provides an optimal balance between the completeness of detection and the accuracy of contour extraction, making it more suitable for autonomous depth image processing systems.

Classification of spacecraft

In the conditions of orbital imaging, textural and color features are often unstable, while the geometric structure of the object remains invariant to the conditions of external illumination. In this regard, the use of multimodal approaches that combine semantic information from the image with information about the spatial structure of the object becomes particularly relevant.

ResNet architectures [15] were chosen for the classification of spacecraft, as their structural features allow for effective solution of this computer vision tasks. The key factor in the choice was the concept of residual learning, implemented through blocks with through-the-stack connections. This architectural solution avoids the problem of gradient decay, which is critical when training deep neural networks. Images of spacecraft are characterized by a high variety of angles, specific illumination conditions in outer space, and the presence of many small structural elements. The ResNet architecture provides deep feature differentiation: the initial layers of the network successfully identify the boundaries and textures of surfaces, while the deeper layers form a high-level representation of the topology of specific types of spacecrafts.

The experiment was conducted using ResNet architectures (18, 34, 50, 101, 152) pre-trained on the ImageNet dataset. The output fully connected layer of each model was replaced with a new linear

Table 2

Training parameters for classifiers

Parameter	Value
Batch size	64
Optimization method	Adam
Initial learning rate	10 ⁻³
Loss function	Cross-entropy
Number of epochs	30

layer with the number of neurons equal to the number of spacecraft classes (90 classes). The training parameters are presented in Table 2.

All input images were scaled to a size of 128×128 pixels. Each model was trained on an Nvidia RTX 2080 TI graphics accelerator with 11 GB of video memory.

Based on the generated scenes with spacecraft, a dataset was prepared for solving the classification task. From each pair of images and depth maps, the area containing the spacecraft was extracted using annotations. The dataset was randomly divided into three non-overlapping sets: training set (70% of the dataset, 13680 images), validation set (15% of the dataset, 2880 images), and test set (15% of the dataset, 2880 images).

Two series of experiments were conducted to evaluate the effectiveness of ResNet. In the first stage, the models were trained exclusively on the original spacecraft images. A comparative analysis of the quality metrics of the ResNet models on spacecraft images is presented in Table 3.

Table 3

Comparative analysis of ResNet model quality metrics on spacecraft images

Model name	Layers number	Accuracy	Precision	Recall	F1-score
ResNet18	18	0.964	0.964	0.964	0.964
ResNet34	34	0.967	0.965	0.965	0.965
ResNet50	50	0.970	0.971	0.971	0.971
ResNet101	101	0.976	0.978	0.977	0.977
ResNet152	152	0.979	0.980	0.979	0.979

The results presented in Table 2 demonstrate an increase in classification quality with an increase in the depth of the architecture. The ResNet18 model shows high accuracy (0.964), which confirms the effectiveness of residual connections even for relatively shallow networks. The transition to ResNet34 and ResNet50 provides an Accuracy increase of 0.3% and 0.6%, respectively, due to a richer hierarchy of extracted features. The best result among models trained on visual images only is demonstrated by ResNet152 (Accuracy 0.979). This shows that deep architecture is capable of capturing subtle differences in textures and shapes of 90 classes of spacecraft. All metrics (Precision, Recall, F1-score) are balanced and almost identical to Accuracy, which indicates that there is no class imbalance in the test set and that the predictions are stable.

The key result of the study was obtained in the second series of experiments, where the classification of combined data (an image supplemented with a depth map) was performed. A comparative analysis of the quality metrics of the ResNet models on combined images is presented in Table 4.

Table 4

Comparative analysis of ResNet model quality metrics on combined images

Model name	Layers number	Accuracy	Precision	Recall	F1-score
ResNet18	18	0.988	0.988	0.987	0.988
ResNet34	34	0.992	0.993	0.992	0.993
ResNet50	50	0.996	0.996	0.996	0.996
ResNet101	101	0.998	0.999	0.999	0.999
ResNet152	152	0.999	0.999	0.999	0.999

Adding depth maps to the original images improves all quality metrics for each of the architectures considered. The baseline ResNet18 model on the combined data (Accuracy 0.988) outperforms the deepest single-modal ResNet152 model (Accuracy 0.979). This strongly suggests that geometric information (depth) is a more stable and informative feature in space imaging conditions than texture or color.

The ResNet34 architecture has the highest relative increase (Accuracy increased from 0.967 to 0.992, an increase of +2.5%). The deepest models – ResNet101 and ResNet152 – achieve almost perfect results (Accuracy 0.998 and 0.999, respectively). The classification error of 0.1% for ResNet152 can be explained by the presence of heavily noisy or non-standard viewing angles, where even geometric information is interpreted ambiguously. Nevertheless, the 99.9% result confirms that the “image + depth map” combination allows ResNet-based networks to solve the task of spacecraft classification with high reliability, minimizing the impact of external conditions and visual interference.

Conclusion

As part of this work, based on synthesized semi-natural data, a complete data processing cycle for automatic spacecraft recognition was developed and tested, including the stages of detection, segmentation and classification. The use of synthesized scenes made it possible to provide accurate reference markings (ground truth) and controlled modeling of various orbital survey conditions, which is important for quantifying the proposed algorithms.

To solve the detection problem, an algorithm based on the analysis of depth maps is proposed. Unlike neural network approaches, it does not require pre-training and demonstrates high efficiency. An experimental comparison with the modern neural network model SAM 3 on a synthetic dataset showed that the proposed algorithm provides superior detection accuracy (Precision 0.917 vs 0.171) while maintaining high completeness (Recall 0.968).

In the classification task, the potential of a multimodal approach that combines standard images and depth maps was explored. A series of experiments with ResNet-based architectures confirmed that adding depth information improves recognition accuracy. Combining images and depth maps allowed the ResNet152 model to achieve high classification rates (Accuracy of 99.9%), while classification based solely on optical images achieved around 97.9% accuracy.

Consequently, the research tasks formulated in the introduction have been fully accomplished. The developed comprehensive approach, which combines fast depth-based detection and accurate multimodal classification, is proven to be an effective and reliable solution for autonomous navigation, inspection, and tracking of space objects at close range, adapting to varying orbital conditions, fully achieving the stated aim of the study.

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DESIGN OF AN AUTOMATED FREIGHT TRANSPORTATION MONITORING SYSTEM BASED ON INTERNET OF THINGS NETWORKS USING BLOCKCHAIN TECHNOLOGY

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Abstract. The paper proposes an architecture for an automated freight transportation monitoring system based on blockchain technology. When integrating standard blockchain solutions with Internet of Things (IoT) devices into a unified techno-logical system, it is necessary to minimize direct requests to the main registry (root blockchain). This requirement remains essential even when participants of the distributed network are granted permissions to modify smart contract parameters, thereby reducing the load on the root registry while ensuring a high level of security during data transmission: from sensors to the mobile node and from the mobile node to the root system. The paper presents a comparative analysis of distributed ledger platforms, taking into account regional specifics and the possibility of integrating certified domestic cryptographic information protection tools. A prototype of an end-to-end freight transportation monitoring system has been developed and implemented, providing continuous tracking of cargo conditions sensitive to environmental factors. Simulation results confirm the effectiveness of using smart contracts for automating control procedures and ensuring the immutability of logistics operation data. The proposed architecture enables the development of scalable and secure industrial monitoring networks for logistics companies.

Keywords: Internet of Things, blockchain, smart contract, cargo transportation, logistics, mobile node, information security

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Научная статья

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ПОСТРОЕНИЕ СИСТЕМЫ АВТОМАТИЧЕСКОГО МОНИТОРИНГА ГРУЗОПЕРЕВОЗОК НА ОСНОВЕ СЕТЕЙ ИНТЕРНЕТА ВЕЩЕЙ С ПРИМЕНЕНИЕМ ТЕХНОЛОГИИ БЛОКЧЕЙН

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Аннотация. В статье предлагаются концепции построения автоматической системы для передачи чувствительной информации в системах мониторинга на базе блокчейн-сетей с распределенной инфраструктурой. Использование существующих методов построения блокчейн-сетей в сочетании с интеграцией устройств Интернета вещей (IoT) в общий технологический стек предполагает следование концепциям, направленным на минимизацию прямого обращения к корневому реестру. Такой подход сохраняется даже при наличии прав на редактирование параметров, что позволяет снизить нагрузку на сеть, обеспечивая при этом высокий уровень безопасности при передаче данных от датчиков к мобильному узлу и от мобильного узла к корневой системе. В работе представлен сравнительный анализ платформ распределенного реестра с учетом региональной специфики и возможности внедрения сертифицированных отечественных средств криптографической защиты информации. Разработан и реализован прототип системы полного жизненного цикла для грузоперевозок, обеспечивающий непрерывный мониторинг состояния грузов, чувствительных к факторам окружающей среды. Результаты имитационного моделирования подтверждают эффективность использования смарт-контрактов для автоматизации контроля и обеспечения неизменности данных о логистических операциях. Предложенный подход позволяет создавать масштабируемые и защищенные промышленные сети мониторинга для логистических компаний.

Ключевые слова: Интернет вещей, блокчейн, смарт-контракт, грузоперевозки, логистика, мобильный узел, защита информации

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Introduction

The transformation of modern logistics toward cost reduction and the implementation of transportation quality control systems has increased the relevance of Internet of Things (IoT) technologies. According to Future Market Insights, spending on IoT solutions in logistics amounted to 50.26 million USD in 2024. It is projected to grow to 189.62 million USD by 2034, with a compound annual growth rate (CAGR) of 14.2% [1].

A similar trend is observed in the market for blockchain-based solutions. According to Global Market Insights, the global blockchain logistics market is demonstrating steady growth driven by increasing requirements for supply chain transparency, the reduction of disputes among supply chain

participants, and the need to ensure the immutability of logistics data¹. The highest demand is concentrated in the areas of product provenance tracking, document workflow automation, and transportation condition monitoring [2].

On the one hand, the scaling of networks integrating various sensors, controllers, and actuating devices opens up new opportunities for improving the quality of freight transportation monitoring. On the other hand, it creates a number of challenges and increases the requirements for the hardware employed and the quality of communication channels [3].

Among the key challenges are the need for real-time transmission of cargo-related data, including geolocation information, and the continuous monitoring of transportation parameters such as temperature, humidity level, vibration loads, and other indicators. The use of sensors optimizes operational processes by replacing manual inspection of cargo and vehicle conditions with automated monitoring at terminals and warehouses. Another significant challenge is the scalability of such systems, where information security in traffic transmission becomes a critical concern, particularly with respect to data immutability and the redistribution of information flows within core storage systems.

Addressing these challenges requires a technological foundation capable of providing an environment for recording key events in logistics processes. One potential solution is the application of blockchain technology in combination with smart contracts, where data collection from IoT devices is performed automatically in accordance with predefined algorithms.

The aim of this study is to assess the applicability and potential approaches to integrating blockchain platforms into the architecture of logistics-oriented IoT networks while taking into account the specifics of the Russian environment. Particular attention is paid to the development of a lightweight service intended for interaction with IoT devices and blockchain infrastructure.

Materials and methods

System monitoring architecture

One of the key problems of traditional logistics chains is the issue of trust among participants, including the sender, carrier, and recipient. In the event of cargo damage (for example, due to a violation of temperature conditions), data obtained from monitoring devices may be falsified by an interested party or lost. The proposed solution involves the creation of an autonomous trusted auditor based on IoT technologies and a distributed ledger implemented through a blockchain network. The core element of the system is a “smart” IoT container capable of independently recording specific environmental parameters (such as temperature, pressure, etc.), signing them with a cryptographic key directly on the end device, and transmitting them to a blockchain ledger that is immutable for unauthorized parties. Such an approach transforms IoT devices into independent observers, eliminating the human factor and preventing data falsification.

A similar approach is discussed in a number of recent studies devoted to the digitalization of supply chains [4, 5]. These works also emphasize that the combination of IoT and blockchain technologies enables the creation of a mechanism for continuous tracking of goods during transportation, in which every event is automatically recorded in a distributed ledger and becomes verifiable by all participants in the supply chain [6].

The conceptual interaction model within the supply chain is based on the separation of areas of responsibility. Regardless of the specific platform implementation, three key logical roles can be identified within the system:

1) **The transportation initiator or a dedicated coordinating entity** acts as the contract administrator with full access privileges. This participant defines the transportation conditions, including permissible

¹ Blockchain in Logistics Market Size, Share, and Industry Analysis, By Technology (Public Blockchain, Private Blockchain, and Others), By Use Cases (Track and Trace, Transparency and Compliance, Smart Contracts, Inventory Management, and Counterfeit Prevention), By Industry (FMCG, Pharmaceutical, Manufacturing, Automotive, and Others), and Regional Forecast, 2026-2034. [online] Available at: <https://www.fortunebusinessinsights.com/thankyou/request-sample-pdf-s-bar-report/111635> [Accessed 16.07.2026].

ranges of temperature, humidity, illumination, and geolocation parameters. In addition, the administrator creates a digital representation of the agreement in the form of a smart contract – an algorithm containing the logic for condition verification – and deploys this contract to the network, thereby initiating the monitoring process.

2) **The mobile agent (carrier)** operates an IoT node located within the cargo compartment. This hardware-software system is installed on the vehicle and functions as a lightweight client of the blockchain network. It continuously collects telemetry data from sensors, performs preliminary onboard data processing in order to reduce network load, and transmits only critical events or periodic reports to the blockchain, authenticated by the device's digital signature [7].

3) **The auditor** is an entity with read-only or validation access to the distributed ledger. At any time, the auditor can verify the cargo status and the integrity of the transportation history, as well as record the completion of the contract upon cargo delivery.

The proposed system is based on the principle of architectural immutability after deployment. Violation detection is performed outside centralized servers, within a decentralized infrastructure built on smart contracts. The lifecycle of the monitoring process can be represented as follows² [8]:

1) **Recording conditions in the smart contract.** Transportation conditions and data related to carriers, recipients, and senders are specified within the smart contract. For example, one of the parameters may define the permissible temperature range for goods during transportation. The smart contract contains a comprehensive set of conditions, which may only be modified by the administrator acting as the responsible entity.

2) **The cryptographic binding of IoT devices** enables the local registration of contract conditions during the initialization of procedures and their subsequent processing within the system. This makes it possible to define multiple operational constraints and develop a mathematical framework for assessing actual parameter variations during transportation.

3) **Incident detection.** If the sensors detect a deviation from the predefined norm, or if aggregated indicators over a certain period reveal a violation of transportation conditions, the IoT device generates a transaction containing information about the violation and records it in the smart contract.

4) **Immutability.** The transaction is included in a block, linked to previous records through cryptographic hashing, and propagated across all nodes in the network. Data deletion or modification is impossible without compromising the integrity of the blockchain; therefore, the proposed structure can be characterized as highly resistant to tampering.

It should be noted that such an architecture corresponds to the concept of “traceability by design,” in which the system is developed with the objective of ensuring subsequent verification of the origin and condition of cargo at every stage of the transportation route [9–11].

Comparative analysis of blockchain networks

Selecting an appropriate blockchain platform for logistics applications and substantiating this choice constitutes one of the primary objectives of the proposed project. For consortium and enterprise-grade solutions, which include the system under development, platforms supporting a permissioned access model while ensuring high transaction throughput and confidentiality are considered. The following platforms satisfy these requirements [12]:

1) **Hyperledger Fabric** is a platform developed by the Linux Foundation and positioned as a framework for enterprise blockchain networks. Its key advantage is a modular architecture and a flexible channel system that enables transaction isolation between specific consortium participants. This feature is critical for logistics scenarios, where the shipper and carrier should not disclose commercial details to the entire network. However, the performance of the platform strongly depends on hardware configuration. Deploying a full peer node on low-power devices (e.g., Raspberry Pi-based units inside cargo containers) is challenging due to high computational requirements. In addition, the use

² MEXC. Chto takoe smart-kontrakty? [What are smart contracts?] [online] Available at: <https://www.mexc.com/ru-RU/learn/article/what-are-smart-contracts-1> [Accessed 16.07.2026].

of non-domestic cryptographic algorithms requires additional layers of adaptation for certification within the Russian jurisdiction³ [13].

2) **Corda**, developed by the R3 consortium, was originally designed for the financial sector but has also found applications in logistics. Its main feature is the absence of a global transaction ledger. Information is stored only between participants of a specific transaction, which ensures a high level of privacy and reduces network overhead. However, since Corda shares data only among parties involved in a given deal, it complicates the creation of a unified dataset. As a result, regulatory authorities face difficulties in verifying the full lifecycle of goods across all stages. Additionally, the issue of certification compliance within the Russian jurisdiction remains unresolved⁴ [14].

3) **Ethereum (Private, Quorum)** enables the use of the Solidity ecosystem and development tools while eliminating the high fees and low throughput of the public network. Quorum provides mechanisms for private transactions and various consensus protocols. However, for the purposes of this study, a critical drawback is the use of cryptographic standards that do not comply with Russian regulatory requirements. Data signed using such cryptography cannot be directly accepted as legal evidence in Russian arbitration proceedings without costly and complex forensic examination⁵ [15].

4) The **“Confident” platform** is a specialized enterprise-grade blockchain solution developed by the Russian company Web3 Tech for building governmental and corporate distributed trusted systems. Unlike foreign counterparts, this platform is designed from the outset to comply with Russian legislation and to integrate with existing IT infrastructure within the Russian market⁶ [16].

A comparison of the main characteristics of the presented platforms is provided in Table 1.

Table 1

Comparative analysis of the presented platforms

Criterion	Hyperledger Fabric	Corda	Ethereum (Private, Quorum)	Confident
Platform type	Permissioned	Permissioned	Permissioned, Private	Permissioned
Consensus	Raft, Kafka, PBFT	Notary-based platform	IBFT, Raft	Asynchronous, based on Russian algorithms
Confidentiality	Channels, private data	“Need-to-know” model	Private transactions	Cryptographic isolation, GOST
Regulatory requirements (RF)	Not compliant	Not compliant	Not compliant	Compliant
Node resource requirements	High	Medium	Medium	Medium

Considering the requirements for product certification, data protection, and ease of integration with heterogeneous IoT devices, as well as the ability to operate under conditions of unstable connectivity, the “Confident” platform represents the most balanced technological solution for developing a domestic fault-tolerant logistics management system under the given constraints.

³ Nefedov N. Hyperledger Fabric dlia Chainikov [Hyperledger Fabric for Dummies]. [online] Available at: <https://habr.com/ru/companies/ibm/articles/444874/> [Accessed 16.07.2026].

⁴ Shunko A. Corda – open source blokchein dlia biznesa [Corda – open-source blockchain for business] [online] Available at: <https://habr.com/ru/articles/452258/> [Accessed 16.07.2026].

⁵ Alexx. Vypolnenie publichnykh i privatnykh tranzaktsii v blokcheine JPMorgan Quorum s ispol'zovaniem Web3 [Executing public and private transactions on the JPMorgan Quorum blockchain using Web3]. [online] Available at: <https://habr.com/ru/articles/456368/> [Accessed 16.07.2026].

⁶ Konfident – blokchein-platforma dlia biznesa i gosudarstva [Confidant – a blockchain platform for business and government]. [online] Available at: <https://web3tech.ru/platform/architecture> [Accessed 16.07.2026].

System design

Currently, there is an issue related to compliance with cargo transportation conditions, particularly with respect to regulations governing the handling of goods. This problem is further exacerbated by the lack of a simple and accessible evidentiary basis for suppliers and their customers. In disputed situations (for example, in cases of cargo damage), it is practically impossible to objectively determine the responsible party – whether the incident is a result of the carrier’s actions or improper packaging by the sender. The existing practice allows one of the contracting parties to manipulate data in its own favor.

To address this problem, an automated cargo monitoring system based IoT and blockchain technologies has been developed. The system is built on Raspberry Pi 4B/5 single-board computers acting as mobile gateways that collect data from a set of IoT sensors. These sensors continuously record critical parameters specific to each type of cargo (such as temperature, humidity, vibration, geolocation, and others), compliance with which is stipulated by contractual conditions. The use of blockchain ensures the immutability of the collected data, fully eliminating the possibility of record falsification by any party. In addition, smart contracts are protected from post-deployment modification after being agreed upon and uploaded to the network, while on-gateway telemetry processing allows hardware noise to be filtered out, thereby minimizing technical errors [17, 18].

This approach enables the system to be used not only for technical monitoring but also as an evidentiary framework in dispute resolution, for example with insurance companies and regulatory authorities, ensuring full compliance with information security legislation requirements.

A key non-functional requirement of the system is to ensure high availability and fault tolerance of the mobile equipment throughout the entire transportation route. This requirement is implemented through the integration of automated IoT-based solutions. Edge sensors are responsible for continuous telemetry data acquisition, while a dedicated service performs initial processing, aggregation, and cryptographic protection of the data prior to its transmission to the platform’s distributed network [19, 20]. This ensures stable system operation under conditions of unstable connectivity and guarantees the integrity of the transmitted information.

Transactions and smart contract execution

A transaction is an atomic operation in a blockchain executed on behalf of a network participant that modifies the global state of the distributed ledger. It represents a fundamental system element: when a transaction is submitted, a node initiates a request containing a set of data for modifying information, access rights, or the state of smart contracts.

Before a transaction is included in a block, it undergoes a strict sequence of validation checks on the node side. If a transaction fails at least one stage of validation, it is rejected and is not added to the pool of confirmed transactions.

Critical validation stages:

1) **Timestamp.** The transaction creation time must not deviate from the time of inclusion of the current block in the blockchain by more than 2 hours backward or 1.5 hours forward. This protects the network against replay attacks.

2) **Versioning and types.** The system verifies whether support for the specified transaction type and version has been activated in the blockchain through the voting mechanism.

3) **Integrity.** A cryptographic signature check is performed. If the transaction data has been modified after signing, the signature becomes invalid, and the node rejects the transaction.

It should be noted that the process of constructing the blockchain ensures that data included in it cannot be removed. If an attacker attempts to delete or modify a transaction in an already created block, the block hash will change, breaking the cryptographic linkage with subsequent blocks, which will cause the entire branch to be rejected by honest nodes [21–23].

The lifecycle of a transaction on the “Confident” platform is illustrated in Fig. 1.

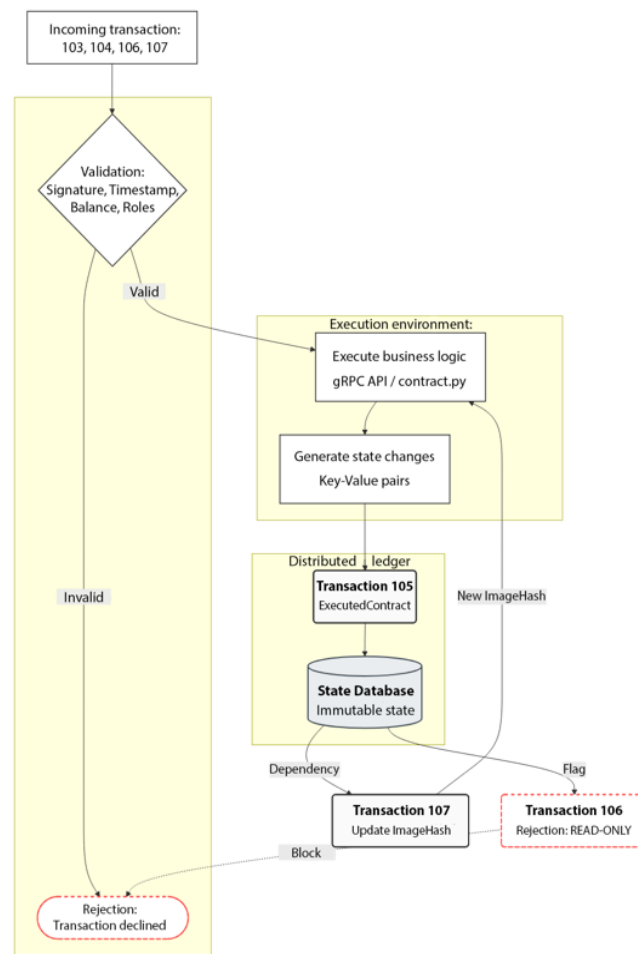


Fig. 1. Smart contract verification process on the “Confident” blockchain platform

On the presented platform, smart contracts are executed in isolated Docker containers. This approach ensures the security of the entire system in the event of a failure of an individual contract and enables the implementation of contract logic in any programming language. The smart contract code is stored off-chain.

The contract initialization process within the system proceeds as follows:

- 1) **Build.** A developer builds a Docker image containing the contract code and uploads it to an external repository, such as Docker Registry.
- 2) **Commitment.** A contract creation transaction is submitted to the blockchain, containing a reference to the image and its cryptographic hash.
- 3) **Execution.** Upon receiving the transaction, network nodes automatically download the specified image from the repository, verify its hash to ensure container integrity, and each participant executes the contract locally.

Thus, the image hash is recorded across all nodes, guaranteeing that all participants execute the same immutable code.

Results and discussion

Hardware-software implementation

To implement the approach described above, a distributed network consisting of three clusters was deployed, simulating a real supply chain, schematically illustrated in Fig. 2.

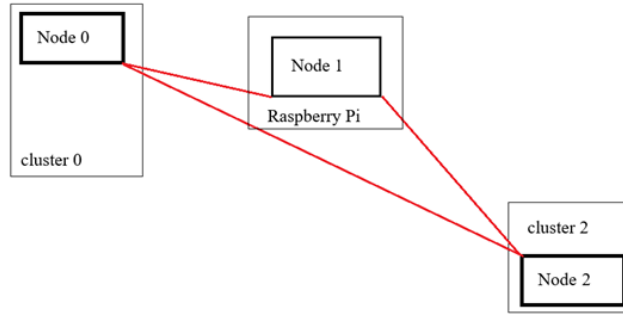


Fig. 2. Network architecture based on the “Confident” blockchain platform

Description of Fig. 2 structure:

1) **Cluster 0 (Sender/Node 0)** is a full-featured validator node acting as a “Control Center.” Through a web interface, the administrator defines smart contract parameters (temperature range, geofencing zones, time constraints, and other conditions associated with the contract waybill) and initiates its deployment across the network. Node 0 compiles the contract logic and signs the contract creation transaction.

2) **Carrier/Node 1** is a mobile node based on a Raspberry Pi device, integrated directly into the transport vehicle. It operates in a “light client” mode optimized for limited computational resources.

3) **Cluster 2 (Customer/Node 2)** is the receiving party, acting as a monitoring and auditing node that synchronizes the ledger to verify cargo status upon arrival.

The primary workload is handled by Node 1 (mobile node), as it collects all data and, in the event of a violation, propagates it to the network. The data processing pipeline consists of the following stages:

1) **Initialization and caching.** At the start of the shipment, Node 1 connects to the network and, using a unique Contract ID, loads the contract conditions (e.g., $t \in [20.0; 35.0]$) into a local cache. This ensures system operability even in the absence of Internet connectivity (GSM/LTE) during transit.

2) **Data acquisition and validation.** A Python-based microservice periodically polls a microcontroller connected to the sensor suite (temperature, light intensity, pressure). The obtained values are immediately compared against the reference contract parameters: if a sensor value falls outside the admissible range $t_{\text{sensor}} \in [t_{\min}; t_{\max}]$, a violation is registered.

3) **Cryptographic commitment.** In the event of a detected violation (e.g., temperature exceeding the permissible range or light sensor activation indicating tampering), the system generates a transaction containing a violation marker. Sensor readings and associated metadata may be stored in full within the Raspberry Pi memory for subsequent analysis and additional evidentiary support.

4) **Finalization.** Upon arrival at the destination, Node 1 submits a smart contract invocation transaction that updates the cargo status in the global ledger.

Experimental evaluation

As an experiment, an arbitrary cargo transportation scenario with predefined storage condition requirements was simulated. During the contract creation stage, the smart contract was configured with a set of permissible parameter ranges, which were subsequently transmitted to the Raspberry Pi device, as shown in Fig. 3.

As shown in Fig. 3, the following permissible ranges were defined: temperature from 20 to 35 °C, illumination from 700 to 1100 lux, and pressure from 900 to 1100 pascals.

During the monitoring process, the microservice detected a deviation in the illumination parameter (light), where the value dropped to 539 at a minimum allowable threshold of 700, as well as a temperature spike up to 40 °C.

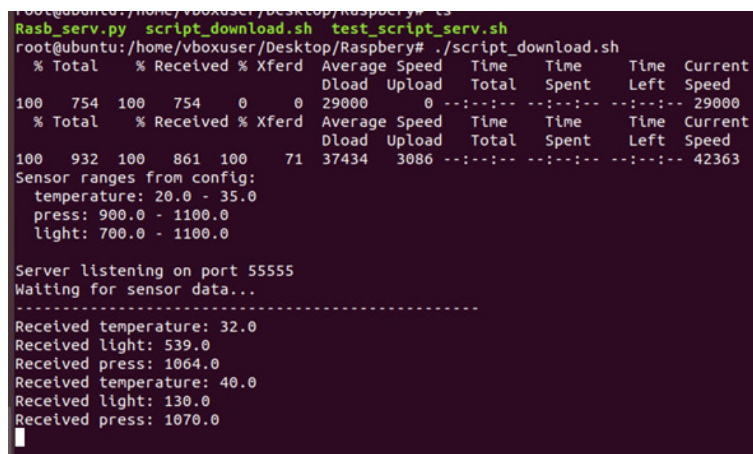


Fig. 3. Smart contract deployment and transmission of retrieved data to the Python service

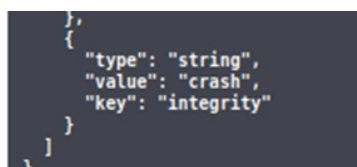


Fig. 4. Updated cargo state in the blockchain ledger

The validation system automatically classified these events as a violation. The processing result was recorded on the blockchain via a smart contract invocation transaction. As shown in the ledger state dump presented in Fig. 4, the cargo integrity variable (*integrity*) was irreversibly set to “crash”.

Conclusion

The presented work proposes an architecture for an automated cargo transportation monitoring system based on blockchain technologies.

Main results:

1. The selection of the “Confident” platform is justified based on a comparative analysis (Hyperledger Fabric, Corda, Ethereum), taking into account technical characteristics and compliance with Russian cryptographic standards (GOST).
2. A three-layer architecture (initiator – mobile agent – auditor) is developed, featuring a clear separation of responsibilities and reduced network load through edge device data processing.
3. A prototype based on a Raspberry Pi single-board computer, simulating an onboard node, and the “Confident” platform was implemented and tested. The prototype confirmed the feasibility of scenarios including initialization, monitoring, violation detection, and the immutability of event recording.
4. Data immutability and transparency were achieved, providing an objective evidentiary basis for dispute resolution between supply chain participants.

Future research is aimed at developing a scalable solution for cargo monitoring, logistics automation, and integration with insurance companies and regulatory authorities.

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KERNEL REGRESSION WITH TREE-INDUCED METRICS

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Abstract. This paper presents a family of kernel models based on metrics derived from the structure of decision trees and random forests. Unlike the standard random-forest proximity, which only checks whether two observations fall into the same leaf, the proposed metrics also use information about decision paths, the depth of their divergence, and the depth of their lowest common ancestor. A weighted variant with trainable depth-dependent parameters is also introduced. The tree-based metrics are aggregated over a forest and used to construct exponential kernels. They can also be combined with the Euclidean distance in the original feature space. We prove that the resulting kernels are positive semidefinite and can therefore be used in standard kernel methods, including Nadaraya–Watson regression and kernel ridge regression. The proposed models are evaluated on classification datasets and in a controlled source-to-target regression experiment with a limited number of labeled target observations. The results show that information about the internal structure of decision trees can be useful beyond simple leaf coincidence. Several proposed variants improve upon conventional geometric kernels and the standard random-forest proximity kernel, while the best-performing metric depends on the prediction method and the dataset.

Keywords: kernel regression, decision trees, tree-based metrics, random forests, Nadaraya–Watson estimator, kernel ridge regression

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ЯДЕРНАЯ РЕГРЕССИЯ С ИНДУЦИРОВАННЫМИ ДЕРЕВЬЯМИ МЕТРИКАМИ

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Аннотация. В работе предложено семейство ядерных моделей, основанных на метриках, формируемых по структуре деревьев решений и случайных лесов. В отличие от стандартной меры близости случайного леса, которая учитывает только попадание двух объектов в один лист, предложенные метрики также используют информацию о путях в дереве, глубине их расхождения и глубине наименьшего общего предка. Кроме того, рассматривается взвешенная метрика с обучаемыми параметрами, зависящими от глубины дерева. Метрики отдельных деревьев агрегируются по лесу и используются для построения экспоненциальных ядер. Они также могут сочетаться с евклидовым расстоянием в исходном пространстве признаков. Для полученных ядер доказана положительная полуопределенность, что позволяет применять их в стандартных ядерных методах, включая регрессию Надарая–Уотсона и ядерную гребневую регрессию. Предложенные модели исследованы на задачах классификации и в контролируемом эксперименте по переносу структуры из исходной задачи в целевую задачу регрессии с малым числом размеченных наблюдений. Результаты показывают, что внутренняя структура деревьев может содержать полезную информацию, не ограниченную совпадением листьев. Несколько предложенных вариантов превосходят традиционные геометрические ядра и стандартное ядро близости случайного леса, при этом выбор наиболее подходящей метрики зависит от метода прогнозирования и набора данных.

Ключевые слова: ядерная регрессия, деревья решений, метрики на основе деревьев, случайные леса, ядерные методы, оценка Надарая–Уотсона, ядерная гребневая регрессия

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Introduction

The random forest algorithm [1, 2] is one of the most widely used ensemble methods in machine learning. Its practical appeal stems from several complementary properties: averaging over many decision trees reduces overfitting, the resulting model is robust to noise and outliers, and feature-importance estimates provide a useful degree of interpretability. Extremely randomized trees [3] further develop this paradigm by choosing split thresholds at random. This additional randomization reduces the computational cost of training, can improve robustness on noisy data, and often yields strong generalization performance in both classification and regression.

In addition to producing predictions, a forest defines an adaptive partition of the feature space. This observation has motivated the use of random-forest proximities as kernels: two observations are considered similar if they frequently fall into the same terminal leaf. Such proximities are attractive

because they inherit the nonlinear and data-dependent geometry of the trained ensemble, but the usual shared-leaf score is a coarse summary of tree structure. It treats all leaf mismatches equally, even though two leaves may diverge just below a deep internal node or immediately below the root. It also ignores whether leaves occupy related subtrees and whether early or late path divergences should be penalized differently.

This limitation is especially relevant when a tree ensemble is used as a representation rather than only as a predictor. In kernel classification and regression, the Gram matrix determines the geometry available to the downstream estimator. It is also relevant in source-to-target structure reuse: a forest trained on one response may encode a useful hierarchical organization of the input space, and this organization can be tested as a prior similarity for a related response with fewer labels. In this paper, we use such a setting as a controlled diagnostic experiment rather than as a full transfer-learning benchmark. A proximity based solely on terminal-node equality may therefore underuse the hierarchy that made the forest informative in the first place.

This paper addresses the lack of a compact framework with explicit theoretical guarantees for converting different aspects of tree hierarchy into positive semidefinite kernels. We focus on distances and similarities that are still simple enough to compute from a fitted tree, but richer than the standard leaf-coincidence score. The proposed constructions use path divergence, lowest common ancestors, path-indicator embeddings, inverse-depth penalties, and learnable depth weights. These structural quantities are then aggregated over a forest and combined with Euclidean geometry in the original feature space.

The contributions of the paper are threefold. First, we formulate several single-tree structural distances on the quotient space induced by terminal leaves and show how they extend to forests. Second, we prove positive semidefiniteness of the corresponding exponential and mixed kernels using conditional negative definiteness and Schoenberg’s theorem. Third, we evaluate the resulting models in supervised classification and in a controlled source-to-target regression experiment that tests reuse of source-trained tree structure for a related target response with fewer labeled examples. The source code of the proposed distances is available at <https://github.com/MaxGoryunov/tree-distance-kernel>.

Related work

Beyond their direct use as predictive models, random forests can also induce kernels and proximity functions. In [4], the kernel connection function, or KeRF, is introduced, defined as the fraction of trees in which two observations fall into the same leaf, and, in the population limit, as the probability of this event. This view makes it possible to interpret random forests as adaptive kernel estimators and to incorporate forest-induced similarities into kernel methods. The related adaptive-nearest-neighbor interpretation of random forests was developed in [5] with forest predictions expressed through data-dependent weights determined by terminal cells. Foundational analyses establish consistency for averaging classifiers [6] and characterize the behavior of a random-forest model under sparse signal structure [7].

Several related constructions have been proposed. In [8], centered and uniform KeRF estimators are analyzed, improved convergence rates are derived, and the reproducing-kernel Hilbert space associated with the centered construction is investigated. In a complementary unsupervised setting [9] random-forest leaf proximities are used as a data-adaptive similarity for clustering and visualization.

Random-forest-induced similarities have also been used beyond direct supervised prediction. In [10], an unsupervised random-forest procedure for mixed data that retains the usual advantages of forest models while identifying clusters is developed. For class-probability estimation [11], aggregation rules and terminal-node sizes can materially affect calibration. Related forest weighting constructions have been used to estimate full conditional distributions and conditional quantiles [12].

The geometry represented by forest proximities has been examined in [13]. The authors argue that traditional proximity measures, including Breiman’s original definition, may fail to preserve the

geometry learned by the forest, which can introduce bias and limit their usefulness as kernels. Their RF-GAP proximity is designed to preserve both geometry and predictive accuracy, making it better suited for kernel-based learning. Other work has considered distances between trees themselves: the Weighted Splitting Variable (WSV) distance [14] measures the difference between trees through weighted variable usage and can be used to identify representative trees, thereby improving interpretability of complex ensembles.

Random forests have also been used for metric learning. The Random Forest Distance (RFD) [15] learns an implicitly position-dependent distance function through a pairwise mapping $\phi(x_i, x_j)$ that encodes both the relative position of two points and their absolute location in feature space. This enables a single metric to adapt to different regions of the input space, combining the locality of metric-learning methods with the efficiency of global models. Distances can also be computed in the presence of missing data [16]: instead of sending an observation with a missing split value along a single path, the method constructs a multi-path subtree $P_T^{MP}(x)$ that contains all possible paths obtained by propagating the observation to both children. This approach has been applied to RatioRF and adapted to other RF distances, including Shi, Zhu, and Ting, and remains robust even with substantial missingness.

Additional lines of work exploit distances either between classes or between observations. The RSCT decision-tree algorithm [17] augments impurity criteria with distances between classes, thereby favoring splits that separate distant classes; both Euclidean and cosine distances are considered. Experiments show improved classification accuracy relative to a classical Gini-based decision tree, both for a single tree and for a random-forest ensemble. RF distances are also known to exhibit robustness in high-dimensional settings [18]: nearest-neighbor classification with RF distances such as Shi and RatioRF can continue to improve as the number of features grows, because tree partitions tend to amplify distinctions between observations and counteract distance concentration. Related approximation results [19] show that observations that are close in the true metric are likely to remain close under RF distances computed from ensembles of extremely randomized trees; the probability of poor approximation decreases exponentially with the number of trees, with RatioRF giving tighter bounds than Shi. Instead, our framework treats tree structure through conditionally negative definite distances, establishes positive semidefiniteness guarantees under forest aggregation, and introduces learnable depth-dependent penalties compatible with kernel prediction.

Materials and methods

Decision Trees and Paths. Throughout the paper, $I[A]$ denotes the indicator of an event or logical statement A : it equals 1 when A is true and 0 otherwise.

A decision tree T is represented as a finite rooted binary tree with vertex set V , root v_0 , internal-node set J , and leaf set L . Each internal node v from J is equipped with a split rule, typically of the form $x_j < t$, which sends a r -dimensional input x to either the left or the right child. Each leaf l from L stores a local prediction, such as a class distribution in classification or an empirical response mean in regression.

For every input x , the split rules determine a unique root-to-leaf path

$$p_T(x) = (v_0, v_1, \dots, v_{\tau_T(x)}),$$

where the last component is the terminal node reached by x , and $\tau_T(x)$ is the depth of that leaf. The depth of the root is 0, and the depth of any other node is the number of edges on the path from the root to that node.

Throughout the single-tree constructions below, the tree T is assumed to be fixed. To avoid cumbersome notation, the dependence of structural distances and auxiliary quantities on T is suppressed

whenever no ambiguity can arise. The corresponding tree indices are restored in forest-level definitions and aggregation formulae.

Leaf-Induced Quotient Sets. Each leaf l from L of a tree T defines an equivalence class

$$[\ell] = \{x \in \mathbb{R}^r : x \text{ falls into leaf } l \text{ of tree } T\}.$$

The corresponding quotient set is

$$X_T := \mathbb{R}^r / \sim_T = \{[l] : l \in L\}.$$

When the tree is fixed, we write X for X_T . All single-tree structural distances below are defined on these classes. This makes the value of a distance independent of the particular representative chosen from a leaf: two observations in the same terminal node are indistinguishable for the structural component associated with that tree.

Random Forests. A random forest is an ensemble of decision trees

$$F = \{T_1, T_2, \dots, T_M\}.$$

The trees are trained using randomized procedures, such as bootstrap resampling of observations and random selection of candidate split variables. Extremely randomized trees additionally randomize split thresholds. Given a new input, the forest aggregates the predictions of its individual trees, for example by majority vote in classification or by averaging in regression.

In this paper, the forest is also treated as a learned partitioning mechanism. Each tree assigns an input to a leaf, while the whole ensemble assigns it to a vector of leaves. The method developed below uses these assignments and the paths leading to them to construct structural distances and kernels.

Nadaraya–Watson Kernel Regression. Let $\mathcal{D} = \{(x_i, y_i)\}_{i=1}^n$ be a supervised training sample, and let $K(x, x_i) \geq 0$ be a kernel similarity between a query point x and a training point x_i . The Nadaraya–Watson estimator predicts a weighted average of the observed responses:

$$\hat{y}_{\text{NW}}(x) = \frac{\sum_{i=1}^n K(x, x_i) y_i}{\sum_{i=1}^n K(x, x_i)}.$$

For classification, the same formula can be applied to one-hot encoded class labels, yielding estimated class probabilities. Thus, kernel regression provides a direct way to turn a similarity function into either a regression model or a probabilistic classifier.

Kernel Ridge Regression (KRR). KRR is a regularized kernel method in a reproducing kernel Hilbert space. Given a kernel K , let K_{train} be the Gram matrix with entries

$$(K_{\text{train}})_{ij} = K(x_i, x_j),$$

and let

$$k_x = (K(x, x_1), \dots, K(x, x_n))^{\top}.$$

For the regularized least-squares objective with penalty parameter $\lambda > 0$, the representer theorem gives coefficients

$$c = (K_{\text{train}} + \lambda I_n)^{-1} y.$$

The prediction at a new point x is therefore

$$\hat{y}_{\text{KRR}}(x) = k_x^\top c = k_x^\top (K_{\text{train}} + \lambda I_n)^{-1} y.$$

For multi-class classification, the same expression can be applied to one-hot encoded labels or to one-vs-rest target vectors.

Positive Semidefiniteness Criterion. We use the standard notion of conditional negative definiteness. A symmetric function d with $d(x, x) = 0$ is conditionally negative definite (CND) if, for all finite sets $x_1, \dots, x_n$ and real coefficients $a_1, \dots, a_n$ with $\sum_i a_i = 0$,

$$\sum_{i,j=1}^n a_i a_j d(x_i, x_j) \leq 0.$$

By Schoenberg's theorem [20], d is CND if and only if $\exp(-\gamma d)$ is positive semidefinite (PSD) for every $\gamma > 0$.

Problem statement

Let $\mathcal{X} \subseteq \mathbb{R}^r$ be the input space. In classification, the response space is $\mathcal{Y} = \{1, \dots, C\}$; in regression, $\mathcal{Y} = \mathbb{R}$. Given a supervised sample

$$\mathcal{D}_{\text{train}} = \{(x_i, y_i)\}_{i=1}^n, \quad (x_i, y_i) \in \mathcal{X} \times \mathcal{Y},$$

the standard objective is to construct a prediction rule $\hat{g} : \mathcal{X} \rightarrow \mathcal{Y}$ that generalizes to unseen observations. In this paper, $\hat{g}$ is obtained from a kernel estimator, so the main modeling problem is to construct a valid kernel

$$K : \mathcal{X} \times \mathcal{X} \rightarrow \mathbb{R}.$$

The central object of interest is a tree-induced structural function. Let a fitted forest F assign each observation x to a collection of terminal leaves. We seek a function $f_F(x, y)$ that measures how far two observations are with respect to this learned forest structure, and then define a kernel of the form

$$K(x, y) = \exp(-D(x, y)),$$

where D may combine f_F with the Euclidean distance in $\mathbb{R}^r$. The mathematical requirement is that the resulting Gram matrix $\left(K(x_i, x_j)\right)_{i,j=1}^n$ be positive semidefinite for every finite sample.

The motivation for this formulation is that standard random-forest proximities usually measure only how often two observations reach the same terminal leaf. This information is useful but coarse: it ignores where two paths separate, how deep their common ancestor is, and how leaves are arranged inside the tree. The problem is therefore to build tree-induced kernels that use richer structural information while remaining mathematically valid and computationally practical for kernel-based classification and regression.

We also consider a controlled source-to-target structure-reuse setting. A source task provides a comparatively large labeled dataset $\mathcal{D}_{\text{src}}$, from which a tree ensemble and the associated structural similarity can be learned. A related target task provides a much smaller labeled dataset $\mathcal{D}_{\text{tgt}}$. The goal is not to learn a general domain-adaptation model, but to test whether the source-induced tree structure

remains informative when used as a kernel or metric for a related target response with limited labeled data.

This formulation leads to four requirements. First, the resulting distances must be well defined on the leaf quotient spaces induced by individual trees. Second, forest-level aggregation must produce positive semidefinite kernels suitable for kernel methods. Third, the construction should allow a controlled combination of tree-induced structure and Euclidean geometry in the original feature space. Fourth, the resulting kernels should be usable in supervised classification, supervised regression, and controlled source-to-target structure-reuse scenarios.

Method

The method turns a trained tree ensemble into a kernel model in three steps. First, for each tree T , observations are projected to the quotient space X_T determined by terminal leaves. A single-tree structural distance or dissimilarity f is then computed on this quotient space. Second, the single-tree quantities are averaged over the forest. Third, the resulting forest-level structural distance is inserted into an exponential kernel, optionally mixed with the Euclidean distance in the original feature space.

Thus, each choice of f defines not only a structural interpretation of tree proximity, but also a complete kernel learning model through the induced Gram matrix. The constructions below differ in how much of the tree hierarchy they use: terminal-leaf agreement, depth of path divergence, explicit Euclidean embeddings of leaves, inverse-depth penalties, or learnable depth-dependent weights. For an ensemble F , the single-tree quantities are aggregated by averaging:

$$f_F(x, y) = \frac{1}{M} \sum_{m=1}^M f_{T_m}(x, y).$$

The associated exponential forest kernel is

$$K_\gamma(x, y) = \exp(-\gamma f_F(x, y)) = \prod_{m=1}^M \exp\left(-\frac{\gamma}{M} f_{T_m}(x, y)\right),$$

which is positive semidefinite whenever the corresponding single-tree exponential kernels are positive semidefinite. The forest induces an equivalence relation in which two observations are equivalent if they are assigned to the same terminal leaf in every tree.

The proposed approach combines two sources of information about object proximity. The structural component captures similarity with respect to data-dependent tree partitions and can represent nonlinear local structure that is not apparent under purely Euclidean distances. The geometric component preserves sensitivity to direct distances between feature vectors. Once a structural forest distance f_F has been obtained, we use the mixed kernel

$$K_{\text{mix}}(x, y) = \exp\left(-\left[\alpha \frac{\Delta_E(x, y)}{h} + (1 - \alpha) \frac{f_F(x, y)}{\sigma_F}\right]\right),$$

where $\Delta_E(x, y) = \|x - y\|_2^2$, $\alpha \in [0, 1]$ is the mixing coefficient, and $\sigma_F > 0$, $h > 0$ are scaling parameters for the structural and Euclidean components, respectively. As α tends to 0, the model emphasizes forest structure; as α tends to 1, it approaches a Euclidean kernel model.

The resulting kernel can be used directly in the Nadaraya–Watson estimator or in KRR. In both cases, each choice of the structural component f induces a different Gram matrix and therefore a different learning model.

We introduce four structural choices for f : a shared-leaf distance based on $1-s(x, y)$, a path-based distance ρ , an inverse-depth metric r based on the lowest common ancestor, and a learnable weighted metric w with depth-dependent weights. The metrics are introduced to capture progressively richer information contained in a fitted tree: terminal-node agreement, the depth at which two decision paths separate, explicit finite-dimensional representations of leaves, and learnable depth-dependent penalties.

Path-Based Structural Kernel Model. Let $d \geq 1$ be the maximum depth of a nontrivial tree T . For an object x , write its path as

$$p_T(x) = (v_0, v_1(x), \dots, v_d(x)),$$

where paths ending before depth d are padded with leaf-specific dummy states. Thus, two observations in the same leaf have identical padded paths, while observations in different leaves differ immediately after their lowest common ancestor. For two objects x, y , define the first depth at which their padded paths differ by

$$\text{diff}_T(x, y) = \min \{i \in \{1, \dots, d\} : v_i(x) \neq v_i(y)\},$$

when such an index exists. The depth of the lowest common ancestor is

$$l(x, y) = \begin{cases} \text{diff}_T(x, y) - 1 & p_T(x) \neq p_T(y) \\ d, & p_T(x) = p_T(y) \end{cases}.$$

This quantity is the basic structural statistic used by the path-based, inverse-depth, and weighted-depth metrics. It equals d for observations assigned to the same leaf under the padded-path convention, which makes the normalized path distance vanish for leaf coincidences.

For a single tree, this model treats two observations as structurally close when their paths diverge only at a large depth, even if they do not end in the same terminal node. The path-based structural distance is the complement:

$$\rho(x, y) = 1 - \frac{l(x, y)}{d}.$$

Hence $\rho(x, y)$ is zero for objects in the same leaf and increases when their paths separate closer to the root.

Proposition 1 (Path-Based Structural Kernel Model). *For the path-based model defined by $\rho(x, y) = 1 - l(x, y)/d$, the function ρ is CND. Hence the forest-aggregated path-based kernel is PSD.*

Proof. Let $\mathcal{V}^*$ be the set of non-root states in the padded tree representation, including the leaf-specific padding states, and define the path-indicator feature map

$$\psi_T(x)_v = \mathbb{I}[v \in p_T(x)], \quad v \in \mathcal{V}^*.$$

Then $\langle \psi_T(x), \psi_T(y) \rangle$ equals the number of shared non-root states on the two padded paths, which is $l_T(x, y)$. Hence

$$k(x, y) = l(x, y)/d = \langle d^{-1/2} \psi_T(x), d^{-1/2} \psi_T(y) \rangle$$

is a PSD kernel with unit diagonal. Therefore, ρ is CND. Since CND functions are closed under non-negative linear combinations, the forest average is also CND. The squared Euclidean distance is CND as well, so the mixed exponent is CND. The PSD property of the corresponding forest and mixed kernels follows by Schoenberg's theorem.

Leaf-Coincidence Kernel Model. For a single tree, this model uses only terminal-node coincidence and ignores the depth at which two paths diverge. Let $\lambda_T(x) \in L$ denote the leaf reached by x . The single-tree similarity and distance are

$$s_T(x, y) = \mathbb{I}[\lambda_T(x) = \lambda_T(y)], \quad d_T^{\text{leaf}}(x, y) = 1 - s_T(x, y).$$

The corresponding forest-level similarity is

$$s(x, y) = \frac{1}{M} \sum_{m=1}^M \mathbb{I}[p_{T_m}(x) = p_{T_m}(y)],$$

the fraction of trees in which x and y lie in the same leaf. The associated exponential kernel is

$$K(x, y) = \exp(-t(1 - s(x, y))), \quad t > 0.$$

This is a distance-based version of the classical random-forest proximity kernel, with t controlling how strongly leaf mismatches reduce similarity. The same distance can also be used in the mixed kernel to combine leaf coincidence with Euclidean geometry.

Proposition 2 (Leaf-Coincidence Kernel Model). *The forest similarity s of the leaf-coincidence model is PSD. Consequently, $1 - s$ is CND and $\exp(-t[1 - s])$ is PSD for every $t > 0$.*

Proof. Let $\lambda_m(x)$ denote the leaf reached by x in tree T_m , and let $\eta_m(x)$ be a $|L_m|$ -dimensional unit vector with $\lambda_m(x)$ -th component equal to one. Then

$$\langle \eta_m(x), \eta_m(y) \rangle = \mathbb{I}[\lambda_m(x) = \lambda_m(y)].$$

With the concatenated feature map

$$\Phi(x) = \frac{1}{\sqrt{M}} \left(\eta_1(x)^\top, \dots, \eta_M(x)^\top \right)^\top,$$

we obtain

$$s(x, y) = \langle \Phi(x), \Phi(y) \rangle.$$

Thus, s is PSD and has constant diagonal $s(x, x) = 1$. Therefore $1 - s$ is CND, and the exponential kernel follows from Schoenberg's theorem.

LCA-Depth Kernel Model. Unlike the path-based distance ρ , which depends linearly on the normalized LCA depth, this model uses an inverse-depth penalty. For $x, y \in X_T$ define

$$r(x, y) = \begin{cases} 0 & x = y \\ \frac{1}{1 + l(x, y)} & x \neq y \end{cases}.$$

Using the metric r produces a kernel model that assigns a strong penalty to pairs separating near the root and a smaller penalty to pairs whose lowest common ancestor is deep in the tree. This metric is useful when early splits are expected to encode coarse, high-level distinctions between observations.

Proposition 3 (LCA-Depth Kernel Model r). *For the LCA-depth model, r is an ultrametric on the leaf quotient space. In particular, r is CND, and therefore $\exp(-\gamma r)$ and the corresponding forest-aggregated mixed kernel are PSD.*

Proof. Let $x, y, z \in X_T$, and set

$$a = l(x, y), \quad b = l(y, z), \quad c = l(x, z).$$

If two of the three classes coincide, the ultrametric inequality is immediate. Otherwise, the common ancestors of (x, y) and (y, z) imply that x and z share an ancestor at depth at least $\min\{a, b\}$. Hence $c \geq \min\{a, b\}$. Since $u \mapsto (1 + u)^{-1}$ is decreasing,

$$r(x, z) = \frac{1}{1+c} \leq \max \left\{ \frac{1}{1+a}, \frac{1}{1+b} \right\} = \max \{r(x, y), r(y, z)\}.$$

Thus, r is an ultrametric. Every finite ultrametric is CND: it can be written as a nonnegative linear combination of partition semimetrics induced by its level sets, and each partition semimetric is CND. Forest averaging and the Euclidean component preserve CND, and Schoenberg's theorem completes the proof.

Weighted-Depth Kernel Model. Consider a tree T of depth d . Introduce parameters $g_j \in \mathbb{R}, j = 0, \dots, d-1$, and define positive increments

$$s_j = \exp(g_j),$$

which determine a decreasing sequence of distances

$$z_i = \sum_{j=1}^{d-1} \exp(g_j) = \sum_{j=1}^{d-1} s_j, \quad i \in \overline{0, d}, \quad z_d = 0.$$

By construction, $z_i > z_{i+1}$ for $i < d$, so the distance decreases as the shared part of the path becomes longer.

The tree distance is then defined as

$$w(x, y) = \begin{cases} 0 & \text{if the leaves containing } x \text{ and } y \text{ coincide} \\ \sum_{j=l(x,y)}^{d-1} \exp(g_j) & \text{otherwise} \end{cases}.$$

Equivalently, the second case can be written as

$$w(x, y) = z_0 - \sum_{j=0}^{l(x,y)-1} \exp(g_j),$$

which is the difference between the maximum path length and the length accumulated along the common part of the two paths.

The exponential parametrization $s_j = \exp(g_j)$ ensures positive, differentiable depth weights, while the use of absolute depth distinguishes subtrees with similar internal structure but different positions in the tree.

Proposition 4 (Weighted-Depth Kernel Model w). *For the weighted-depth model, with positive increments $s_j = \exp(g_j)$, the distance w is CND. Hence $\exp(-\gamma w)$ and the corresponding forest-aggregated mixed kernel are PSD.*

Proof. Use the padded tree representation from the path-divergence definition. For each non-root padded state v at depth $u \in \{1, \dots, d\}$, set $a_v = s_{u-1}$ and define the weighted path feature map

$$\chi(x)_v = \sqrt{a_v} \mathbb{I}[v \in p_T(x)].$$

The inner product

$$k(x, y) = \langle \chi(x), \chi(y) \rangle$$

equals the total weight accumulated along the common part of the two padded paths. Its diagonal is constant and equal to $z_0 = \sum_{j=0}^{d-1} s_j$. If two observations lie in the same leaf, then $k(x, y) = z_0$; otherwise $k(x, y) = \sum_{j=0}^{l(x,y)-1} s_j$. Therefore $z_0 - k(x, y)$ is CND and coincides with $w(x, y)$. Forest averaging and the Euclidean component preserve CND, and Schoenberg's theorem implies the stated PSD guarantees.

Numerical experiments

The proposed tree-induced kernel models were evaluated in two experimental settings. First, we study standard supervised learning on classification tasks, using real benchmark datasets. Second, we study a controlled source-to-target regression setting, where the tree structure and the induced metric are learned from a source response with more labeled data and then used as a structural similarity for prediction on a related target response with fewer labeled examples. The experiments compare several variants of the mixed structural-geometric kernel with classical kernel baselines, random forests, and nearest-neighbor methods.

Models and baselines. Across all experiments, we compare the proposed tree-induced kernel models with standard kernel methods and non-kernel baselines. The first group comprises variants of the proposed models, with the mixing parameter α tuned over the set $\{0.0, 0.25, 0.50, 0.75\}$. Here, zero corresponds to a purely structural kernel without a Euclidean component.

The learnable variant uses the weighted-depth distance w . In the classification setting, the depth-weight parameters, mixing parameter α and the bandwidths σ and h of the structural and Euclidean components are optimized jointly during training by gradient descent. In the source-to-target regression setting, only the bandwidth and depth-weight parameters are optimized by gradient descent, while α is selected from the set $\{0.0, 0.25, 0.50, 0.75\}$ as the value yielding the lowest training loss. Therefore, we refer to this learnable weighted-depth model as Grad. The trainable parameters of the Grad model are optimized for 300 epochs using AdamW with a learning rate of 5×10^{-3} and weight decay 0.01. The learning rate is adjusted according to a cosine annealing schedule implemented with CosineAnnealingLR. Since tree depths are different for the forest trees, for each tree we train a separate depth-weight parameter vector during joint optimization. The optimization objective is the mean squared error for regression tasks and the cross-entropy loss for classification tasks. To reduce the trivial self-similarity effect, each training observation is excluded from the Nadaraya–Watson sum when its own prediction is computed. This yields a leave-one-out training objective for all trainable

parameters. In the classification setting, the parameter α is optimized by gradient descent, and it is parameterized as the sigmoid of an unconstrained trainable variable to restrict values of α to the range $[0,1]$. The bandwidth parameters σ and h are parameterized as exponentials of unconstrained trainable variables in both learning settings.

We additionally consider three Nadaraya–Watson kernel predictors based on an RBF kernel (RBF), a Laplace kernel (LAPL), and a mixture of Euclidean and Laplace distances in an exponential kernel (R+L), where the Laplace kernel employs l_1 -norm.

Another baseline is a Nadaraya–Watson predictor based on the random forest kernel (KeRF), defined as the fraction of trees in which two observations fall into the same terminal leaf. We also evaluate an extremely randomized random forest (ET) consisting of 100 extremely randomized trees with a tuned maximum depth on a grid from 1 to 15. The same ensemble of trees is used to construct the structural component of the proposed kernel models. Finally, we include a k-nearest-neighbor predictor (KNN), for which the integer-valued number of neighbors K is tuned on a grid from 1 to 10.

Unless stated otherwise above for the Grad model, hyperparameters are selected using grid search by the target metric AUROC for classification and R^2 for regression. Each trial is evaluated using 2-fold cross-validation performed exclusively within the corresponding training partition. For every inner cross-validation split, preprocessing and the tree ensemble were fitted using only the corresponding inner-training subset. Thus, the test folds used for the final evaluation do not influence hyperparameter selection. For all kernel-based methods we tune bandwidth parameters in range $[0.01 \cdot d_{\max}, 2 \cdot d_{\max}]$, where $d_{\max}$ is the maximum value over distance matrix, for which the bandwidth is tuned, 20 logarithmically scaled samples are used.

In the supervised classification setting, we evaluate the models using four times repeated stratified holdout with train size 20%. In each of four repetitions, the data were partitioned into five stratified folds. Each fold was used once as the 20% outer training set, while the union of the remaining four folds was used as the 80% outer test set. This produced 20 outer train-test splits. Hyperparameters were selected by 2-fold cross-validation performed only within each outer training set. Categorical features are one-hot encoded and continuous features are standardized. Missing values are filled by median. All preprocessing transformations are fitted exclusively on each training fold and then applied to the corresponding test fold. In the supervised learning setting, the training and test observations are drawn from the same distribution. These experiments therefore examine whether tree-induced structural kernels improve predictive performance in the absence of transfer between tasks or domains. Classification performance is measured using the area under the receiver operating characteristic curve (AUROC). For the multiclass Dermatology and Website Phishing datasets, we use micro-averaged one-vs-rest AUROC. The experiments use classification datasets obtained from the UCI Machine Learning Repository [21]. Their main characteristics are summarized in Table 1.

Table 2 reports mean AUROC values over 20 outer test folds (5 folds $\times$ 4 repetitions), multiplied by 100. The two best values in each row are highlighted. Grad achieves the best result in most cases, while simpler non-learnable variants also often exceed classical baselines, including the KeRF built from the same forest.

For compactness, standard deviations are shown separately in Table 3. These values characterize the variability of the results across repeated data splits.

We use a controlled source-to-target regression setting to test whether the hierarchical partition learned by a forest for a source response can be reused as a structural representation for a related target response. Because the source-target relationship is known by construction, the experiment isolates structure reuse from uncontrolled changes in domains, covariates, or label semantics.

The controlled setting contains a source task A and a target task B. The complete data-generation, splitting, training, tuning, and evaluation procedure was repeated in 12 independent experiments. Each generated dataset contains 210 observations and is divided as follows:

Table 1

Characteristics of the classification datasets

Title	Samples	Features	Classes
Wisconsin Breast Cancer (WBC)	569	30	2
Diabetic Retinopathy (DR)	1151	19	2
EEG Eyes (EEG)	14980	14	2
Haberman (Hab)	306	3	2
Ionosphere (Ion)	351	34	2
Tic-Tac-Toe (TTT)	958	9	2
Website Phishing (WPh)	1353	9	3
Dermatology (Drm)	366	34	6

Table 2

AUROC mean, %

	<i>s</i>	<i>p</i>	<i>r</i>	Grad	RBF	LAPL	R+L	KeRF	ET	KNN
WBC	<u>99.29</u>	99.27	99.23	99.34	97.49	98.79	97.91	99.19	98.10	88.60
DR	78.94	78.45	80.28	81.93	74.21	75.90	74.81	<u>81.92</u>	74.18	61.33
EEG	93.87	<u>94.17</u>	94.52	92.14	74.37	92.64	87.23	88.69	94.08	92.50
Hab	65.13	64.49	64.96	65.92	64.97	65.13	64.93	<u>65.77</u>	64.23	55.88
Ion	<u>97.13</u>	96.93	96.67	96.53	89.58	95.14	95.10	96.52	97.38	77.27
TTT	95.60	94.13	93.53	94.53	94.42	94.42	94.53	92.97	94.61	88.78
WPh	96.48	97.01	<u>97.47</u>	97.60	96.37	96.72	96.71	97.13	96.83	82.41
Drm	<u>99.82</u>	99.81	99.74	99.82	76.84	97.78	97.84	99.81	99.54	82.30

Table 3

AUROC standard deviation, %

	<i>s</i>	<i>p</i>	<i>r</i>	Grad	RBF	LAPL	R+L	KeRF	ET	KNN
WBC	0.76	0.83	0.74	0.79	0.66	0.68	0.81	0.67	0.73	0.96
DR	2.12	1.95	1.82	2.01	2.95	1.80	2.18	1.58	2.54	2.82
EEG	1.31	0.97	1.17	1.06	2.97	0.98	1.43	0.98	1.03	1.30
Hab	0.60	0.97	0.29	0.51	0.81	0.91	0.78	0.33	0.80	0.73
Ion	0.69	0.91	0.84	0.83	1.11	0.72	0.94	0.76	0.66	2.00
TTT	0.69	1.06	1.03	0.98	1.01	1.28	1.39	1.09	1.43	1.00
WPh	0.66	0.70	0.73	0.83	0.86	0.74	0.83	0.91	0.89	1.70
Drm	0.92	0.70	0.76	0.69	1.76	0.81	0.93	0.75	0.70	1.52

1. D_A contains 105 observations (50%) and is used only to train the source forest and construct the structural metrics.

2. D_B contains 35 observations (16.7%) and provides the limited target-task labels used for adaptation. The source trees remain fixed. Baseline models are trained directly on the same DB subset.

3. D_T contains 70 observations (33.3%) and is used only for final evaluation. All target-model hyperparameters are selected without access to D_T , and performance is reported using R^2 .

For classification, preprocessing and the tree ensemble were refitted within each inner-training fold. In the source-to-target experiment, the source forest was fitted on D_A and kept fixed, while target-model hyperparameters were selected by 2-fold cross-validation on D_B . This protocol prevents target-test information from influencing either the source partition or model selection. It therefore evaluates whether a representation learned from task A remains useful when only a small labeled sample from task B is available.

The selected synthetic dataset is a multidimensional Archimedean spiral. A parameter t is randomly sampled from the uniform distribution over the interval from 0 to 6π , and the four informative coordinates follow the smooth embedding $x = (t \sin t, t \cos t, t \sin 2t, t \cos 2t)$. Four additional Gaussian noise coordinates are appended, giving eight input features in total. The scale of each noise coordinate is matched to the corresponding informative coordinate using $\sigma_i = \text{median}(|X_i - \text{median}(X_i)|)$. The additional coordinates act as nuisance variables for the source task and make ambient Euclidean neighborhoods less reliable, while the informative observations remain ordered along one continuous curved manifold.

For the Linear A source task, the response is $y_A = 3t + 2$. The Simple B target response is $y_B = 0.5y_A + 0.3\|x\|_2 + \varepsilon$, where ε is independent Gaussian noise with standard deviation 0.1. The target therefore retains a substantial source-task component but also depends directly on feature-space geometry. This construction is useful for the present purpose because it does not predetermine that either a purely structural distance or a purely Euclidean distance must be optimal.

The mixing coefficient α controls the Euclidean contribution: $\alpha = 0$ gives a purely tree-structural model, whereas $\alpha > 0$ combines the transferred structure with direct feature-space geometry. For the Grad model, α is selected from the set $\{0.0, 0.25, 0.50, 0.75\}$ using the leave-one-out training loss. For KRR, λ is selected from 15 logarithmically spaced values between 10^{-10} and 10^4 . All proposed models and baselines are tuned under the same data-access restrictions.

Table 4 reports means and standard deviations over all 12 independent experiments, no best-seed or best-split selection is used. All competing methods are presented depending on the type of kernel regression (KRR or NW) when applicable. Grad is evaluated only with NW because its trainable metric parameters are optimized through the NW leave-one-out objective.

Table 4

R^2 (mean $\pm$ standard deviation) for the source-to-target structure-reuse task

Method	KRR	NW
s	0.45 ± 0.07	0.85 ± 0.04
ρ	0.80 ± 0.05	0.88 ± 0.03
r	0.89 ± 0.04	0.86 ± 0.04
Grad (w)	—	0.90 ± 0.02
RBF	-0.06 ± 0.13	0.08 ± 0.10
LAPL	0.43 ± 0.07	0.16 ± 0.08
R+L	0.35 ± 0.09	0.15 ± 0.09
KeRF	-0.13 ± 0.14	0.84 ± 0.03
ET	0.70 ± 0.05	
KNN	0.03 ± 0.11	

The strongest baseline is KeRF with NW, which reaches R^2 0.84. Several proposed configurations improve on this reference: s with NW reaches 0.85, p with NW reaches 0.88, r with KRR reaches 0.89, and Grad reaches 0.90. The absolute improvement of Grad over the strongest baseline is 0.06. Expressed in terms of unexplained variance, $1 - R^2$ decreases from 0.16 to 0.10, a reduction of 37.5%. This is a practically meaningful gain in a setting where only 35 target-labeled observations are available for adaptation.

The results also reveal a useful distinction between fixed and learned structural representations. The fixed LCA-Depth metric r is strongest with KRR and $\alpha = 0$, indicating that the source forest alone captures most of the transferable ordering. The table does not show uniform dominance of every proposed configuration, which is important for interpreting the result. For example, s combined with KRR reaches only 0.45, whereas s with NW reaches 0.85; conversely, r is stronger with KRR than with NW. The benefit therefore depends on compatibility between the structural metric and the prediction rule. Grad provides the highest mean score, but the fixed r configuration is close at 0.89. The evidence consequently supports a family of tree-induced kernels and an adaptive hybrid model, not a claim that one metric must dominate on every task.

The real-data classification experiments show a more heterogeneous but still favorable pattern. The proposed structural kernels improve over classical geometric baselines on several datasets and often outperform the standard leaf-coincidence kernel. This suggests that terminal-leaf equality is not the only useful signal contained in a trained forest: the depth and organization of the paths also contribute to predictive performance. At the same time, the results are not uniformly dominated by a single structural metric. This is expected, since different datasets may favor different levels of locality: leaf coincidence is very restrictive, path-based metrics introduce graded similarity, and the weighted-depth model can adapt the contribution of shallow and deep splits.

The source-to-target regression experiment supports the central motivation for using tree-induced structure as a reusable representation. A forest trained only on task A remains informative for task B under limited target supervision, and the strongest results are obtained when the transferred organization is retained while a controlled Euclidean contribution is allowed.

The scope of this conclusion is deliberately limited. The experiment uses a controlled synthetic relationship, 210 observations, and a known source-target construction; it does not reproduce the full variety of real transfer-learning shifts. The reported values are averages over 12 complete independent repetitions. Finally, positive semidefiniteness guarantees that the proposed functions are valid kernels, not that every forest partition will be useful. Performance depends on whether the source forest captures structure that is genuinely relevant to the target task.

Conclusion

This paper introduced a family of tree-induced kernel models that combine structural information from random forests with Euclidean geometry in the original feature space. The construction is based on several tree-defined distances and similarities: shared-leaf coincidence, path divergence, an inverse-depth LCA metric, and a learnable weighted-depth distance. For these constructions, we established positive semidefiniteness of the associated exponential and mixed kernels under forest aggregation.

The framework turns each structural metric into a distinct kernel model that can be used with Nadaraya–Watson prediction or KRR. Empirical results support its usefulness in supervised classification on real datasets and in a controlled source-to-target regression experiment that tests reuse of source-trained tree structure for a related target response. In these settings, structural information beyond leaf equality often improves over the standard random-forest proximity kernel and classical geometric baselines.

Future work will apply the proposed framework to real transfer-learning and domain-adaptation problems in tabular-data settings. A possible theoretical extension is to use the learned tree metrics to handle auxiliary feature vectors in multiple-instance learning. Another interesting direction is to study the sensitivity of the models to tree depth and bandwidth selection, and further develop adaptive depth-dependent weighting schemes. Such extensions would make it possible to calibrate the model to particular datasets while preserving its connection with positive semidefinite kernel theory.

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HYBRID INTELLIGENT SYSTEM FOR STRATIFYING THE RISK OF CORONARY HEART DISEASE

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Abstract. The article proposes a hybrid intelligent system for stratifying the risk of coronary heart disease (CHD). It includes ensemble forecasting, natural language processing, and explainable AI technologies. It is demonstrated that the integration of structured clinical features and unstructured text data improves the accuracy of CHD risk assessment compared to the traditional SCORE2 scales. On test datasets, high values of AUC-ROC and F1-score were achieved, while the interpretability of the predictions is ensured by constructing waterfall plots that reflect the contribution of key risk factors. The developed software package will be useful in cardiology for supporting clinical decision-making.

Keywords: hybrid intelligent system, ensemble machine learning, cardiovascular outcome prediction, natural language processing, artificial intelligence, SHAP analysis, clinical decision support

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УДК 004



ГИБРИДНАЯ ИНТЕЛЛЕКТУАЛЬНАЯ СИСТЕМА СТРАТИФИКАЦИИ РИСКА ИШЕМИЧЕСКОЙ БОЛЕЗНИ СЕРДЦА

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Аннотация. В статье предложена гибридная интеллектуальная система для стратификации риска ишемической болезни сердца (ИБС), которая объединяет ансамблевое прогнозирование, обработку естественного языка и технологии объяснимого ИИ. Показано, что интеграция структурированных клинических признаков и неструктурированных текстовых данных повышает точность оценки риска ИБС по сравнению с традиционными шкалами SCORE2. На тестовых выборках достигнуты высокие значения метрик качества AUC-ROC и F1-score, при этом интерпретируемость прогнозов обеспечивается построением диаграмм типа «водопад» (waterfall plots), отражающих вклад ключевых факторов риска. Разработанный программный комплекс найдет применение в кардиологии для поддержки принятия врачебных решений.

Ключевые слова: гибридная интеллектуальная система, ансамблевое машинное обучение, прогнозирование сердечно-сосудистых исходов, обработка естественного языка, искусственный интеллект, SHAP-анализ, поддержка принятия врачебных решений

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Introduction

There is a growing clinical need for tools that enable physicians to rapidly and reliably assess the risk of adverse outcomes in patients with coronary heart disease (CHD). The effectiveness of such tools depends directly on the completeness and relevance of the data used. Contemporary electronic health record systems provide access to a wide range of information – from structured measurements to narrative clinical notes – creating new opportunities for more advanced prognostic models.

The object of the study in this paper is the clinical data from patients with CHD: anthropometric and laboratory parameters, electrocardiographic measurements, as well as electronic medical records. Based on these data, a hybrid intelligent risk stratification system is developed, that is intended for practical application in routine clinical practice.

Current approaches to risk stratification for CHD have evolved along several parallel lines. Each makes a significant contribution in prediction, yet none fully resolves the problem.

A substantial body of research relies on structured clinical and laboratory data in combination with traditional statistical models or ensemble machine-learning (ML) methods. Classical risk stratification scores widely used due to their simplicity and transparency; however, their predictive capability is limited in heterogeneous patient populations. ML methods can improve prediction accuracy compared to linear models and clinical risk scores, especially when accounting for nonlinear interactions among predictors. At the same time, such models often behave as “black boxes”, which impedes their adoption in clinical practice, where the physicians must understand the rationale behind a prediction.

A separate line of research addresses automated analysis of instrumental data, in particular electrocardiograms (ECGs). The use of convolutional neural networks and deep-learning methods for ECG signal processing demonstrates high sensitivity to early signs of ischemia, including cases in which visual interpretation is challenging [1].

An important source of clinically relevant information is the unstructured text in electronic medical records (EMRs). Recent years have seen rapid development of natural language processing (NLP) methods for entity extraction, term normalization, and identification of key features in physician notes. The use of libraries such as spaCy, as well as transformer models (BERT, BioBERT), makes it possible to extract symptoms, diagnoses, risk factors, and trajectories of patient status from texts with acceptable accuracy [2, 3]. Nevertheless, most NLP-solutions in cardiology target classification or information retrieval tasks rather than direct integration into decision-support systems for risk stratification.

NLP methods enable automatic encoding of symptom dynamics, qualitative descriptions of the patient's status, and mentions of comorbidities and therapy.

In [4–7], NLP pipelines based on rules, dictionaries of medical terms (including adapted Russian-language resources), and neural architectures (BERT-like models for Russian) are described¹. It has been shown that adding NLP-derived features to structured data improves the predictive performance, with an increase in AUC-ROC of 0.02–0.05 depending on the task and dataset. This supports the hypothesis that unstructured data carry additional prognostic value.

Since the early 2010s, ML models have been increasingly applied in cardiology, demonstrating higher predictive accuracy compared to traditional risk scores. In some cases, ML models outperform SCORE scales by 10–30 % in AUC-ROC, supporting a transition toward more flexible algorithms.

In [8, 9], the implementation of ML solutions in clinical practice is addressed: integration with medical information systems (MISs) for automatic risk calculation during patient registration; development of physician-facing interfaces in which the prediction is accompanied by an explanation; pilot projects in inpatient and outpatient settings, where the system helps prioritize patients for further examination.

To address the “black box” problem, in [10], explainable AI methods are actively employed: SHAP (SHapley Additive exPlanations), which quantifies the contribution of each feature to a prediction and enables comparison of factor effects across patients; LIME, which provides local explanations for individual predictions; and waterfall plots, that visualize which factors increase or decrease risk. In cardiological studies, SHAP analysis is used to interpret models predicting major adverse cardiac events (MACE), mortality, and the risk of hospitalization. It helps identify unexpected patterns and align model conclusions with clinical insight.

Another promising direction is ensemble methods, which are widely used in medical prediction. In [11–15], architectures in which individual models are trained on different subsets of features are described; the final prediction obtained through weighted voting or stacking; different types of data are processed by specialized modules whose outputs are then combined. Such hybrid systems demonstrate more stable results on independent datasets and generalize better across data from different institutions. At the same time, ensuring clinical interpretability remains a key challenge: physicians must understand why the system produced a given prediction. Several publications describe architectures that combine structured data with imaging results or signals from wearable devices [16–20]. Moreover, there is growing interest in hybrid models in which ML algorithms are complemented by rule-based, ontology-based, or fuzzy-logic components, improving robustness of predictions and partially addressing interpretability [21–24]. Despite these advances, the literature contains virtually no studies in which such a hybrid architecture has been implemented as a unified decision-support

¹ Cardiovascular diseases (CVDs), Available: [https://www.who.int/news-room/fact-sheets/detail/cardiovascular-diseases-\(cvds\)](https://www.who.int/news-room/fact-sheets/detail/cardiovascular-diseases-(cvds)) (Accessed 13.10.2026)

tool for CHD risk stratification that simultaneously processes structured data, narrative records, and instrumental measurements, while providing explanations intelligible to clinicians.

Despite active development of intelligent clinical decision-support systems in cardiology, their widespread adoption in clinical practice is still hindered by a number of significant barriers. Key limitations include the need for external validation on independent patient cohorts, concerns about data quality and representativeness, and strict regulatory requirements for medical software. These factors directly affect clinician trust in algorithms and determine the feasibility of integrating such solutions into existing MISs.

The aim of this study is to present a hybrid intelligent system for risk stratification in CHD and to demonstrate its effectiveness and practical applicability in a clinical setting. To achieve this goal, the study implements an architecture that combines an ensemble of ML models with a NLP module, and also carries out a set of validation procedures aimed at assessing the stability of predictions and ensuring reproducibility of results.

Methods

A comprehensive approach was employed in developing a hybrid intelligent system for risk stratification in CHD, combining statistical analysis, ML methods, model interpretation techniques, and the software implementation of an analytical pipeline.

In this study, a publicly available dataset (`heart.csv`) was used, containing patient records, clinical features, and a binary outcome indicating CHD status. During the data preprocessing stage, the following procedures were carried out:

- imputation of missing values;
- encoding of categorical variables;
- standardization of numerical features to a common scale.

Because the outcome was imbalanced, we applied class-balancing procedures to reduce the model's bias toward the majority class.

For the initial examination of the data structure, descriptive statistical analysis was used, including the calculation of key characteristics and visualization of feature distributions. Correlation analysis was applied to identify strong associations between predictors and the outcome, as well as to detect multicollinearity. Cluster analysis was employed at certain stages to test whether natural subgroups of patients with similar clinical profiles exist – a question relevant to the choice of a stratified modelling approach.

Since the task of risk stratification requires high accuracy and robustness to data variability, an ensemble method was developed that combines several algorithms with different inductive biases: gradient boosting as the primary predictor; logistic regression to obtain interpretable coefficients and to verify the linearity of relationships; random forest to assess feature importance and to ensure robustness to outliers. The final prediction was generated through weighted voting, with weights determined based on their performance in cross-validation. This approach allowed us to account for both quantitative patterns and qualitative features of clinical scenarios typical of different patient subgroups.

To objectively assess the quality of the models and to mitigate overfitting, the data were split into training (80 %) and test (20 %) sets while maintaining the class distribution. The performance was evaluated using metrics adapted for imbalanced data. To obtain a more reliable assessment of the results stability, cross-validation with repeated runs was used.

A key component of the hybrid system is the clinical interpretability of the predictions. To achieve this, SHAP analysis was used, which allows obtaining both a global assessment of feature importance and local explanations for individual predictions. This ensures that model conclusions align with clinical understanding and helps identify unexpected patterns that may warrant further investigation.

The study was developed in Python using the following libraries:

- Pandas and NumPy – for data processing and transformation;
- Scikit-Learn – for basic ML methods, cross-validation, and metrics;
- Imbalanced-Learn – for class imbalance handling;
- XGBoost – for building gradient boosting models;
- SHAP – for model interpretation;
- spaCy – for preprocessing text fields;
- Matplotlib and Seaborn – for result visualization;
- Streamlit and FastAPI – for developing the user interface and API of the hybrid system.

Thus, the proposed methodological framework ensures not only high accuracy in predicting the risk of CHD but also transparency of the decisions made by the system, which is crucial for the implementation of such tools in clinical practice.

Results and discussion

Methods of analysis and the procedure for calculating indicators

The study uses the open dataset heart.csv, which is widely used in research on CHD prediction [16]. The dataset contains 918 records, 11 initial clinical features, and a binary target variable indicating the presence of CHD. The class distribution is as follows: 508 patients (55.3 %) with CHD and 410 patients (44.7 %) without CHD (moderate class imbalance).

Feature description:

- Numerical: age (Age), resting blood pressure (RestingBP), cholesterol (Cholesterol), maximum heart rate (MaxHR), ST-segment depression (Oldpeak).
- Categorical: sex (Sex), chest pain type (ChestPainType), fasting blood sugar level (FastingBS), resting ECG results (RestingECG), presence of exercise-induced angina (ExerciseAngina), ST-segment slope (ST_Slope).

Artifactual zeros in the restingBP and cholesterol fields (which cannot be clinically equal to 0) were replaced with NaN and subsequently imputed using median values calculated from non-zero observations.

Stratified splitting into a training set (80 %) and a test set (20 %) was performed while preserving the class proportions.

To improve the model's predictive performance and capture clinically relevant interactions, eight features were developed:

- Age_Chol_Interaction = age × cholesterol;
- Age_BP_Interaction = age × resting blood pressure;
- Age_squared;
- BP_Category;
- Cholesterol_Category;
- HR_Angina_Interaction;
- Slope_Oldpeak_Interaction;
- Pain_Sex.

All the features were included in the final set along with the original eleven parameters. To automatically extract eleven clinical parameters from unstructured Russian text, an NER model was developed based on the spaCy library (version 3.7.2). Since there were no annotated clinical texts in Russian, a synthetic corpus was created by generating a variable text for each of the 918 dataset records; the text contains randomly selected marker phrases for each feature and a random order of their mention.

The spaCy ru_core_news_sm model was used as the initial base, to which an NER component with 11 labels (feature names) was added. The model was trained for 20 epochs with a batch size of 8 and a dropout rate of 0.35. The optimizer used was adam (with the default learning rate in spaCy).

The extracted values are checked for compliance with clinical ranges and normalized: “yes” → 1, “no” → 0 for binary features; “male” → M, “female” → F; textual variants of diagnoses are converted to the standard values used in the model (e.g., ASY, ATA, NAP, TA).

Three algorithms were evaluated:

- Logistic Regression with L2 regularization (parameter $C = 0.1$, solver: liblinear);
- Random Forest with 150 trees;
- XGBoost with hyperparameters tuned using GridSearchCV ($n_estimators = 100$, $max_depth = 3$, $learning_rate = 0.1$).

A pipeline was used for all models: Preprocessing (standardization of numerical features, one-hot encoding of categorical features); SMOTE for class balancing in the training set; model.

A VotingClassifier with soft voting was built. The model weights were selected empirically: XGBoost – 0.5, Random Forest – 0.25, Logistic Regression – 0.25.

Stratified five-fold cross-validation was applied to the training set (X_train , y_train) to tune hyperparameters and assess stability. Final testing was performed on the held-out test set (X_test , y_test). Metrics included AUC-ROC, Recall (sensitivity), Precision, F1 score, and Calibration (calibration curve). The SHAP method was used to explain the predictions [17]. The analysis was carried out for XGBoost as the most influential component of the ensemble. Global feature importance was estimated using the mean absolute SHAP values. Local interpretation was implemented as waterfall plots showing the contribution of each feature to the prediction for a specific patient.

All developed modules were integrated into a web application built with the streamlit framework (version 1.2+). The application includes three tabs:

1. *Prediction and Interpretation*: for manual input of 11 parameters via sliders and drop-down lists, and for displaying the prediction;
2. *Text Analysis*: for entering unstructured text in Russian, a button to launch the NLP module, and displaying the extracted values with visual confirmation (checkmarks) in the sidebar;
3. *Methodology*: a description of model, metrics, and interpretation.

The application is implemented using a modular structure (Files: app.py, utils.py, config.py), which ensures scalability and ease of maintenance.

System output characteristics and analysis of predictive accuracy

The results on the held-out test set are presented in Table 1. The ensemble outperforms each of the base models across all metrics, achieving AUC-ROC of 0.938, Recall of 0.912, and Precision of 0.930.

Table 1

Quality metrics on the test set

Model	AUC ROC	Recall	Precision	F1 score
Logistic Regression	0.889	0.833	0.882	0.857
Random Forest	0.908	0.863	0.902	0.882
XGBoost	0.931	0.892	0.917	0.904
Ensemble (Voting)	0.938	0.912	0.930	0.921

Stratified five-fold cross-validation on the training set demonstrated the stability of the results: mean AUC-ROC = 0.932 ± 0.030 , mean Recall = 0.882 ± 0.040 , mean Precision = 0.901 ± 0.035 . The calibration curve (Fig. 1) shows a good agreement between the predicted probabilities and the actual frequencies, which confirms the reliability of the model’s probabilistic estimates.

On the test set (20 % of the 938 generated examples), the following metrics were achieved: Precision = 0.73, Recall = 0.71, F1 score = 0.72.

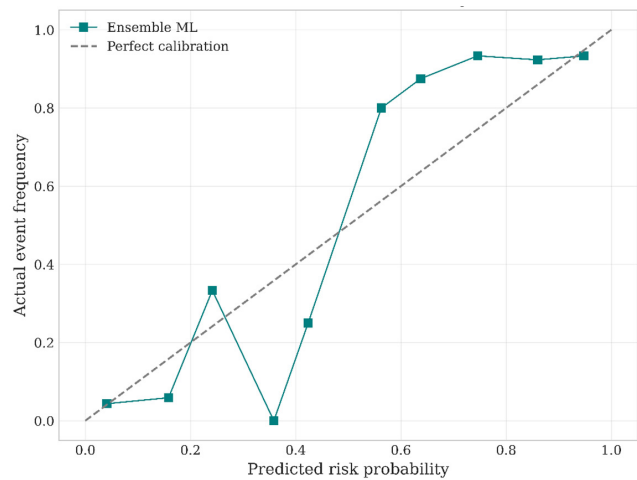


Fig. 1. Calibration curve

The best performance was observed for the Age, Sex, and FastingBS ($F1 > 0.80$) features (Table 2). The features RestingECG and ST_Slope proved to be the most challenging to extract, which is due to their lower frequency of mention in the generated texts.

Table 2

Detailed metrics of the NLP module by entity type

Feature	Precision	Recall	F1 score
Age	0.89	0.92	0.90
Sex	0.91	0.88	0.89
ChestPainType	0.78	0.75	0.76
RestingBP	0.79	0.72	0.75
Cholesterol	0.82	0.76	0.79
FastingBS	0.84	0.86	0.85
RestingECG	0.64	0.60	0.62
MaxHR	0.77	0.73	0.75
ExerciseAngina	0.72	0.70	0.71
Oldpeak	0.70	0.66	0.68
ST_Slope	0.59	0.56	0.57

Global feature importance analysis (Fig. 2) showed that the greatest impact on the prediction is exerted by: ST_Slope (Slope UP), Pain_Sex_Interaction_M_ASY, ChestPainType_ASY.

To illustrate the local interpretation, Fig. 3 shows a waterfall plot for a patient at high risk (probability of CHD 0.87). The plot reveals that the main factors increasing the risk were ST_Slope = UP (0.84), Age_BP_Interaction (0.21), and FastingBS_0 (0.18). The greatest risk-reducing effect was provided by ChestPainType_ASY (−0.56), Pain_Sex_Interaction_M_ASY (−0.5).

The developed application allows you to:

- Enter data manually and get a prediction and a SHAP plot in real time;
- Upload a clinical report text, automatically extract the parameters, and use them for prediction;
- Save the results as a report (the functionality is being expanded).

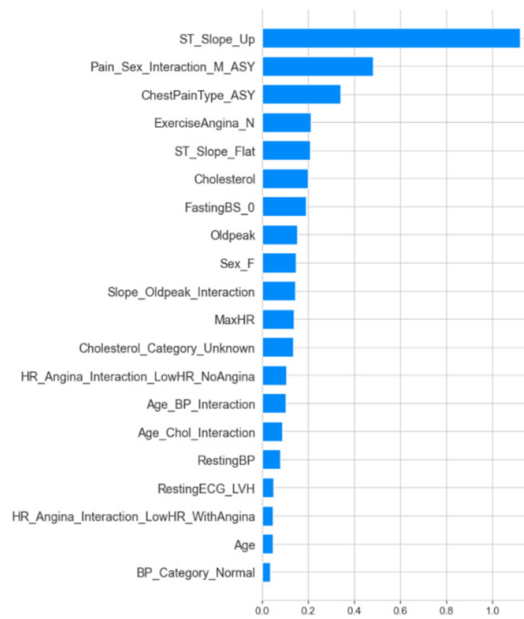


Fig. 2. Histogram of the mean absolute SHAP importance (overall predictive power of the features)

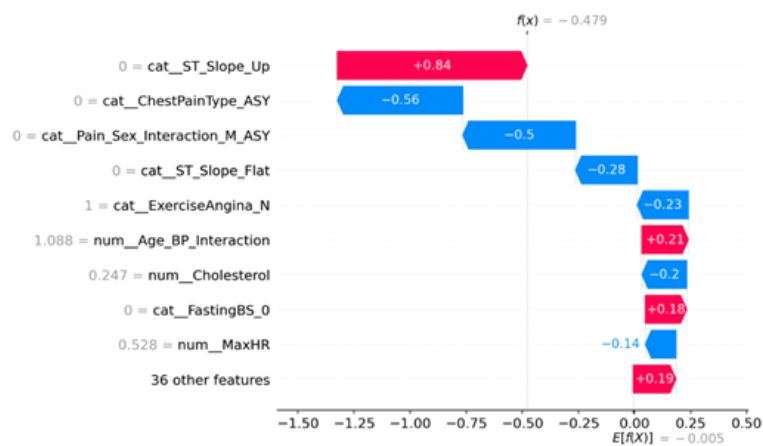


Fig. 3. Personalized analysis of factors (SHAP-waterfall)

Testing the application on 50 anonymized clinical cases confirmed the correct integration of all modules and a response time of less than 3 seconds per calculation (including SHAP).

Analysis of the obtained data and assessment of practical significance

The proposed system outperforms the traditional SCORE/SCORE2 scales in terms of accuracy (AUC ROC 0.938 vs 0.75–0.80). The high Recall (0.912) is of critical clinical importance – it reduces the likelihood of missing patients with CHD.

Compared to other studies on the use of ML for CHD prediction, the system is distinguished by the integration of NLP for automatic data input and a built-in mechanism for explaining predictions. This helps overcome the “black box” barrier and increases physician trust in the system.

Automatic data extraction from text can reduce the time a physician spends filling out forms by up to 50 % (according to the data provided in the technical specification). This is achieved through the use of an NLP module that successfully recognizes 11 parameters with an F1-score of 0.72 – an acceptable level for decision support (the target of $F1 \geq 0.70$ has been achieved).

Interpretability via SHAP allows the physician to understand which factors had the greatest impact on the prediction and to justify the need for additional examinations or therapy adjustments.

1. Data: A single dataset was used, which does not reflect the full diversity of real clinical data. External validation on independent samples from different medical centers is required.

2. NLP module: trained on synthetic data, which may lead to a decrease in performance when processing texts containing specific abbreviations, spelling errors, and complex syntactic structures.

3. Model: the use of SMOTE for class balancing may lead to the generation of unrealistic examples in small datasets; in the future, other methods (e.g., class weighting) could be employed.

4. Hardware dependency: the application is designed to run on a server with 2+ vCPU and 4 GB of RAM; in case of low performance, the response time may exceed 3 seconds.

Conclusion

In this work, a hybrid intelligent system for stratifying the risk of CHD has been developed and validated, including:

- an ensemble of ML models with an AUC-ROC of 0.938 and a Recall of 0.912, which significantly outperforms existing clinical scales;
- an NLP processing module based on spaCy, which enables the extraction of 11 clinical parameters from Russian text with an F1-score of 0.72;
- an explainable AI module based on SHAP, which visualizes the contribution of factors to the individual prediction.

All components are integrated into a Streamlit-based web application, which can be used in clinical practice as a decision-support tool for physicians. The system is ready for further clinical trials and potential integration into electronic health records.

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STABILIZED CURRENT SOURCE IN 180 NM CMOS

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Abstract. This paper presents a comparative analysis of four CMOS stabilized current source architectures: the beta-multiplier, an op-amp-enhanced beta-multiplier, the Nagata current source, and a modified Nagata source with active feedback based on an op-amp. The study focuses on evaluating their performance in terms of thermal stability, dependence on supply voltage and the output noise current spectral density. Analytical considerations were validated through simulation using the Mikron JSC 180 nm 1.8 V CMOS process. The findings reveal the trade-offs between circuit complexity, supply voltage and temperature independence, as well as noise level. The op-amp-enhanced Nagata current source is the best of the considered circuits and has the following characteristics: nominal current 15.14 μA , supply voltage dependence of the reference current 0.1 $\mu\text{A/V}$, RMS output noise current 63.98 nA (within 0.1 Hz to 1 MHz band), current temperature coefficient 66.15 ppm/ $^{\circ}\text{C}$. This circuit has been chosen for the layout implementation. Layout sizes are $18 \times 28 \mu\text{m}$.

Keywords: CMOS, reference current source, output noise current, PTAT current, CTAT current

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ИСТОЧНИК СТАБИЛИЗИРОВАННОГО ТОКА ПО ТЕХНОЛОГИИ КМОП 180 НМ

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Аннотация. Представлен сравнительный анализ четырех архитектур стабилизированных источников тока на основе КМОП-технологии: бета-умножителя, улучшенного бета-умножителя с операционным усилителем, источника тока Нагаты и модифицированного источника Нагаты с активной обратной связью на основе операционного усилителя. Рассматриваются температурная стабильность, зависимость от напряжения питания и спектральная плотность выходного шумового тока. Проведено моделирование с использованием КМОП-технологии АО «Микрон» 180 нм 1,8 В. Представлен компромисс между сложностью схемы, зависимостью от напряжения питания и температуры, а также уровнем шума. Источник тока Нагаты с операционным усилителем является лучшей из схем и имеет следующие характеристики: номинальный ток 15,14 мкА, зависимость опорного тока от напряжения питания 0,1 мкА/В, среднеквадратичный выходной шумовой ток 63,98 нА (в диапазоне частот от 0,1 Гц до 1 МГц), температурный коэффициент тока 66,15 ppm/°C. Эта схема была выбрана для реализации топологии. Размеры топологии составляют 18 × 28 мкм.

Ключевые слова: КМОП, источник тока, спектральная плотность шумового тока, ток пропорциональный температуре, ток обратно пропорциональный температуре

Финансирование: Производство интегральной микросхемы было выполнено за счет средств Министерства науки и высшего образования Российской Федерации в рамках федерального проекта «Подготовка кадров и научного фундамента для электронной промышленности» по государственному заданию «Разработка методики прототипирования электронной компонентной базы на отечественных микроэлектронных производствах на основе сервиса MPW» (FSMR-2023-0008).

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Introduction

High-precision current references are fundamental building blocks in modern CMOS integrated circuits, serving as the backbone for biasing of analog stages, data converters, and radio-frequency front-ends. As semiconductor technologies scale down to the nanometer range, the reduction in supply voltage (V_{dd}) and the increase in process variations introduce significant challenges for maintaining stable bias currents [1–3].

Among a variety of circuit solutions, the beta-multiplier current reference is widely used due to its simplicity and relative independence from supply voltage compared to basic mirrors [3]. However, the classical beta-multiplier architecture often suffers from channel length modulation and limited temperature stability. As established in [3], the integration of an operational amplifier into the beta-multiplier loop can significantly enhance supply rejection by equalizing the drain voltages of the sensing transistors, effectively isolating the output current from V_{dd} fluctuations.

The Nagata current source offers an alternative approach to stabilization [4, 5]. Originally developed to provide a current output that is relatively insensitive to input current variations, the Nagata cell utilizes a self-biasing mechanism with a nonlinear transfer characteristic. Unlike a standard current mirror, where the output current scales linearly with the input, the Nagata architecture is designed to reach a stable equilibrium point. This inherent property not only improves supply decoupling but also provides additional degrees of freedom for temperature compensation. By selecting appropriate transistor geometries and resistance values, the circuit can be tuned to minimize the overall temperature coefficient [6, 7].

This paper provides a comparison of four architectures – the classical beta-multiplier, the op-amp-enhanced beta-multiplier, the Nagata source, and the modified Nagata source – evaluating their trade-offs in terms of stability and noise level.

General considerations

Beta-multiplier

The beta-multiplier generates a current based on the transconductance asymmetry between two MOSFETs. Assuming that both MOSFETs (M1 and M2 in Fig. 1, *a*) operate in the saturation region and that the channel length modulation is negligible ($\lambda = 0$), the equation for the reference current can be derived as follows:

$$I_{out} = \frac{2}{\mu_n C_{ox} \left(\frac{W}{L} \right)_1 R^2} \left(1 - \frac{1}{\sqrt{K}} \right)^2, \quad (1)$$

where K is the sizing ratio factor between M2 and M1. This equation does not consider the dependence on supply voltage variation due to neglecting of λ and non-idealities of pMOSFETs-based current mirror. However, it demonstrates a fundamental limitation in current stabilization. The output current is inversely proportional to the square of the resistance R , so even small fluctuations in resistance (e.g. process corners) will significantly affect the nominal value of the output current.

To minimize the impact of supply voltage fluctuations, an op-amp is added to the beta-multiplier circuit to implement an active feedback loop. The main function of the op-amp is to equalize the drain voltages of the current-sourcing MOSFETs (M1 and M2). This feedback ensures that both branches of the circuit operate under identical V_{ds} conditions, with an accuracy inversely proportional to the op-amp gain, so the currents in the right and left branches are equal. In essence this technique helps to boost the output resistance of the pMOSFETs-based current mirror and suppress the channel length modulation effect. A similar effect can be achieved by utilizing long-channel transistors or cascode structure, although it is less efficient in terms of voltage headroom and supply rejection.

Nagata current source circuit

The Nagata current source uses a different method of current stabilization, which differs fundamentally from the ΔV_{gs} subtraction technique used in beta-multiplier. To demonstrate this, the Nagata current mirror, which is at the core of this circuit, was examined. Unlike a traditional current mirror, the gate of the output MOSFET M2 is connected to the drain of the input MOSFET M1, thereby forming a negative feedback loop. Consequently, when the input current increases, the voltage drop across resistor R begins to limit the gate potential of the output transistor, creating a non-monotonic (peaking) transfer characteristic $I_{out} = f(I_{in})$. By selecting the resistor value and the magnitude of the input and output currents appropriately, the operating point can be fixed at the peak where the sensitivity of the current to changes in the supply voltage is close to zero ($\partial I_{out} / \partial V_{dd} = \partial I_{out} / \partial I_{in} = 0$). This circuit solution can be used in technologies lacking complementary devices (e.g. GaAs MMICs). In such cases, it is impossible to create a pMOSFETs-based current mirror for power

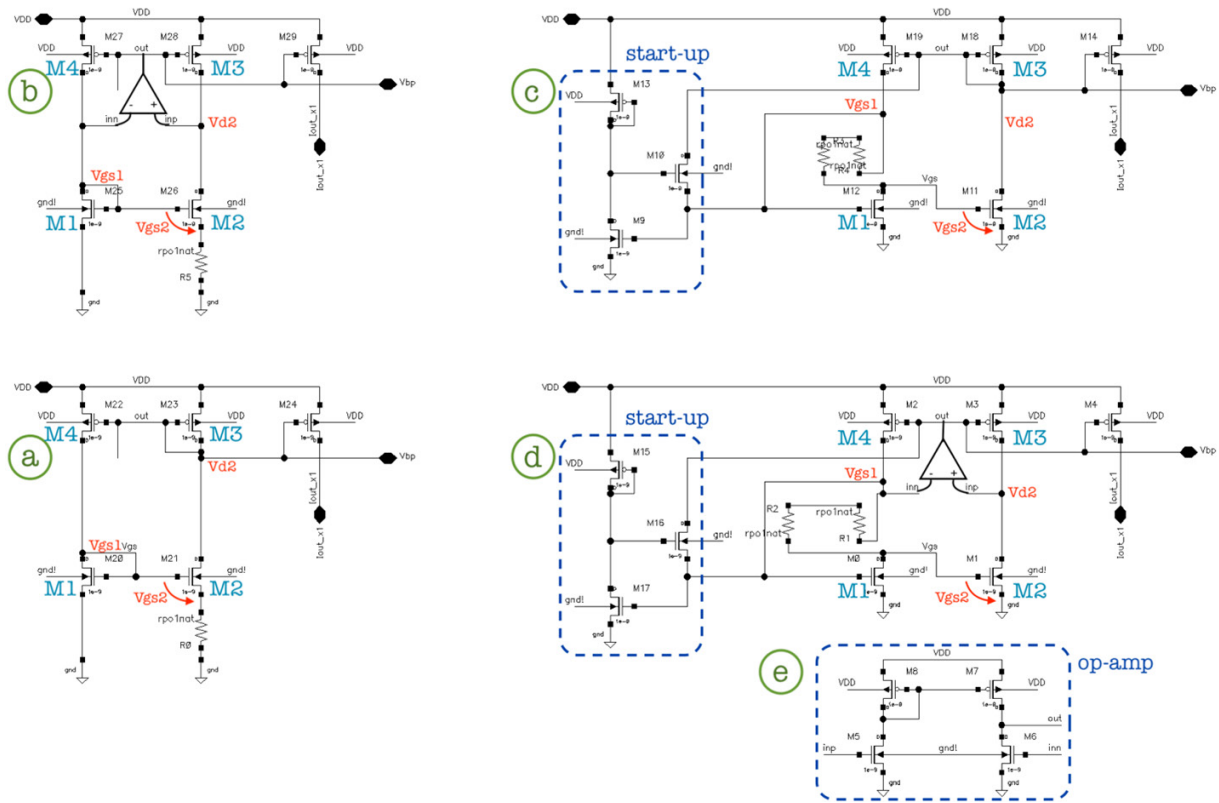


Fig. 1. Stabilized reference current source circuits: beta-multiplier (a); op-amp-enhanced beta-multiplier (b); self-biased Nagata circuit (c); op-amp-enhanced Nagata circuit (d); op-amp circuit (e)

decoupling nor can an op-amp be used to equalize the voltages at the transistor drains. The Nagata circuit is one of the few that allows the output current to be stabilized with respect to the supply voltage.

In contemporary CMOS circuit design, an active load in the form of a pMOSFETs-based current mirror is used to ensure branch current balancing and power supply decoupling. Using resistors as a load is impractical in CMOS designs because generating microampere-range currents requires resistances of around 100 kΩ. Even when high-resistance polysilicon resistors are used, they occupy a significantly larger area than the rest of the circuit. When using an active load in the form of a pMOSFETs-based current mirror, an additional positive feedback loop is formed. Let us examine the feedback in the Nagata circuit in more detail to understand the main difference from the beta-multiplier circuit.

Supply voltage dependence

In a self-bias circuit, there are two feedback loops: a negative feedback loop (comprising MOSFETs M1, M2, and a resistor R) and a positive feedback loop (implemented as a pMOSFETs-based current mirror). Positive feedback allows the output current of MOSFET M2 to be linked to the input current of MOSFET M1. As the current through M2 changes, the input current of M1 changes in the same way. Negative feedback operates similarly to a Nagata current mirror: as the current through M1 increases, the voltage drop across resistor R increases. This reduces $V_{ds1} = V_{gs2}$, which in turn reduces the current through M2 and subsequently leads to a reduction in the current through M1 via the current mirror. Thus, the combination of positive and negative feedback loops creates self-bias and brings the circuit to a state of stable equilibrium. However, a side effect is the need for a startup circuit, which is required to ensure the correct functioning of the circuit. It is important to note that

the loop gain in the Nagata circuit is significantly greater than in the beta-multiplier circuit. In the Nagata circuit, changes in the input current (through MOSFET M1) are transmitted to the gate of MOSFET M2 via the voltage drop across the resistor. This causes a significant change in the current through M2, which is proportional to the transfer conductance. The open-loop gain is determined by equation

$$LG_N = 1 - g_{m1} \cdot R. \quad (2)$$

It is important to note that the open-loop gain is negative, with a magnitude of 15 for 180 nm CMOS process.

In the beta-multiplier circuit, a change in the input current does not directly affect the V_{gs2} voltage, but rather through the source degeneration negative feedback. This provides milder feedback, which changes the current in the output branch smoothly until a steady-state equilibrium of the input and output currents is reached. The open-loop gain is described by formula

$$LG_\beta = \frac{g_{m2}/g_{m1}}{1 + g_{m2} \cdot R} \quad (3)$$

and, unlike Nagata's, it is positive and relatively small (~ 0.2 for 180 nm CMOS process).

Let us consider the dependence of the bias current on the supply voltage. Although the pMOS-FETs-based current mirror is intended to provide supply decoupling, the dependence of the reference current on the supply voltage remains significant due to the strong influence of channel length modulation in short-channel transistors. When the supply voltage changes, the gate voltage of MOSFET M1 changes too, leading to a change in the reference current. For simplicity, therefore, we will base our further discussion on V_{gs1} rather than V_{dd} , assuming that they are related via the dependence $I_{d_pMOS}(V_{ds})$. While both circuits have an output resistance equal to $1/g_{m1}$ at the V_{gs1} node, the critical output resistance is that of the current-sourcing MOSFET, which is M2 in both circuits. In the beta-multiplier circuit, the output resistance is determined by the feedback resistor (source degeneration) according to expression

$$R_{out\beta} = r_{ds2} \cdot (1 + g_{m2} \cdot R) + R. \quad (4)$$

In the Nagata circuit, the output resistance of the current-sourcing transistor is equal to r_{ds2} , resulting in a stronger dependence of the reference current on the supply voltage.

In the case of MOSFETs with a channel length of $1...3 \cdot L_{min}$, the channel length modulation effect is significant, potentially resulting in a supply voltage dependence of up to 30 %/V. Therefore, the use of op-amp-enhanced architectures is highly recommended for use with short-channel technologies. By incorporating an active gain stage that forces the drain potentials of the transistor pair to be identical, the circuit effectively isolates the reference core from external voltage fluctuations. This architectural modification converts the source-degenerated branch into a regulated cascode structure, where any error signal caused by V_{dd} variation is amplified by the open-loop gain A_v of the op-amp before being applied to the gate of the regulating transistor, thereby counteracting the change. The quantitative advantage of this active regulation can be estimated by multiplying the output resistance by a value of $(1 + A_v)$ which, for 180 nm CMOS process, can exceed 20. Despite these advantages, using of the op-amps can increase the output noise current.

Thermal stability

Classical solutions

The simplest method of achieving temperature insensitivity is to bias the current-sourcing MOSFET at its Zero Temperature Coefficient ($V_{gs} = V_{ZTC}$) operating point (Fig. 2, *a*) [8]. This arises from the mutual compensation of two temperature-dependent mechanisms: carrier mobility (μ) and threshold voltage (V_{th}). At low V_{gs} levels (near the subthreshold region), the drain current exhibits a positive temperature coefficient, primarily due to the reduction in V_{th} as temperature rises. Conversely, at higher V_{gs} levels in strong inversion, mobility degradation becomes the dominant factor, resulting in a negative temperature coefficient for the drain current. At the specific bias point $V_{gs} = V_{ZTC}$, these competing effects introduce equal and opposite changes, ensuring that the drain current remains stable over a certain temperature range. However, this approach is highly sensitive to external variations. Any process corner shifts or V_{dd} fluctuations significantly displace the V_{ZTC} point, leading to significant degradation the circuit thermal stability.

Circuit designs based on bandgap circuits are among the most precise methods of generating a thermally stable current [9, 10]. This approach is based on the sum of currents with opposite temperature coefficients (Fig. 2, *b*) according to the expression

$$I_{ref} = \alpha \cdot I_{PTAT} + \beta \cdot I_{GTAT}, \quad (5)$$

where α and β are the proportionality coefficients. A typical circuit diagram of such reference source is shown in Fig. 2, *c*. The output current component IPTAT (Proportional To Absolute Temperature) has a positive temperature coefficient and can be implemented using a bandgap circuit with bipolar transistors. The second component, I_{GTAT} (Complementary To Absolute Temperature), has a negative temperature coefficient and the possible realizations are a single current-sourcing bipolar transistor or beta-multiplier.

This approach has drawbacks. When mixing currents, only the first-order temperature derivatives of the current can be compensated. All second-order effects continue to influence the system, resulting in a parabolic rather than constant temperature dependence. Additionally, due to the presence of multiple current paths (requiring two: CTAT and PTAT sources) increases noise, power consumption and die area. However, it is worth noting that using a bandgap circuit as the I_{PTAT} current source should reduce the variation in the reference current parameters due to corner deviations and mismatch, because the bipolar transistors used as current-sourcing elements in such a circuit have very small variations across corners and mismatch.

Beta-multiplier thermal stability

The beta-multiplier architecture is fundamentally limited to a monotonic temperature response. Even by adjusting the temperature coefficient of the resistor, it is nearly impossible to achieve temperature compensation. This limitation arises from the circuit feedback loop gain: the source degeneration resistor R forces the currents in both branches to change synchronously. Consequently, even if transistors are biased at different points relative to their V_{ZTC} in order to cancel out thermal effects, the feedback mechanism ensures that any temperature-induced variation alters the current in both branches equally. This synchronization preserves the core linear temperature dependence and prevents flexible adjustment of the temperature coefficient. The only degree of freedom is that M1 and M2 can be biased above or below V_{ZTC} thereby producing a positive or negative temperature coefficient. For typical transistor sizes the operation point is above V_{ZTC} , which causes a CTAT current. In order to create PTAT current, both MOSFETs should be biased below the VZTC voltage, which requires significant increase in W/L to raise the V_{ZTC} . However, this result is not stable because V_{ZTC} changes dramatically with process variations.

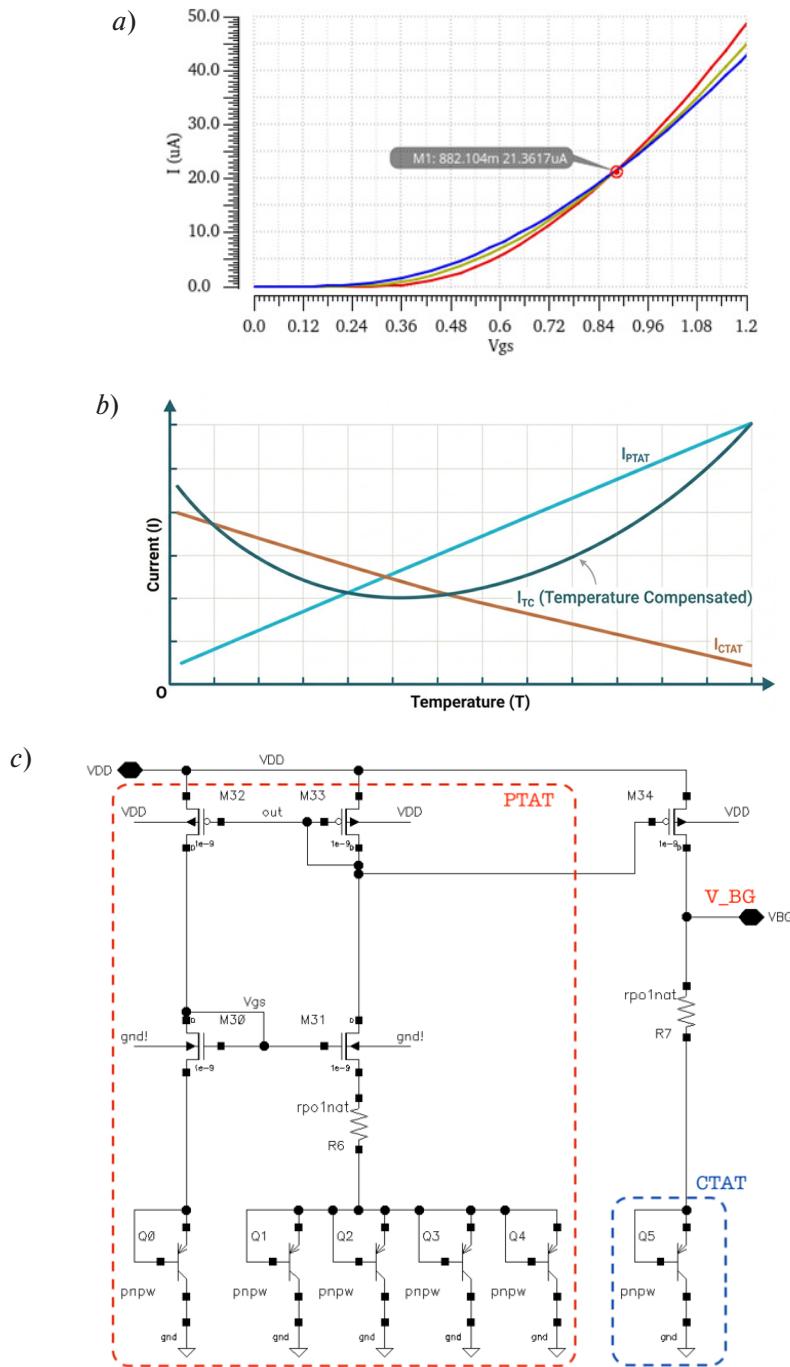


Fig. 2. Zero temperature coefficient voltage V_{ZTC} (a); concept of generating a thermally stable current by combining PTAT and CTAT currents (b); possible bandgap circuit solution (c)

Nagata circuit thermal stability

The temperature stabilization mechanism in the Nagata current source can be explained by analyzing the dynamic balance within its self-biased loop. Let us assume that both MOSFETs M1 and M2 are biased below their V_{ZTC} point, meaning their drain currents inherently exhibit a PTAT characteristic due to the dominant influence of the threshold voltage shift ($\partial V_{th} / \partial T$). Furthermore, the polysilicon resistor R possesses a negative temperature coefficient, which also contributes to a potential current increase as temperature rises.

As temperature increases, the current through M1 tends to rise due to its positive temperature coefficient. This current increment increases the voltage drop across the resistor R . According to the loop gain equation, this reduces the gate-source voltage of M2. Specifically, the change in V_{gs2} is governed by the relation

$$V_{gs1} = V_{gs2} + I_{ref} R. \quad (6)$$

Since the resistance R decreases with temperature, the loop gain slightly decreases causing less effective regulation. In other words, the rise in M1 current acts to suppress the current flowing through M2. However, since M2 is also a PTAT current generator, this suppression is partially cancelled by the own thermal sensitivity of M2. Anyway, the correction signal (current) formed by this loop is fed back to M1 via the pMOSFETs-based current mirror, ultimately stabilizing the reference current.

It is important to note that while the temperature coefficient of the resistor plays a role, it is not the primary driver of the temperature insensitivity. The core stabilization arises from the different thermal sensitivity between M1 and M2. According to the loop equation (6), MOSFET M1 always operates at a higher inversion level (higher current density) than M2. Consequently, even though both are biased below V_{ZTC} , the current in M2 is significantly more sensitive to temperature variations due to the stronger relative influence of V_{th} at lower current densities.

By meticulously optimizing the MOSFET geometries (W/L ratios), these competing thermal increments can be tuned. This leads to a non-monotonic, parabolic temperature dependence of the reference current I_{ref} , characterized by an extremum point where $\partial I_{ref} / \partial T = 0$.

It was originally assumed that the operating voltages of MOSFETs M1 and M2 would be below V_{ZTC} . However, it is also acceptable for MOSFET M1 to be near V_{ZTC} , even if slightly above it. This can, however, lead to the following problem. If V_{gs1} rises significantly above the thermally stable point, the feedback loop in the Nagata circuit will be unable to overcome the CTAT behavior of MOSFET M1, and the circuit will lose its thermal stability.

Since V_{gs1} is significantly higher than V_{gs2} , it is difficult to shift M1 below V_{ZTC} and keep M2 in saturation. To achieve this, the MOSFET geometry must be modified to increase the V_{ZTC} voltage. Experimental findings indicate that the MOSFET channel length has the greatest impact on the V_{ZTC} voltage, with a decrease observed as the channel length increases. To illustrate, when the channel length increases from 0.18 to 2 μm , the voltage V_{ZTC} decreases from 750 to 660 mV. Since both MOSFETs M1 and M2 must be shifted below the V_{ZTC} point ($V_{gs1} < V_{ZTC1}$ and $V_{gs2} < V_{ZTC2}$) then for the correct setting of the operating points we need to ensure that $L_1 < L_2$. The width should also be smaller, although not necessarily in the same proportion, in order to maintain equal currents in both branches.

Simulation results

To verify the theoretical considerations, simulations were performed using the Mikron JSC 180 nm CMOS process. The paper analyzes four circuits: the classical beta-multiplier and Nagata current source circuit, as well as their op-amp-enhanced versions (Fig. 1). To ensure an objective comparison, all circuits were designed with a nominal current of 15 μA and with comparable lengths and widths of the nMOSFETs and pMOSFETs in both the Nagata and beta-multiplier circuits.

Figs. 3–4 show simulation results, which demonstrate dependencies on temperature and supply voltage. Fig. 5 depicts the output noise current spectral densities.

Comparison

Table 1 summarizes the simulation results of four considered circuits. As seen, implementations that use a simple current mirror as the self-bias circuit are significantly dependent on the supply voltage (4.7 $\mu\text{A/V}$ for the beta-multiplier and 2.3 $\mu\text{A/V}$ for the Nagata circuit, 31 and 15 %/V, respectively,

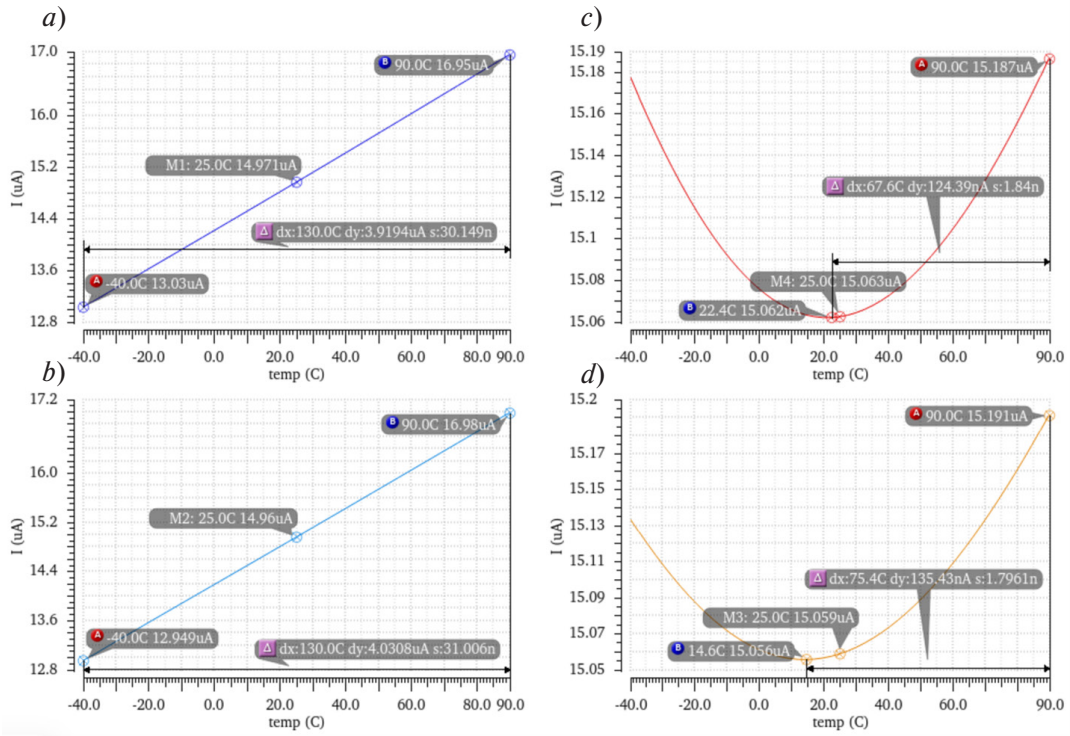


Fig. 3. Temperature dependences of the reference current for (a) classical beta-multiplier current source, (b) op-amp-enhanced beta-multiplier, (c) self-biased Nagata current source, (d) op-amp-enhanced Nagata circuit

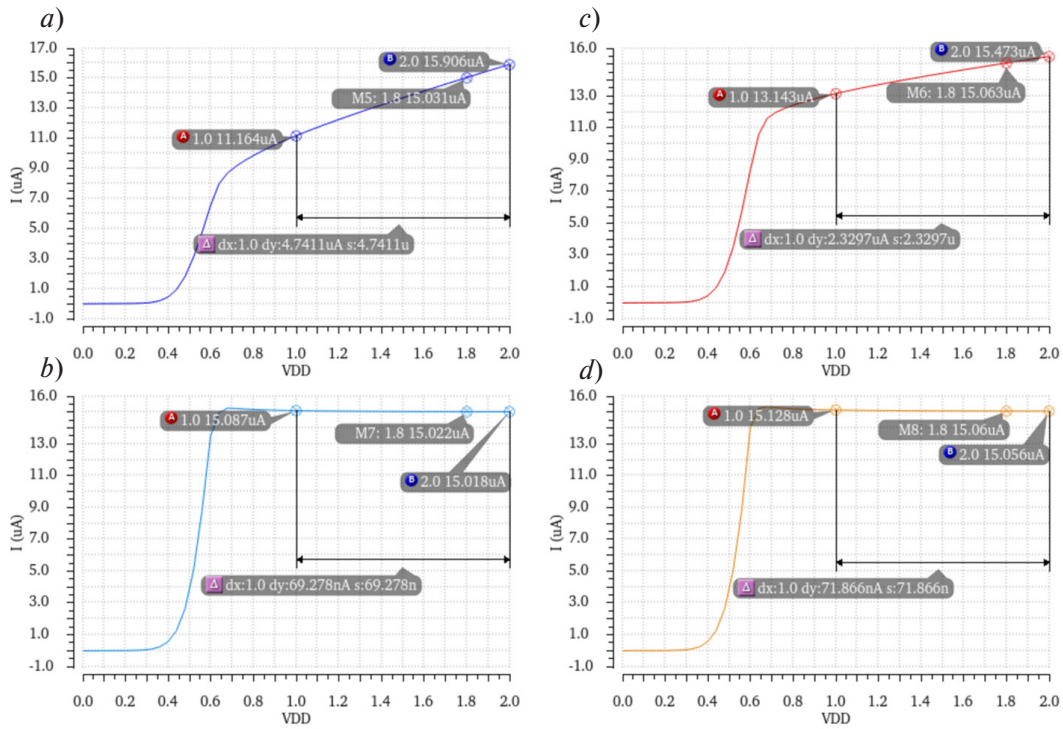


Fig. 4. Supply voltage dependences of the reference current for (a) classical beta-multiplier current source, (b) op-amp-enhanced beta-multiplier, (c) self-biased Nagata current source, (d) op-amp-enhanced Nagata circuit

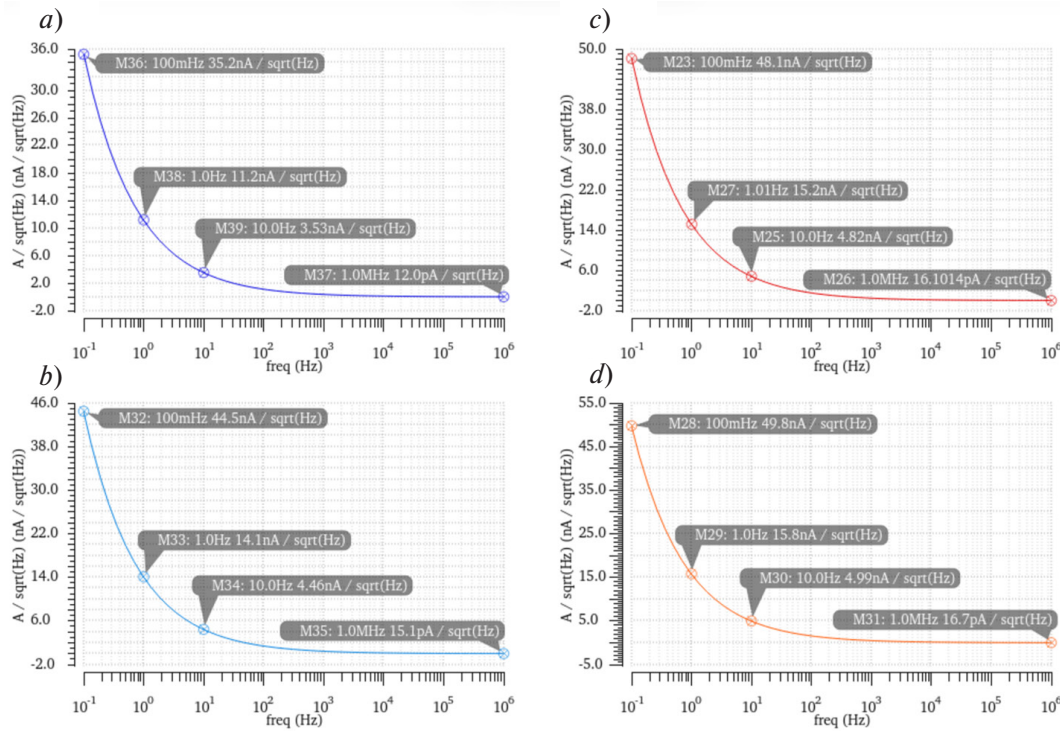


Fig. 5. Reference current noise spectral density for (a) classical beta-multiplier current source, (b) op-amp-enhanced beta-multiplier, (c) self-biased Nagata current source, (d) op-amp-enhanced Nagata circuit

relative to the nominal value). Although both circuits have poor supply decoupling, the RMS value of the output noise current of the Nagata circuit is 62 nA, which is higher but comparable to that of the beta-multiplier circuit where the output noise current is 45 nA RMS.

Table 1

Comparison of the results

	Beta-multiplier (Fig. 1a)	Op-amp-enhanced beta-multiplier (Fig. 1b)	Self-biased Nagata current source (Fig. 1c)	Op-amp-enhanced Nagata current source (Fig. 1d)
Nominal current	15.11 μA	15.1 μA	15.14 μA	15.14 μA
Supply voltage dependence of the reference current (% from nominal value)	4.74 $\mu\text{A/V}$ (31.37%)	0.1 $\mu\text{A/V}$ (0.66%)	2.32 $\mu\text{A/V}$ (15.32%)	0.1 $\mu\text{A/V}$ (0.66%)
RMS output noise current (within 0.1 Hz to 1 MHz band)	45.31 nA	57.22 nA	61.82 nA	63.98 nA
Current temperature dependence (% from nominal value)	3.92 μA (26%)	4.03 μA (26.8%)	0.12 μA (0.79%)	0.13 μA (0.86%)
Current temperature coefficient	2000 ppm/ $^{\circ}\text{C}$	2060 ppm/ $^{\circ}\text{C}$	60.77 ppm/ $^{\circ}\text{C}$	66.15 ppm/ $^{\circ}\text{C}$

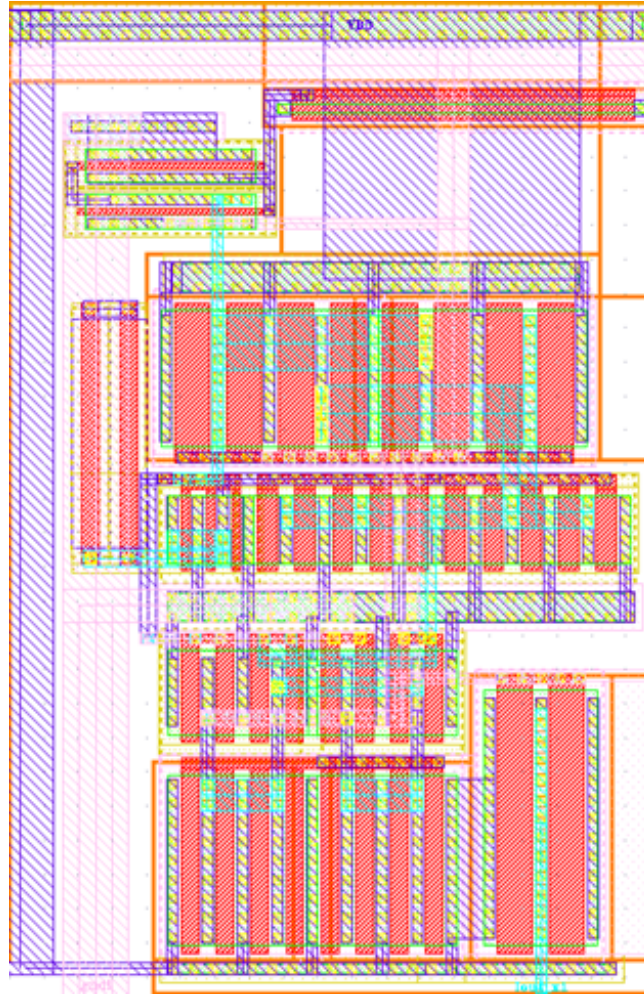


Fig. 6. Layout of the op-amp-enhanced Nagata current reference core

Using a simple four-MOSFETs op-amp provides power decoupling. The dependence on the supply voltage is $0.1 \mu\text{A/V}$ for the beta-multiplier and $0.1 \mu\text{A/V}$ for the Nagata circuit, which is 0.6 and 0.5 %/V of the nominal value, respectively. However, the op-amp-enhanced versions of both circuits have worse noise characteristics but the RMS values for the Nagata circuit and for the beta-multiplier became closer to each other.

The output current of the beta-multiplier has a positive temperature coefficient and remains constant regardless of the selected operating points of the MOSFETs. As expected, the temperature coefficient is $2000 \text{ ppm/}^\circ\text{C}$ (within the typical operating range of -40°C to $+85^\circ\text{C}$). The temperature dependence of the Nagata circuit depends significantly on the choice of operating points and MOSFETs dimensions and, for the two presented modifications equals to 61 and $66 \text{ ppm/}^\circ\text{C}$.

From the comparison in Table 1, the op-amp-enhanced Nagata current source has the best overall characteristics. Thus, it has been chosen for the layout implementation which is shown in Fig. 6. Layout sizes are $18 \times 28 \mu\text{m}$.

Conclusion

The developed reference current source circuit based on the Nagata design achieves a zero-temperature-coefficient output current behavior at the target operating temperature, providing a robust CMOS-only alternative to traditional reference architectures. Simultaneously, the Nagata current

source is more power-efficient due to its simple architecture. Unlike traditional bandgap reference circuits, which require multiple auxiliary branches to generate and then combine the PTAT and CTAT current components, the Nagata topology provides temperature compensation within a single primary current loop. By eliminating the additional current paths and summing amplifiers typically found in bandgap reference architectures, the Nagata source minimizes the total current consumption.

The results of the comparison show that the Nagata circuit has advantages in all parameters except noise, where the beta-multiplier circuit has a slightly lower value due to its different feedback loop structure. Opting for a Nagata architecture necessitates a conscious design trade-off, prioritizing thermal stability over the spectral purity of the output current.

Therefore, the use of the op-amp-enhanced Nagata current source is a promising alternative to the widely used op-amp-enhanced beta-multiplier. For a typical 180 nm CMOS process with a rated current of around 15 μA , the current versus temperature sensitivity is 66 ppm/ $^{\circ}\text{C}$, the current versus supply voltage response is 0.1 $\mu\text{A/V}$ and the RMS noise current is 64 nA. Despite a minor disadvantage in RMS output noise current (ca. 12%), the current temperature coefficient of the Nagata circuit is about 30 times better than that of the beta-multiplier.

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ELECTROSTATIC SHUNT RF MEMS SWITCH WITH A FLOATING ELECTRODE FOR S-BAND APPLICATIONS: ARCHITECTURE AND MATHEMATICAL MODELING

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Abstract. This paper presents the design and modeling of an electrostatically actuated capacitive shunt RF MEMS switch with a floating electrode for S-band operation. The proposed architecture incorporates a mechanically fixed, electrically floating metal electrode positioned above the signal line and separated from it by a high- k TiO_2 dielectric layer. This configuration substantially increases the down-state capacitance and improves signal isolation without requiring extremely small interelectrode gaps. The switch is implemented on a coplanar waveguide and uses an aluminum membrane with meander suspensions and perforation to reduce the effective stiffness, actuation voltage, and switching time. The main electromechanical parameters were evaluated analytically and verified by finite element modeling in COMSOL Multiphysics, while the RF performance was analyzed using electromagnetic simulation in ANSYS HFSS. The final design demonstrates a pull-in voltage of 2.7 V, a closing time of 18 μs , a down-state capacitance of 247 pF, and an up-state capacitance of 9.6 fF. In the 2–4 GHz range, the simulated up-state insertion loss is from -0.012 to -0.14 dB, and the down-state isolation is from -43.3 to -89.75 dB. The results show that the floating-electrode architecture provides a high capacitance ratio and significantly enhances the RF performance of the capacitive shunt MEMS switch.

Keywords: RF MEMS switch, shunt architecture, insertion loss, S-parameters, floating electrode, S-band

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РАЗРАБОТКА АРХИТЕКТУРЫ И МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ РЕЖИМОВ РАБОТЫ РАДИОЧАСТОТНОГО МЭМС-ПЕРЕКЛЮЧАТЕЛЯ С ПЛАВАЮЩИМ ЭЛЕКТРОДОМ

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Аннотация. Представлены разработка архитектуры и математическое моделирование электростатического шунтирующего радиочастотного МЭМС-переключателя с плавающим электродом, предназначенного для работы в S-диапазоне. Отличительной особенностью предложенной конструкции является введение неподвижного металлического плавающего электрода, размещенного над сигнальной линией и отделенного от нее слоем high-k диэлектрика TiO_2 , что обеспечивает существенное увеличение емкости в замкнутом состоянии и повышение изоляции. Переключатель реализован на основе копланарного волновода и содержит алюминиевую мембрану с меандровыми подвесами и перфорацией, обеспечивающими снижение эффективной жесткости и рабочего напряжения. Выполнены аналитический расчет основных электромеханических параметров, моделирование переходных процессов в COMSOL Multiphysics и электромагнитное моделирование в ANSYS HFSS. Для разработанной конструкции получены следующие характеристики: напряжение срабатывания 2,7 В, время замыкания 18 нс, емкость в замкнутом и разомкнутом состояниях 247 пФ и 9,6 фФ соответственно. В диапазоне 2–4 ГГц рассчитаны вносимые потери от $-0,012$ до $-0,14$ дБ и изоляция от $-43,3$ до $-89,75$ дБ. Показано, что использование плавающего электрода позволяет существенно увеличить отношение емкостей и обеспечить улучшение радиочастотных характеристик.

Ключевые слова: РЧ МЭМС-переключатель, шунтирующая архитектура, вносимые потери, S-параметры, плавающий электрод, S-диапазон

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Introduction

Modern wireless communication systems, radar systems, satellite platforms, and Internet of Things devices impose increasingly stringent requirements on radio-frequency (RF) switching components operating in the ultrahigh-frequency range. For such devices, low insertion loss in the transmitting state, high isolation in the blocked state, low power consumption, and technological compatibility with integrated fabrication processes are critical. Conventional semiconductor switches, including PIN diodes and field-effect transistors, provide high switching speed and compactness; however, at high frequencies they are characterized by noticeable losses. Against this background, RF MEMS

switches are regarded as a promising class of devices combining low insertion loss, high isolation, high linearity, and low power consumption [1–4].

Electrostatically actuated capacitive shunt RF MEMS switches are of particular interest. This architecture provides efficient shunting of the signal to ground in the down state and makes it possible to achieve high isolation over a wide frequency range at low control power. However, two limitations remain relevant for this class of devices: a relatively high pull-in voltage and the need to increase the capacitance ratio between the up and down states, which directly determines the ultimate radio-frequency performance of the switch. It has been shown in the literature that the pull-in voltage can be reduced by decreasing the effective stiffness of the movable element, using meander suspensions, introducing membrane perforation, and selecting a material with suitable mechanical properties. At the same time, increasing the capacitance ratio requires special design solutions that go beyond the conventional “membrane–dielectric–signal line” configuration [2, 5–8].

In recent years, RF MEMS switch designs aimed simultaneously at low-voltage actuation, while actively investigating improved isolation. Modified geometries of elastic elements, combined contact configurations, and additional capacitive elements have been used for this purpose, making it possible to control the effective capacitance of the structure. However, in many known solutions, improved radio-frequency characteristics are achieved either at the cost of more complex fabrication technology or by reducing the interelectrode gaps. This, in turn, increases the sensitivity of the device to fabrication tolerances, residual mechanical stresses, stiction, and dielectric charging effects [6–11]. Therefore, the search for architecture that provides a substantial increase in the down-state capacitance without using critically small interelectrode gaps remains highly relevant.

One promising approach to this problem is the use of a floating electrode, i.e., an additional fixed metal plate located above the signal line and separated from it by a thin high- k dielectric layer. When the membrane is pulled down, this configuration forms an equivalent system with a substantially higher shunt capacitance than that of a conventional capacitive switch. As a result, high isolation can be achieved while maintaining an acceptable pull-in voltage and technologically feasible structural dimensions. The complete set of electromechanical and electromagnetic characteristics of such an architecture, including the pull-in voltage, switching time, capacitance ratio, and S-parameters, requires comprehensive analytical and numerical investigation [9–11].

The practical significance of developing such switches is associated with the expansion of their application areas in modern wireless and satellite systems, as well as in reconfigurable radio-frequency front ends. For the S-band, this problem is of particular interest because this frequency range is widely used in communication systems, satellite channels, and a number of mass-market radio interfaces. Recent studies, including review papers, emphasize that further progress in RF MEMS devices is associated with the search for designs that combine low actuation voltage, high isolation, technological reproducibility, and stable performance [10–13].

In this paper, an electrostatically actuated capacitive shunt RF MEMS switch with a floating electrode is considered. The switch is implemented on a coplanar waveguide (CPW) and is intended for operation in the S-band. The proposed design includes an aluminum membrane with meander suspensions and perforation, as well as a floating electrode separated from the signal line by a TiO_2 layer. The aim of this work is to perform mathematical modeling of an electrostatically actuated capacitive shunt RF MEMS switch with a floating electrode for the S-band and to evaluate the possibility of achieving competitive electromechanical and radio-frequency characteristics.

Methods

Switch architecture and operating principle

The investigated device is an electrostatically actuated capacitive shunt RF MEMS switch implemented on a sapphire substrate with a CPW. The schematic design is shown in Fig. 1. The shunt configuration

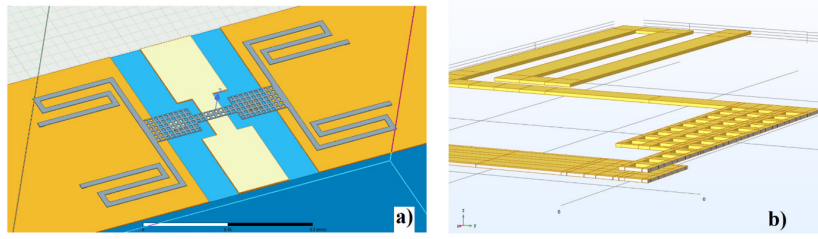


Fig. 1. Proposed design of the electrostatically actuated capacitive shunt RF MEMS switch with a floating electrode: geometrical model (a); top view of the membrane with meander suspensions and perforation (b)

was selected because such structures combine low insertion loss in the signal-transmission state and high isolation in the signal-blocking state [3, 6, 14, 15]. A bridge-type architecture with a movable metal membrane located above the signal line and the actuation electrodes was used as the baseline design.

The key feature of the proposed design is the introduction of a floating electrode, i.e., a fixed metal plate placed above the signal line and separated from it by a thin TiO_2 high- k dielectric layer. This configuration forms a metal–dielectric–metal (MDM) capacitor and substantially increases the equivalent shunt capacitance in the down state compared with a conventional capacitive switch [9, 16]. The movable element is an aluminum membrane with meander suspensions and perforation. The meanders are used to reduce the effective stiffness of the movable system and decrease the pull-in voltage [15, 17, 18], whereas the perforation is introduced for both technological and electromechanical reasons: it facilitates the removal of the sacrificial layer during membrane release, decreases the membrane mass, and affects the dynamic characteristics of the switch [17, 18].

In the up state, the membrane is separated from the floating electrode, and the signal line is not shunted to ground. When a control voltage is applied between the membrane and the lower electrodes, an electrostatic force arises and deflects the membrane toward the signal line. After the pull-in voltage is reached, the membrane comes into contact with the electrode. As a result, the equivalent shunt capacitance sharply increases, and the signal propagating along the line is suppressed. Thus, the structural novelty of the investigated device consists in combining a floating electrode, meander suspensions, and a perforated membrane within a single shunt architecture.

The main design parameters of the RF MEMS switch are given in Table 1. The design dimensions were chosen to provide operation in the 2–4 GHz range, match the CPW to a characteristic impedance of $50\ \Omega$, and maintain technologically feasible interelectrode gaps.

Analytical model

For a preliminary assessment of the switch characteristics, a lumped-parameter model was used. The model relates the geometrical dimensions of the structure, the mechanical properties of the membrane, and the electrostatic actuation force. The total equivalent stiffness of the movable system (K_{full}) was calculated by taking into account the contributions of the central membrane section, the wider membrane sections, the meander suspensions, and the connecting beams [7, 10, 15, 17]:

$$K_{full} = \left(\frac{1}{K_m} + \frac{2}{K_{mb}} + \frac{4}{K_{meand} + K_{beam}} \right)^{-1}, \quad (1)$$

where K_m is the stiffness of the central narrow part of the membrane, K_{mb} is the stiffness of the wider membrane sections, K_{meand} is the stiffness of the meander suspensions, and K_{beam} is the stiffness of the connecting beams between the meanders and the membrane.

The stiffnesses of the meander suspensions and the connecting beams were determined using the following expressions [7, 15, 17]:

Table 1

Main design parameters of the RF MEMS switch

Parameter	Value
Substrate material	Sapphire
Substrate thickness	500 μm
Material of the membrane and suspensions	Al
Material of the conductive layers	Cr–Cu
Dielectric material	TiO ₂
Width of the central CPW conductor, W_s	100 μm
CPW slot width, g_{cpw}	60 μm
Width of the ground planes, W_g	400 μm
Membrane length, L_m	80 μm
Membrane width, W_m	20 μm
Membrane thickness, t	1 μm
Meander length, L_{meand}	150 μm
Meander width, W_{meand}	10 μm
Gap between the membrane and the actuation electrode, g_0	2 μm
Gap between the membrane and the signal line, $g_s \approx g_0 - H_{mdm} - t_d$	1.3 μm
TiO ₂ layer thickness, t_d	100 nm
Floating-electrode thickness, H_{mdm}	0.6 μm
Perforation-window size, $W_{perf} \times L_{perf}$	6 $\times$ 6 μm

$$K_{meand} = \frac{EW_{meand}t^3}{L_{meand}^3N}; \quad (2)$$

$$K_{beam} = \frac{EW_{beam}t^3}{L_{beam}^3}. \quad (3)$$

Here, E is the Young's modulus of the membrane material, t is the membrane thickness, W_{meand} and L_{meand} are the width and length of the meander, W_{beam} and L_{beam} are the width and length of the connecting beam, N is the number of horizontal meander segments.

For the considered asymmetric gap configuration, in which the membrane–actuation-electrode gap differs from the membrane–signal-line gap, the pull-in voltage was calculated as [15, 17]:

$$V_p = \sqrt{\frac{8K_{full}g_0^2(g_0 - g_s)}{27\epsilon_0 A_{eff}}}, \quad (4)$$

where g_0 is the gap between the membrane and the actuation electrode, g_s is the gap between the membrane and the signal line, A_{eff} is the effective overlap area, and ϵ_0 is the electric constant.

The mechanical natural frequency was estimated using the following relation [7, 15, 17]:

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{K_{meand}}{M_{mem}}}, \quad (5)$$

where M_{mem} is the membrane mass. The closing and release times were evaluated using [7, 15, 19]

$$T_s = \frac{3.67V_p}{V_s\omega_0}; \quad (6)$$

$$T_r = \frac{\pi}{2\omega_0} = \frac{1}{4f_0}, \quad (7)$$

where V_s is the control voltage and $\omega_0 = 2\pi f_0$.

The up-state capacitance of the switch was determined with allowance for the fringing capacitance [15, 16]:

$$C_{up} = \frac{\epsilon_0 A_{con}}{g_s + t_d/\epsilon_r} + C_f, \quad C_f = 0.35C_{up}^{(0)}, \quad (8)$$

where A_{con} is the interaction area between the membrane and the lower electrode, t_d is the dielectric thickness, and ϵ_r is the relative permittivity of TiO_2 . The down-state capacitance was represented by two parallel contributions: the MDM capacitance of the floating-electrode/ TiO_2 /signal-line stack and the membrane-to-actuation-electrode capacitance [15–17]:

$$C_{down} = \frac{\epsilon_0 \epsilon_r A_{mdm}}{t_d} + \frac{2\epsilon_0 A_{con}}{g_0 - g_s}, \quad (9)$$

where A_{mdm} is the floating-electrode area.

To account for the decrease in the effective membrane area after perforation, the perforation coefficient was introduced as

$$K_{perf} = \frac{A_{perf}}{A}, \quad A_{eff} = A(1 - K_{perf}), \quad (10)$$

where A_{perf} is the total area of the perforation windows, A is the initial membrane area, and A_{eff} is the effective area after perforation.

For a preliminary analytical estimate of the radio-frequency characteristics, a simplified lumped model of the shunt switch was used [5, 20, 21]. The characteristic electrical resonant frequency of the equivalent down-state circuit was determined as

$$f_{c,down} = \frac{1}{2\pi\sqrt{LC_{down}}}, \quad (11)$$

where L is the equivalent inductance of the signal line and C_{down} is the down-state capacitance of the switch. The corresponding angular electrical resonant frequency is

$$\omega_{c,down} = 2\pi f_{c,down}. \quad (12)$$

Unlike the mechanical natural frequency of the membrane, which determines the switching dynamics, f_c characterizes the electrical response of the equivalent radio-frequency circuit.

For the down state, the estimated values of the S_{21} parameter, i.e., the isolation, were then calculated as

$$S_{21}^{down} = -20 \log \left| \frac{2}{2 + j\omega_{c,down} C_{down} Z_0} \right|, \quad (13)$$

where $Z_0 = 50 \Omega$ is the characteristic impedance of the transmission line.

These relations were used for an approximate analytical evaluation of the C_{down} effect on the radio-frequency response of the switch in the down state at the S-band boundaries. The complete frequency dependences of S_{21} and S_{11} (the reflection coefficient) in the range of 2–4 GHz were obtained from electromagnetic simulation in ANSYS HFSS.

Numerical modeling

Numerical analysis was performed in several stages using COMSOL Multiphysics, ANSYS HFSS, and MATLAB Simulink. At the first stage, a simplified model of a rectangular membrane without meanders or perforation was constructed in COMSOL to determine the natural frequencies and mode shapes. At the second stage, meander suspensions were introduced into the model, which made it possible to investigate the effect of reduced equivalent stiffness on membrane deflection, pull-in voltage, and dynamic characteristics. At the third stage, the final design with perforation and a floating electrode was considered; for this design, the static pull-in voltage, time-dependent deflection, and the capacitances in the up and down states were determined. This step-by-step approach made it possible to trace the contribution of each structural element to the final device characteristics.

In the COMSOL electromechanical model, a coupled formulation combining electrostatics and solid mechanics was used. The air gap between the membrane and the lower electrodes was 2 μm ; under the membrane, a TiO_2 layer with a thickness of 100 nm was modeled. A control voltage increasing to 5 V was applied to the lower electrodes. The pull-in voltage was determined from the abrupt nonlinear increase in the membrane deflection, whereas the switching time was defined as the time required for the membrane to reach the contact position with the floating electrode. To calculate the capacitance in the down state, a separate configuration with the established contact between the membrane and the floating electrode was used. This reduced the numerical error associated with mesh deformation at the moment of contact. In parallel, a parameterized computational scheme was developed in MATLAB Simulink. This scheme reproduced analytical relations for stiffness, mass, pull-in voltage, switching time, and capacitance and was used for comparison with the results of finite element modeling (FEM).

Electromagnetic simulation was performed in ANSYS HFSS using a three-dimensional model of the CPW with the integrated switch. Wave ports were assigned with a characteristic impedance of $Z_0 = 50 \Omega$. The metal elements in the model were treated as perfect conductors, and the outer boundaries of the air volume were specified as radiating boundaries, which made it possible to minimize artificial reflections of the electromagnetic field from the boundaries of the computational domain. The S-parameters were calculated in two states: with the membrane in the up position and with the membrane pulled down to the floating electrode. The investigated frequency range was 2–4 GHz. The values obtained in HFSS were used to determine isolation, insertion loss, return loss and were then compared both with the analytical model, as well as with published data for shunt CPW MEMS switches of similar architecture [20–23].

Results and discussion

At the first stage of the numerical study, a simplified model of a rectangular membrane without meanders or perforation was considered. This model was used to estimate the natural frequencies of vibration and the limiting level of pull-in voltage for a high-stiffness movable element. The analysis showed that the first natural frequency of this membrane was 79.6 kHz, whereas the calculated pull-in voltage reached 64.8 V. This result indicates that a simple beam structure without additional elastic elements is unsuitable for low-voltage actuation and requires a reduction in the equivalent stiffness of the movable system. This conclusion is consistent with the general understanding of the influence of elastic-element geometry on the electromechanical characteristics of RF MEMS switches [15, 17, 18].

At the second stage, meander suspensions were introduced into the design, which substantially reduced the pull-in voltage. For the intermediate model without a floating electrode but with meanders, the pull-in voltage was approximately 2.1 V, the down-state capacitance was 6.26 pF, the up-state capacitance was 46.9 fF, and the switching time was about 23 μ s. Therefore, it was confirmed that reducing the stiffness effectively decreases the required control voltage; however, this approach alone does not provide a high capacitance ratio, which is necessary for a substantial isolation increase in the S-band [16–18]. Consequently, an additional design solution was required to increase the shunt capacitance in the down state and improve the radio-frequency characteristics.

The final model included a perforated membrane and a floating electrode. The calculated dependence of membrane deflection on the control voltage is shown in Fig. 2. This dependence demonstrates that at a voltage of approximately 2.7 V, the deflection increases sharply, which corresponds to the loss of stability and the transition of the membrane into the pulled-down state. This result agrees well with the analytical estimate of the pull-in voltage according to equation (4). The small discrepancy between the analytical calculation and the simulation results is caused by the fact that the stiffness of the perforated membrane and the distribution of the electrostatic field are taken into account only approximately in the analytical model, whereas in COMSOL they are described more accurately. Such discrepancies are typical for electrostatically actuated MEMS structures [5, 15].

The time dependence of membrane deflection for the final model is shown in Fig. 3. The obtained dependence indicates that at a control voltage of 5 V, the closing time is approximately 18 μ s. Compared with the intermediate model, the decrease in switching time is primarily associated with the reduction in membrane mass due to perforation. Thus, in the investigated design, perforation has a dual but generally favorable effect: on one hand, it slightly increases the pull-in voltage because of the reduced effective area of electrostatic interaction; on the other hand, it decreases the membrane mass and accelerates the transient process. Therefore, the perforation parameters should be selected as a compromise between mechanical compliance, technological feasibility, and dynamic characteristics.

A comparison between the analytical calculation and the finite element modeling results for the final design is given in Table 2. The differences in the key parameters are small: the pull-in voltage differs by 0.15 V, the down-state capacitance differs by 7 pF, and the switching time differs by less than 1 μ s. This confirms that the analytical model is suitable for the preliminary selection of design parameters. At the same time, the final quantitative assessment of the switch characteristics should be based on numerical modeling.

The capacitance ratio is one of the key parameters of a shunt capacitive RF MEMS switch because it determines the difference between the radio-frequency properties of the two operating states. A small value of C_{up} provides weak shunting of the signal line in the up state and thus contributes to low insertion loss, whereas a large value of C_{down} in the down state leads to efficient signal shunting to ground and enhanced isolation. Therefore, increasing the C_{down}/C_{up} ratio is directly associated with a stronger radio-frequency contrast between the two states of the switch.

For the investigated design, this ratio is approximately $C_{down}/C_{up} \approx 2.57 \times 10^4$, which substantially exceeds the values typical of conventional capacitive RF MEMS switches [6, 7, 16, 23]. This result

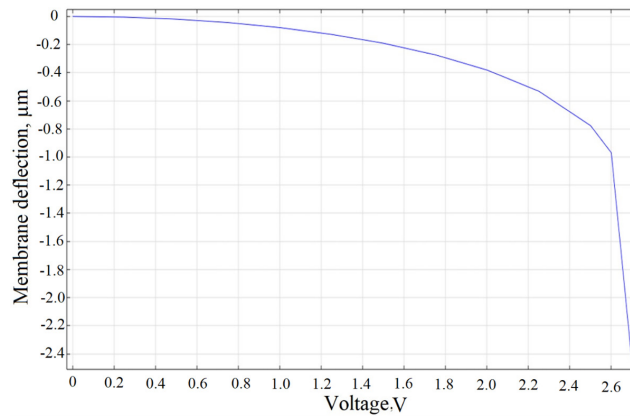


Fig. 2. Dependence of the perforated-membrane deflection on the control voltage for the final model of the RF MEMS switch with a floating electrode

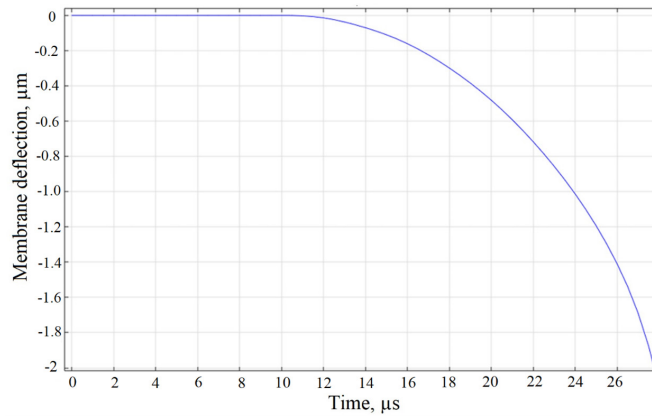


Fig. 3. Time dependence of membrane deflection during RF MEMS switch closing at a control voltage of 5 V

Table 2

Comparison between analytical calculation and finite element modeling results for the final design

Parameter	Analytical calculation	FEM
Pull-in voltage (V)	2.55	2.70
Down-state capacitance, C_{down} (pF)	240	247
Up-state capacitance, C_{up} (fF)	7.2	9.6
Closing time (μ s)	18.6	18

is due to the introduction of the floating electrode and the use of a high-k dielectric, which provide a sharp increase in the down state shunt capacitance while maintaining a low capacitance in the up state. Thus, in the proposed architecture, the floating electrode plays a decisive role in forming the high-isolation properties of the device.

The complete frequency dependences of S_{21} and S_{11} in the down and up states, obtained from electromagnetic simulation in ANSYS HFSS, are shown in Fig. 4. In the down state, which corresponds to the pulled-down membrane, the switch demonstrates high isolation over the entire S-band.

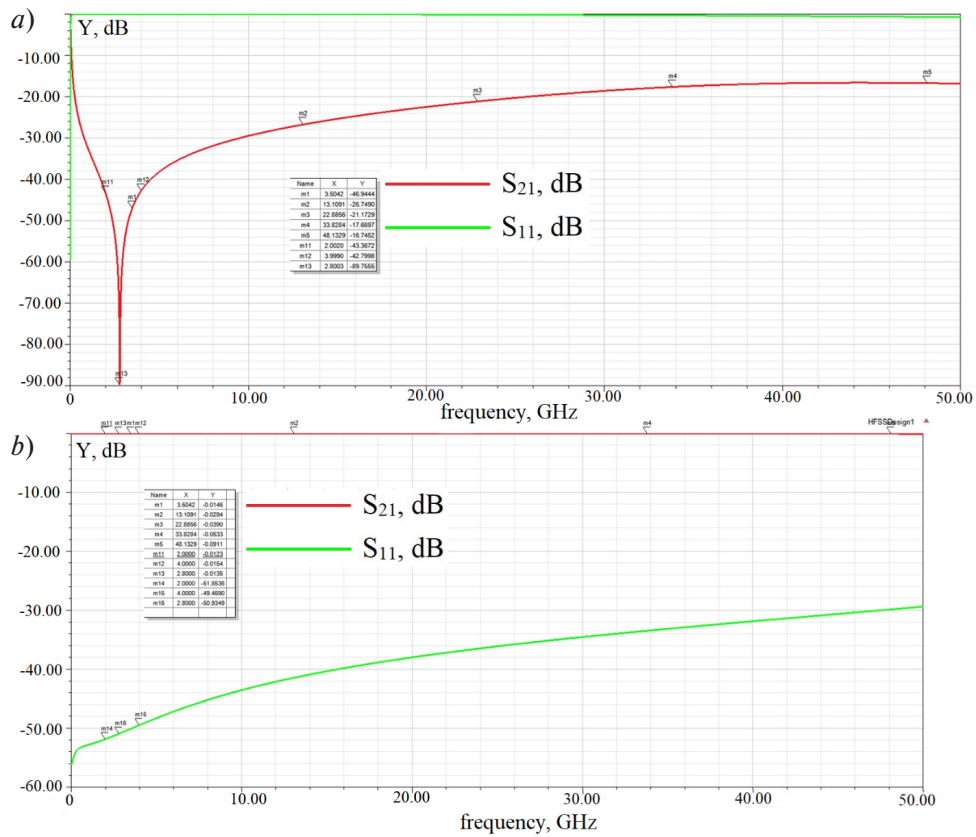


Fig. 4. Frequency dependences of the RF MEMS switch S-parameters in the S-band: down state (a); up state (b)

At 2 GHz, the transmission coefficient S_{21} is -43.3 dB; at 2.8 GHz, a deep minimum of -89.75 dB is reached; and at 4 GHz, S_{21} is -42.8 dB. The pronounced minimum near 2.8 GHz can be interpreted as a manifestation of resonant interaction between the equivalent shunt capacitance and the inductive properties of the transmission line [14, 20]. In the up state, the switch is characterized by low insertion loss: -0.012 dB at 2 GHz, -0.14 dB at 2.8 GHz, and -0.015 dB at 4 GHz. The reflection coefficient S_{11} in the up state is -51.85 , -50.94 , and -49.47 dB at 2, 2.8, and 4 GHz, respectively.

The S-parameter values of the developed model at representative points of the frequency range are summarized in Table 3.

Table 3

S-parameters of the RF MEMS switch in the 2–4 GHz range

Frequency (GHz)	Switch state	S_{21} (dB)	S_{11} (dB)
2.0	down	-43.3	—
2.8	down	-89.75	—
4.0	down	-42.8	—
2.0	up	-0.012	-51.85
2.8	up	-0.14	-50.94
4.0	up	-0.015	-49.47

The obtained results show that the proposed design combines low pull-in voltage values with high radio-frequency performance. From an engineering point of view, this is particularly important because, in conventional shunt switches, improved isolation is often achieved by reducing the gap to the submicron level, which complicates the fabrication process and reduces the reproducibility of the device characteristics. In the present case, a high isolation level is achieved at a gap of 2 μm , that is, under substantially less stringent technological requirements. This provides grounds for considering the proposed architecture to be more robust against parameter variations arising during fabrication.

Conclusion

In this work, an architecture of an electrostatically actuated capacitive shunt RF MEMS switch for S-band operation has been proposed. The distinctive feature of the switch is the use of a floating electrode separated from the signal line by a high k TiO_2 dielectric layer. It has been shown that the combination of a floating electrode, meander suspensions, and a perforated aluminum membrane makes it possible to reduce the pull-in voltage and substantially increase the shunt capacitance in the down state.

Analytical calculation and numerical modeling established that the final design has a pull-in voltage of 2.7 V, a closing time of 18 μs , a down-state capacitance C_{down} of 247 pF, and an up-state capacitance C_{up} of 9.6 fF. The comparison between the analytical model and the finite element modeling results showed good agreement for the main electromechanical parameters, confirming the validity of the selected approach to preliminary design calculation.

Electromagnetic simulation in ANSYS HFSS showed that in the frequency range of 2–4 GHz, the proposed switch provides insertion loss from -0.012 to -0.14 dB and isolation from -43.3 to -89.75 dB. The highest level of signal suppression is achieved near 2.8 GHz, which is associated with the resonant interaction between the equivalent shunt capacitance and the transmission-line parameters. The obtained results indicate that introducing a floating electrode is an effective way to improve isolation without reducing the interelectrode gaps to extremely small values.

Thus, the study confirms that the use of a floating electrode in a capacitive shunt RF MEMS switch is an effective design solution for achieving low-voltage actuation, a high capacitance ratio, and high isolation in the S-band. The developed design can be used in transceiver modules, reconfigurable filters, and other radio-frequency devices for which low power consumption, low signal loss, and high isolation are critical.

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DESIGN OF GaAs pHEMT FRONT-END MMIC FOR DOWNCONVERTER

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Abstract. This paper details the design of a multifunctional front-end microwave monolithic integrated circuit (MMIC) intended for downconverter applications in the 1–3 GHz frequency range. The primary objective of this research is to develop a compact, high-performance MMIC that integrates three critical receiver functions – a low-noise amplifier (LNA), a 2-bit digital attenuator, and a single-pole five-throw (SP5T) switch – on a single gallium arsenide (GaAs) pHEMT die using a domestic technological process. The LNA employs a two-stage cascaded common-source configuration with RC-feedback networks to achieve wideband matching and low noise. The digital attenuator is constructed using a bridged T-network for 6 dB attenuation and a Π -network for 12 dB attenuation. The SP5T switch utilizes a series-shunt topology with a five-way combining junction to minimize chip area. Electromagnetic simulation results for the complete front-end demonstrate excellent performance, achieving a gain of no less than 29.9 dB, a noise figure not exceeding 1.21 dB, and an input and output return loss better than -8.4 dB across the operating band. The linearity figures, a P1dB of 20.6 dBm and an OIP3 of 30.1 dBm, confirm its suitability for demanding receiver systems. Furthermore, a comparative analysis against commercial analogues shows that the designed MMIC offers a competitive combination of wide bandwidth, low noise, moderate current consumption (under 85 mA at 5 V), and a compact layout (3.4×3.2 mm), validating its potential as a viable domestic alternative for high-performance microwave modules.

Keywords: GaAs pHEMT, MMIC, front-end, LNA, attenuator, SP5T

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РАЗРАБОТКА МОНОЛИТНОЙ ИНТЕГРАЛЬНОЙ СХЕМЫ ВХОДНОГО СВЧ ТРАКТА ДЛЯ ПРЕОБРАЗОВАТЕЛЯ ЧАСТОТЫ НА ОСНОВЕ GaAs pHEMT

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Аннотация. В данной работе подробно описывается разработка многофункциональной входной СВЧ монолитной интегральной схемы (МИС), предназначенной для применения в понижающих преобразователях частоты в диапазоне 1–3 ГГц. Основной целью исследования является создание компактной высокопроизводительной МИС, интегрирующей три ключевые функции приёмного тракта – малошумящий усилитель (МШУ), 2-битный цифровой аттенюатор и коммутатор на пять направлений с одним общим входом (SP5T) – на одном кристалле GaAs pHEMT, изготовленном на основе отечественного технологического процесса. МШУ построен по двухкаскадной схеме с общим истоком с цепями RC-обратной связи для обеспечения широкополосного согласования и низкого уровня шума. Цифровой аттенюатор выполнен на основе мостовой Т-образной схемы для ослабления 6 дБ и П-образной схемы для ослабления 12 дБ. Коммутатор SP5T использует последовательно-параллельную топологию с пятиплечевым объединяющим узлом для минимизации площади кристалла. Результаты электромагнитного моделирования полного входного тракта демонстрируют превосходные характеристики: коэффициент усиления не менее 29,9 дБ, коэффициент шума не более 1,21 дБ и потери на отражение по входу и выходу лучше –8,4 дБ во всей рабочей полосе. Показатели линейности – точка компрессии по уровню 1 дБ, равная 20,6 дБм, и точка пересечения третьего порядка OIP3, равная 30,1 дБм, – подтверждают пригодность схемы для применения в требовательных приемных системах. Кроме того, сравнительный анализ с коммерческими аналогами показывает, что разработанная МИС обеспечивает конкурентоспособное сочетание широкой полосы пропускания, низкого уровня шума, умеренного потребления тока (менее 85 мА при 5 В) и компактной топологии (3,4×3,2 мм), что подтверждает ее потенциал в качестве отечественной альтернативы для высокопроизводительных СВЧ-модулей.

Ключевые слова: GaAs pHEMT, СВЧ монолитная интегральная схема, входной тракт, малошумящий усилитель, аттенюатор, коммутатор

Финансирование: Производство интегральной микросхемы было выполнено за счет средств Министерства науки и высшего образования Российской Федерации в рамках федерального проекта «Подготовка кадров и научного фундамента для электронной промышленности» по государственному заданию «Разработка методики прототипирования электронной компонентной базы на отечественных микроэлектронных производствах на основе сервиса MPW» (FSMR-2023-0008).

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Introduction

Modern radio engineering systems require the development of compact, highly efficient, and reliable building blocks, one of which is the frequency conversion module. A key trend in their design has been the use of microwave monolithic integrated circuits (MMICs) based on gallium arsenide (GaAs) pHEMT technology [1–3]. This technology provides an excellent combination of low noise, high gain, and good linearity in the microwave frequency range [4, 5].

Multifunctional MMICs, which integrate several devices on a single chip, are of particular practical interest. For example, an RF front-end (Fig. 1) comprising a low-noise amplifier (LNA), an attenuator, and a switch. The use of multifunctional MMICs enables significant reduction in module size, lower interconnection losses, improved repeatability of performance characteristics, and shortened design cycles – all of which underscore the relevance of this work [6–9].

Currently, the global semiconductor market faces a shortage of specialized solutions. Moreover, access to many foreign foundries producing GaAs-based MMICs is restricted. Therefore, particular emphasis is placed on expanding the range of MMICs manufactured using domestic technological processes (for instance, at JSC Svetlana-Rost) [10–12].

This paper examines the features of the design of a multifunctional front-end MMIC in the 1–3 GHz frequency range based on domestic GaAs pHEMT technology using integrated design tools for solid-state microwave devices (PDK_pHEMT05D).

The aim of this work is to design the topology of the front-end MMIC using domestic GaAs pHEMT technology, which integrates the functions of a LNA, a 2-bit attenuator, and a single-pole 5-throw (SP5T) switch.

The required specifications for the front-end MMIC are as follows:

- operating frequency range: 1–3 GHz;
- minimum gain: 25 dB;
- adjustable gain control within the range of 0–18 dB with a step of 6 dB;
- noise figure (NF) not exceeding 1.3;
- current consumption not exceeding 90 mA at a supply voltage of 5 V.

To achieve this aim, the following research tasks were formulated:

1. To conduct a comparative analysis of LNA, digital attenuator and switch to determine suitable structure of each subcircuit.

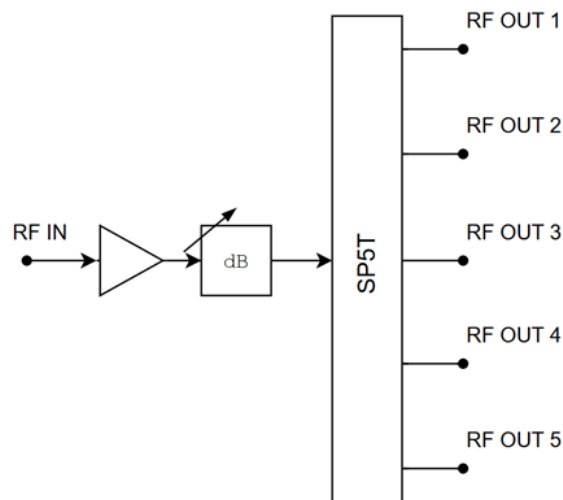


Fig. 1. Front-end block diagram

2. To calculate periphery of key elements (transistors, inductors, capacitors) to ensure the required specifications.

3. To evaluate the key electrical parameters (S-parameters, NF, P_{idB}) of whole front-end circuit through electromagnetic simulation and compare them with existing analogs.

LNA

LNAs are critical front-end components in any receiver system, responsible for amplifying weak signals received from the antenna while adding minimal noise.

The most fundamental challenge in LNA design is the inherent trade-off between noise and power matching. The minimum noise figure (NF_{min}) occurs at a specific source reflection coefficient Γ_{opt} , while maximum power transfer (minimum input return loss) requires the source impedance to be the complex conjugate of S_{11} ($\Gamma_s = S_{11}^*$). These two impedance points are generally different for a given transistor [13, 14].

The noise figure of a two-port can be expressed as:

$$NF = NF_{min} + \frac{4R_n}{Z_0} \cdot \frac{|\Gamma_s - \Gamma_{opt}|^2}{(1 - |\Gamma_s|^2) \cdot (|1 + \Gamma_{opt}|^2)}, \quad (1)$$

where R_n is the equivalent noise resistance and Z_0 is the characteristic impedance [15]. This equation shows that any deviation from Γ_{opt} increases the noise figure.

The most widely used technique to reconcile noise and input matching is source degeneration – a small inductor placed between the source terminal of the pHEMT and ground [13, 14, 16]. This inductive feedback has several beneficial effects:

1. It shifts Γ_{opt} toward the conjugate of S_{11}^* on the Smith chart, enabling simultaneous noise and power match.
2. It improves amplifier stability by increasing the Rollett stability factor [17]:

$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2|S_{12}S_{21}|}; \quad (2)$$

$$\Delta = S_{11}S_{22} - S_{12}S_{21} \quad (3)$$

and supplemental stability factor:

$$B1 = 1 + |S_{11}|^2 - |S_{22}|^2 - |\Delta|^2. \quad (4)$$

3. It reduces the noise resistance R_n , making the noise figure less sensitive to impedance mismatch.

The most prevalent topology for GaAs pHEMT LNAs is the multi-stage cascaded common-source (CS) amplifier. This approach is used from S-band through Ka-band and beyond. RC-feedback topology is used for wideband matching. Since the feedback is negative, there is an accompanying decrease in gain with increasing feedback. Therefore, a compromise is generally made between the amount of improvement in VSWR/noise figure and the gain reduction one is willing to take [18].

The transistor gate width selection involves trade-offs between noise figure, gain, and power consumption. Smaller devices offer lower noise but also lower gain, while larger devices provide higher gain and better linearity at the cost of higher current consumption and noise [19].

Unconditional stability ($K > 1$ and $B1 > 0$ for all frequencies) is a mandatory requirement. Several stabilization techniques are employed:

- Source degeneration inherently improves stability [14].
- Series resistors at the drain output improve stability but reduce gain and increase noise, so they are typically used in later stages [15].

- RC networks (lossy match) are used in bias circuits to suppress low-frequency oscillations [18].

After comparative study of LNA, a stage-level design methodology is proposed:

1. **First stage:** optimized for minimum noise figure at the input, using source degeneration and noise-matched input network. Common approach for the first stage is to bias the transistor at approximately 10–30% of its saturation current (I_{dss}). Lower drain current generally yields lower NF_{min} but also lower gain, so a compromise must be found. The input matching networks must transform the $50\ \Omega$ source impedance to Γ_{opt} for minimum noise, while also providing reasonable return loss. Common techniques include:

- LC ladder networks;
- self-biased networks that simultaneously provide DC bias and RF matching;
- lossy match (resistive elements) to improve gain flatness at the expense of some increase in noise figure.

2. **Intermediate stages:** designed to provide maximum gain while maintaining flat frequency response. Interstage matching networks are carefully designed to maximize power transfer between stages while maintaining flat gain across the band.

3. **Final stage:** often uses a larger transistor and may be optimized for output power and linearity rather than noise.

The schematic of designed LNA is presented in Fig. 2. To achieve MMIC specifications two stages of CS transistors were used. Instead of using source degeneration and classic LC ladder networks, RC-feedbacks were implemented. This technique reduces number of inductors needed for transistor matching which leads to minimizing LNA topology.

It was calculated, that the best compromise between noise figure and gain is obtained when the first transistor has a periphery of $8 \times 45\ \mu\text{m}$ and is operated at 24.4 mA current, which is achieved with a drain-source voltage V_{d1} of 5 V and a gate-source voltage V_{g2} of $-1.1\ \text{V}$. At the next step, the bias networks (C2, C3, L2, R1, R3, R4), negative feedback network (C4, R2) were optimized for the best noise figure and highest associated gain.

The transistor dimensions of the second stage are taken higher than the first stage ($8 \times 80\ \mu\text{m}$ instead of $8 \times 45\ \mu\text{m}$) in order to improve the linearity of the amplifier. The bias conditions of the second stages

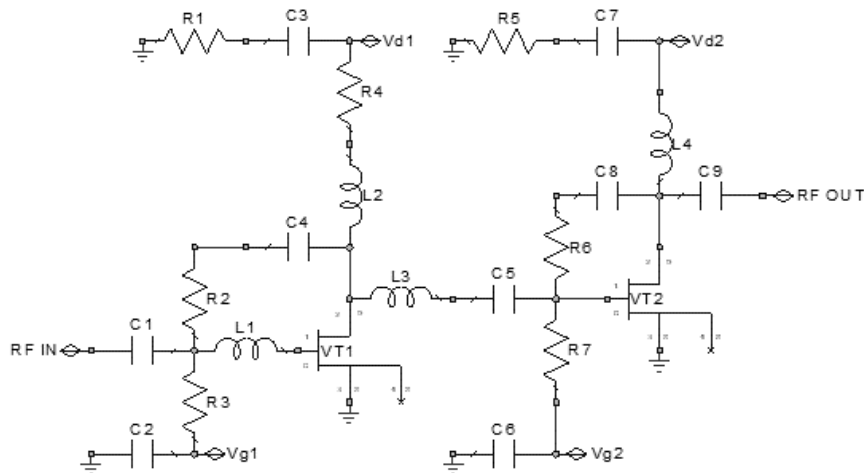


Fig. 2. Simplified schematic of LNA

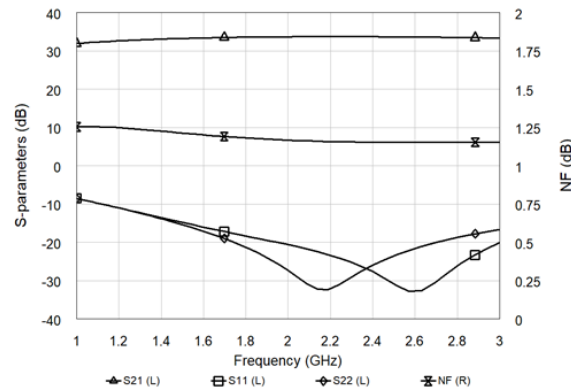


Fig. 3. S-parameters and NF of LNA

are identical ($V_{d2} = 5$ V and $V_{g2} = -1.1$ V, $I = 59.1$ mA). The bias networks (C6, C7, L4, R5, R7), negative feedback network (C8, R6) and interstage matching network (L3, C5) were optimized to achieve flat gain and highest linearity. Capacitors C1 and C9 are used for DC-blocking.

Simulation results of the designed LNA are presented in Fig. 3. Gain (S21) is no less than 31.8 dB, input and output return loss (S11 and S22) are less than -8 dB and NF does not exceed 1.26 dB.

The 1 dB compression point P_{1dB} of the LNA is 21.2 dB at 2GHz and the output third intercept point OIP3 for two close frequencies is 32.2 dB. Total current consumption is 83.5 mA at 5 V.

Digital attenuator

These devices provide precise, digitally controlled attenuation of RF signals with advantages over analog attenuators in terms of linearity, accuracy, thermal stability, and ease of control.

In digital attenuators, the GaAs pHEMT is operated in cold-FET mode (drain-source voltage is 0 V), where it functions as a voltage-variable resistor controlled by the gate voltage. When the gate voltage is 0 V, the channel is fully open and the drain-source resistance R_{on} is low (typically a few ohms). When the gate voltage is below the pinch-off voltage (e.g., -5 V), the channel is fully depleted and the device behaves as a small capacitor C_{off} in parallel with a large resistor.

The choice of pHEMT gate periphery (gate width W_g) involves a critical trade-off [20–23]:

- larger W_g leads to lower R_{on} , which means lower insertion loss and higher power handling;
- smaller W_g leads to lower C_{off} , which means better high-frequency isolation and broader bandwidth.

Digital attenuators are constructed by cascading individual attenuation bits, each providing a fixed binary-weighted attenuation value (e.g., 0.5, 1, 2, 4, 8, 16 dB). Different topologies are suited to different attenuation values and operating frequencies.

The switched T-type topology [20] consists of a series pHEMT switch (FET1), a shunt pHEMT switch (FET2), and two identical resistors (R1) in the series arms, plus a shunt resistor (R2) to ground. In the reference (low-loss) state, FET1 is ON and FET2 is OFF, providing a low-resistance path. In the attenuation state, FET1 is OFF and FET2 is ON, routing the signal through the resistive T-network to ground. This topology offers low insertion loss and good high-frequency capability because it uses a small number of devices with minimal parasitic capacitances. It is typically employed for small attenuation bits (1 and 2 dB).

For very small attenuation values (0.25, 0.5, and 1 dB), a simplified T-type topology omits the series switch transistor and one of the series resistors to reduce insertion loss [21, 22]. In this configuration, only a shunt pHEMT switch and a single resistor are used. When the shunt switch is OFF, the signal passes with minimal loss. When the shunt switch is ON, signal is partially shunted to ground through the resistor, creating the desired attenuation.

The bridged T configuration adds a series pHEMT switch across the two series resistors of the T-network, with a shunt switch connected to ground through a resistor [20, 22]. The bridged T offers a good trade-off between insertion loss, attenuation accuracy, and bandwidth. An appropriate series inductance can be added to create a resonant effect that improves isolation at high frequencies.

The Π -type attenuator uses a series pHEMT switch and two shunt pHEMT switches, along with three resistors [21–23]. Compared to the T-type, the Π -type can provide larger attenuation while maintaining good input/output return loss (VSWR), but occupies larger chip area at low microwave frequencies compared to T-type designs. It is therefore commonly used for medium-value bits such as 4 dB and 8 dB.

For the largest attenuation bits (typically 8 or 16 dB), the switched-path topology is often the preferred choice [22, 23]. This configuration uses two SPDT (Single-Pole Double-Throw) switches to select between a reference path (low-loss transmission line) and an attenuation path comprising a fixed resistive Π -network. This approach provides superior bandwidth and very low insertion phase shift between states, because the phase through the reference path can be compensated using a microstrip line of appropriate length.

Based on the reviewed literature, a design procedure for GaAs pHEMT digital attenuators can be summarized:

1. Select topologies per bit:
 - 0.25–1 dB: simplified T-type or switched T;
 - 2 dB: switched T or cascade of two 1 dB bits;
 - 4 dB: bridged T or Π -type;
 - 8 dB: Π -type or cascade of two 4 dB bits;
 - 16 dB: switched-path with SPDT switches or cascade of two 8 dB bits.
2. Calculate initial resistor values using standard formulas [24].
3. Select pHEMT sizes considering the trade-off between ON-resistance (insertion loss) and OFF-capacitance (bandwidth/isolation).
4. Place bits with better return loss at the input and output of the cascade to improve overall VSWR.
5. Perform EM simulation of the passive network (including all interconnect parasitics and via holes), optimize transmission-line dimensions and resistor values.

The functional assembly of the designed attenuator includes two sections with nominal attenuation of 6 dB and 12 dB respectively. Bridged T-network for 6 dB attenuation (Fig. 4, *a*) and Π -network for 12 dB attenuation (Fig. 4, *b*) were chosen to achieve a good trade-off between insertion loss, VSWR and attenuation accuracy.

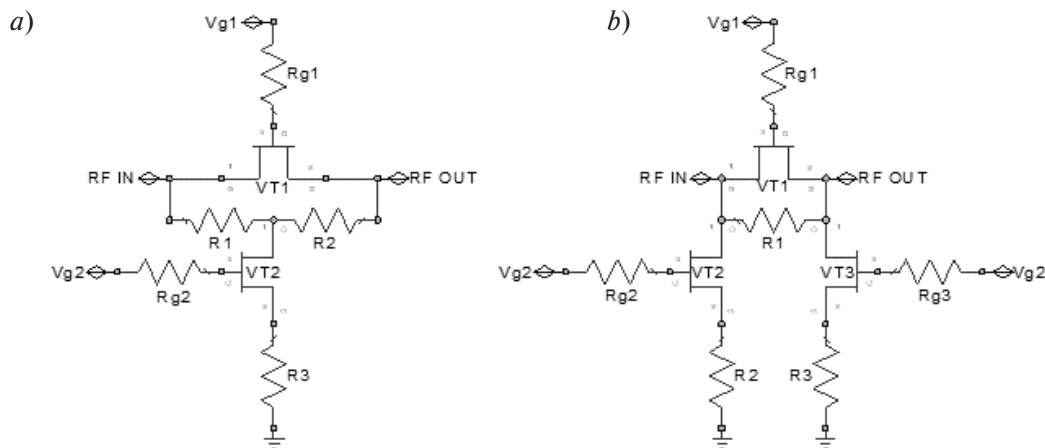


Fig. 4. Simplified circuits of attenuator sections: bridged T-network (*a*); Π -network (*b*)

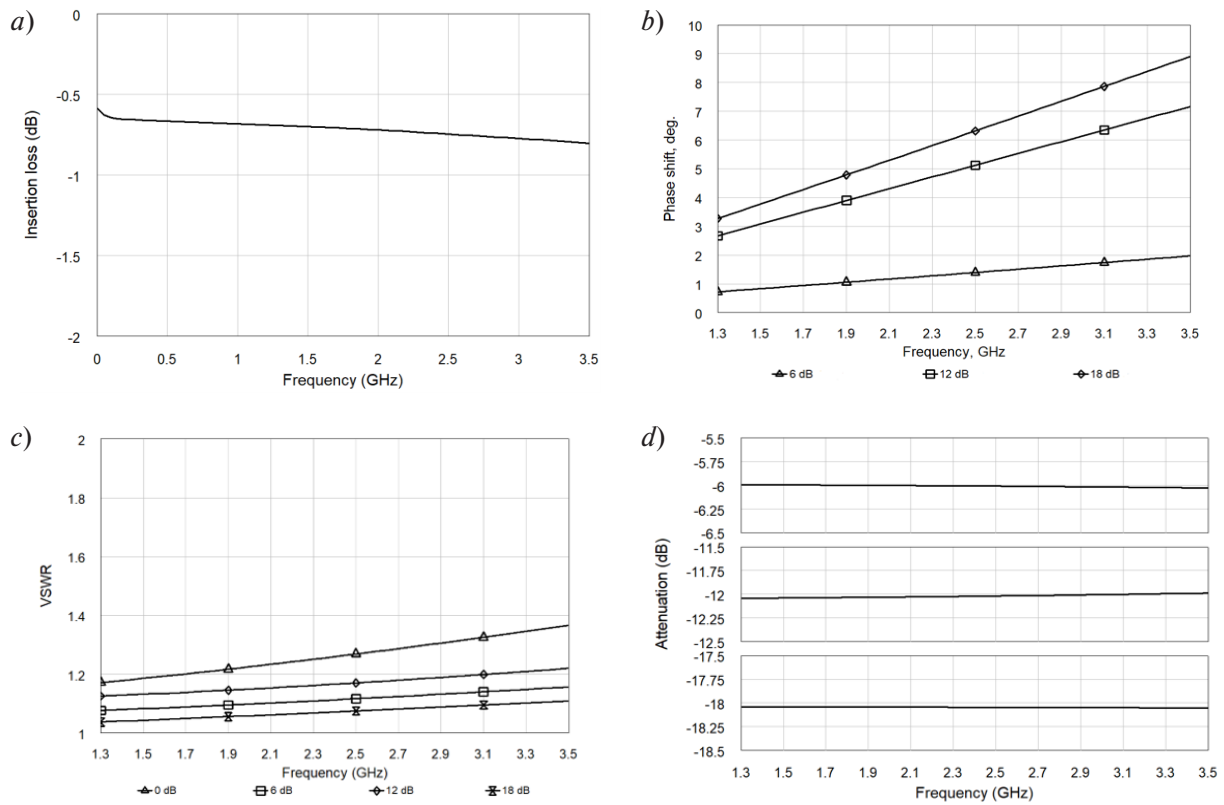


Fig. 5. Simulation results: insertion loss (a); phase shift (b); VSWR (c); attenuation (d)

Each section consists of switching FETs and metal film resistors. Element parameters obtained using parametric optimization are provided in Table 1. Large-valued gate resistors R_g (4.5 k Ω) are used to prevent RF leakage through bias lines while maintaining DC isolation.

Table 1

Element parameters

Element	T-network	Π -network
VT1	8×100 μm	8×50 μm
VT2	2×25 μm	2×30 μm
VT3	—	2×30 μm
R1	17.8 Ω	83.3 Ω
R2	17.8 Ω	16.7 Ω
R3	4 Ω	16.7 Ω

The results of the analysis of the attenuator are shown in Fig. 5. Insertion loss is less than 0.9 dB, VSWR is less than 1.4 and phase shift between reference state and attenuation states does not exceed 9 degrees.

SP5T switch

The design of such Single-Pole-Multi-Throw (SPMT) switches involves careful consideration of the circuit topology, device sizing, layout techniques, and matching networks to achieve low insertion loss, high isolation and good VSWR.

The FET gate periphery determines RF characteristics of a switch the same way as described for attenuators: large W_g decrease R_{on} (lower insertion loss) but increase C_{off} (lower isolation at high frequencies). Conversely, small W_g increase R_{on} (higher insertion loss) but decrease C_{off} (better isolation).

The choice of topology depends on the required number of throws, frequency band, and performance specifications.

The simplest switch topology uses a series-connected switch device in each branch. In SPDT form, when branch 1 is ON and branch 2 is OFF, the signal passes through the ON FET (low R_{on}) while the OFF FET presents a high impedance. However, at higher frequencies, the C_{off} of the shunt path provides a leakage path, degrading isolation [25].

In shunt-type switches, the FET is connected from the transmission line to ground. When the FET is ON, it creates a short circuit to ground, providing high isolation. When OFF, it presents a small capacitance that is resonated out by inductive elements or absorbed into the transmission line impedance [26, 27].

Combining series and shunt FETs in each branch yields the best trade-off between insertion loss and isolation. This topology is the most common for high-performance SPMT switches. The series FET provides the main signal path control, while the shunt FET to ground improves OFF-state isolation by providing a low-impedance path for leakage signals [28, 29].

For SPMT switches, the design challenges include:

- maintaining consistent channel-to-channel performance;
- managing layout parasitics due to increased routing complexity;
- ensuring impedance matching at the common junction.

Based on the reviewed literature, a design procedure for GaAs pHEMT SPMT switch is proposed:

1. Choose branch topology (series, shunt or series-shunt type);
2. Optimize pHEMT sizes considering the trade-off between insertion loss and bandwidth/isolation.
3. Match input and outputs for desired impedance.
4. Perform EM simulation of the passive network (including all interconnect parasitics and via holes).

The schematic of designed SP5T switch is presented in Fig. 6. Simulation showed that for 1–3 GHz frequency range series-shunt FET topology is the best choice for SPST branch. In order to reduce chip, the five-way combining junction is used instead of design SPDTs and directly connecting them to form SP5T switch. Each branch consists of $4 \times 60 \mu\text{m}$ series FET and $4 \times 80 \mu\text{m}$ shunt FET. Inductors

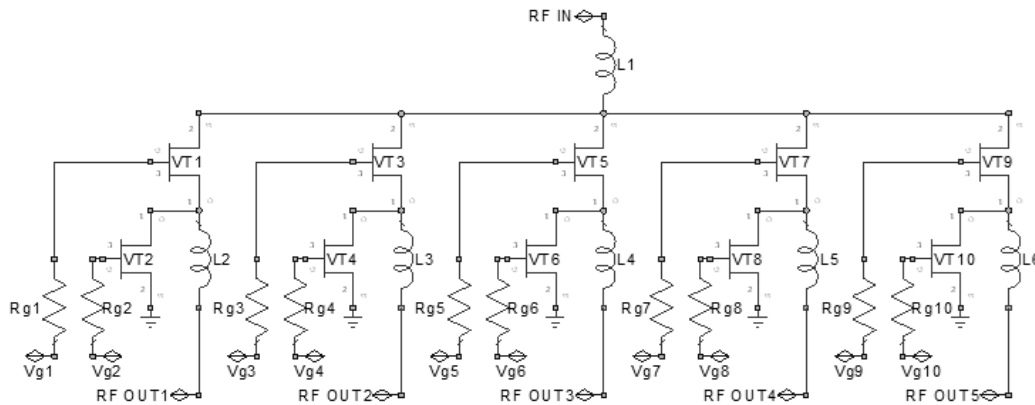


Fig. 6. Simplified schematic of SP5T switch

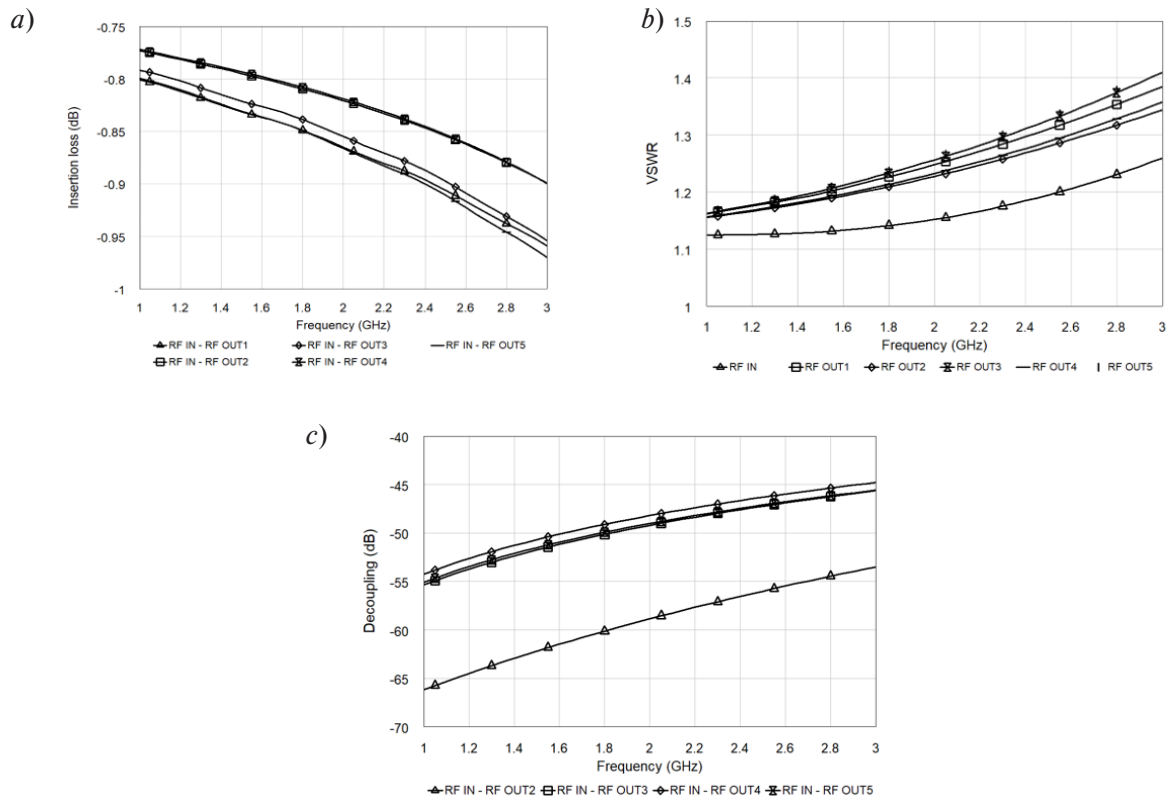


Fig. 7. Simulation results: insertion loss (a); VSWR (b); decoupling (c)

L1–L6 matches input and output of the circuit to 50Ω ($L1 = 0.68 \text{ nH}$, $L2\text{--}L6 = 0.41 \text{ nH}$). The nominal for all gate resistors is the same as for the designed 2-bit attenuator ($4.5 \text{ k}\Omega$ for $R_{g1}\text{--}R_{g10}$).

Simulation results of the designed SP5T switch are presented in Fig. 7. Insertion loss is less than 1 dB, VSWR is less than 1.5 and decoupling does not exceed -44 dB .

Front-end

The layout of the designed front-end is presented in Fig. 8. The MMIC dimensions are $3.4 \times 3.2 \text{ mm}$. The microwave outputs were spaced in such a way as to simplify the routing of the printed circuit board traces to the MMIC.

The circuit design, simulation and optimization were performed using AWR Design Environment. Electromagnetic analysis of the passive structures conducted using AXIEM simulator. The results of the analysis of the designed front-end in the small-signal mode is demonstrated in Fig. 9. Gain ($|S_{21}|$) is no less than 29.9 dB, input and output return loss ($|S_{11}|$ and $|S_{22}|$) are less than -8.4 dB and NF does not exceed 1.21 dB.

The 1 dB compression point $P_{1\text{dB}}$ of the front-end is 20.6 dB at 2 GHz and the output third intercept point OIP3 for two close frequencies is 30.1 dB. Total current consumption is less than 85 mA at 5 V.

A comparison of the results shows that the main parameters of the designed front-end are comparable to foreign analogues, and in some cases even surpasses them. For example, the Qorvo QPM2101¹ GaAs multi-chip operates over 2.5–4 GHz frequency range, has a comparable gain (30 dB typical) and superior NF (1 dB typical). It has wider gain control range (0–31.5 dB with 0.5 dB step) than the designed front-end. However, Qorvo's chip has significantly larger dimensions ($7.0 \times 7.0 \text{ mm}$), poor linearity level ($P_{1\text{dB}}$ is 14 dBm at 3.1 GHz), and total current consumption reaches 175 mA at 3.3 V.

¹ Multi-Chip T/R Module. QPM2101. [online] Available: <https://www.qorvo.com/products/p/QPM2101> (Accesses: 25.06.2026).

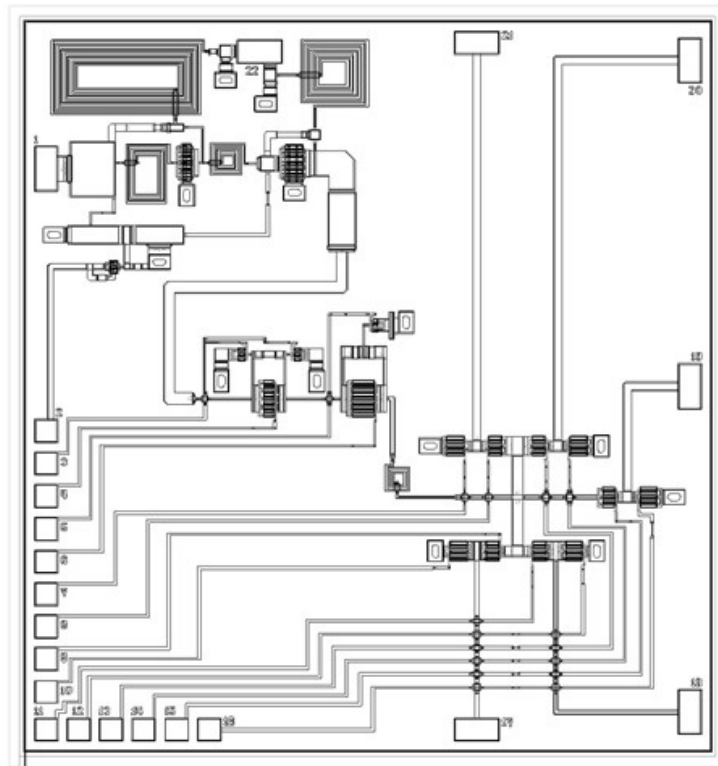


Fig. 8. Layout of front-end

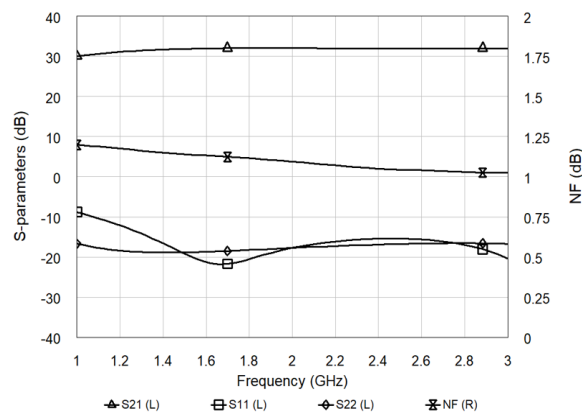


Fig. 9. S-parameters and NF of front-end

Another analogue, ADRF5549, the dual-channel front-end from Analog Devices², incorporating chips on Si and GaAs processes, has the highest gain (35 dB at 2.3 GHz), comparable NF (1.4 dB at 2.3 GHz) and linearity (P_{1dB} is 19 dB at 2.4 GHz), but the shortest operating frequency range (1.8–2.8 GHz), poor gain control (17–35 dB with only 1 step) and larger dimensions (6.0×6.0 mm). Current consumption is the same as for the designed front-end (85 mA at 5 V).

² Receiver Front End. ADRF5549. [online] Available: <https://www.analog.com/en/products/ADRF5549.html> (Accesses: 25.06.2026).

Conclusion

As a result of this research, a multifunctional front-end for downconverter applications in the 1–3 GHz frequency range was designed using domestic GaAs pHEMT technology. The designed MMIC integrates a LNA, a 2-bit digital attenuator, and a SP5T switch on a single die, achieving a compact layout of 3.4×3.2 mm. A stage-level design methodology was proposed for the LNA, combining RC-feedback networks and optimized transistor peripheries to meet required specifications. The attenuator sections were realized using bridged T- and Π -networks, while the SP5T switch employed a series-shunt topology with a five-way combining junction to minimize chip area.

The simulated performance of the complete front-end meets all specified targets: gain is no less than 29.9 dB, NF is no more than 1.21 dB, input and output return loss better than –8.4 dB, and total current consumption below 85 mA at 5 V. The linearity figures ($P_{1dB} = 20.6$ dBm, OIP3 = 30.1 dBm) confirm its suitability for modern receiver systems.

A comparative analysis with commercial analogues (QPM2101 and ADRF5549) demonstrates that the designed MMIC offers a competitive combination of wide operating bandwidth, low noise, moderate current consumption, and compact size. While some analogues provide wider gain control ranges or slightly higher gain, they often suffer from larger dimensions, inferior linearity, or narrower frequency coverage. The proposed front-end thus represents a viable domestic alternative, highlighting the potential of local GaAs pHEMT processes for high-performance MMICs.

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APPLICATION OF OPTIMAL AMPLITUDE-PHASE MODULATION SIGNALS IN CHANNELS WITH DOPPLER FREQUENCY SHIFT

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Abstract. The paper addresses the problem of improving the spectral efficiency of radio communication systems operating in channels with Doppler frequency shift by employing optimal signals with amplitude-phase modulation. The relevance of the study is driven by the need for high data rate transmission in low-Earth orbit satellite communication systems, where conventional signals based on RRC pulses exhibit significant energy losses when the symbol rate is increased. A synthesis technique for optimal shaping pulses is proposed, based on the criterion of out-of-band emission suppression under given constraints on the cross-correlation coefficient that determines the BER performance. A computer simulation model of the transmission channel is developed, taking into account carrier frequency instability, timing synchronization offset, and Doppler shift modeled with time-scale transformation. Numerical simulations for 64APSK constellation and coding rate 4/5 demonstrate that the use of optimal signals with doubled symbol rate provides a spectral efficiency gain of up to 12.7% compared to RRC-based signals when the occupied bandwidth is estimated by the 99% energy concentration criterion. The associated energy penalties range from 3 to 4 dB depending on the satellite elevation angle, which is attributed to the need for wider receiver front-end bandwidth under Doppler-induced spectral distortions. It is shown that the choice of the cross-correlation coefficient enables a trade-off between BER performance and spectral efficiency. The obtained results confirm the feasibility of optimal signals in satellite communication systems with high spectral efficiency requirements and limited link power budgets.

Keywords: optimal signals, APSK, Doppler shift, spectral efficiency, satellite communications, FTN, DVB-S2X

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ПРИМЕНЕНИЕ ОПТИМАЛЬНЫХ СИГНАЛОВ С АМПЛИТУДНО-ФАЗОВОЙ МОДУЛЯЦИЕЙ В КАНАЛАХ С ДОПЛЕРОВСКИМ СМЕЩЕНИЕМ ЧАСТОТЫ

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Аннотация. Рассмотрена задача повышения спектральной эффективности радиотехнических систем передачи сообщений в каналах с доплеровским смещением частоты на основе применения оптимальных сигналов с амплитудно-фазовой модуляцией. Актуальность исследования обусловлена необходимостью обеспечения высоких скоростей передачи данных в системах связи с низкоорбитальными космическими аппаратами, где традиционные сигналы с формирующими импульсами типа RRC демонстрируют значительные энергетические потери при попытке увеличения символьной скорости. Предложена методика синтеза оптимальных амплитудных импульсов на основе критерия минимизации внеполосных излучений при заданных ограничениях на коэффициент корреляции, определяющий помехоустойчивость приема. Разработана компьютерная имитационная модель канала передачи, учитывающая нестабильность несущей частоты, сдвиг временной синхронизации и доплеровское смещение, моделируемое с учетом масштабирования временной шкалы сигнала. В ходе численного моделирования для сигнального созвездия 64APSK и скорости кодирования 4/5 установлено, что применение оптимальных сигналов с удвоенной символьной скоростью обеспечивает прирост спектральной эффективности до 12,7% по сравнению с RRC-сигналами при оценке полосы частот по критерию концентрации 99% энергии. При этом энергетические потери составляют 3–4 дБ в зависимости от угла возвышения космического аппарата, что обусловлено необходимостью расширения полосы пропускания приемных трактов в условиях доплеровских искажений. Показано, что выбор значения коэффициента взаимной корреляции позволяет управлять компромиссом между помехоустойчивостью и спектральной компактностью сигнала. Полученные результаты подтверждают целесообразность использования оптимальных сигналов в системах спутниковой связи с высокими требованиями к спектральной эффективности и ограниченным энергетическим бюджетом радиолинии.

Ключевые слова: оптимальные сигналы, APSK, доплеровский сдвиг, спектральная эффективность, спутниковая связь, FTN, DVB-S2X

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Introduction

The efficiency of radio communication systems is determined by their spectral and energy performance relative to the Shannon limit [1, 2]. Approaching this limit is achieved, among other techniques, through the application of Faster-Than-Nyquist (FTN) concepts [3–6]. The fundamental

idea of FTN signaling is to increase the symbol rate R , i.e., to pack a larger number of modulation symbols into a limited time resource. In general, increasing the symbol rate R leads to a higher degree of non-orthogonality of the transmitted signals, which may result in significant degradation of BER performance.

These effects raise the question of how to approach the Shannon limit when using FTN technology. By approaching the Shannon limit, we mean increasing the spectral efficiency $R_b/\Delta F$, where ΔF is the occupied frequency bandwidth and $R_b = R \cdot \log_2(M)$ is bit rate (M is channel alphabet size, which determines the number of bits per symbol), while minimizing energy losses. It is known that increasing the symbol rate to $R > 1.1/T$ with RRC pulses leads to a sharp deterioration in BER performance [7, 8], which prevents the desired approach to the Shannon limit.

Additional opportunities for reducing energy losses are provided by the use of optimal spectrally efficient signals [7–9]. Such signals, depending on the chosen optimization criterion, allow synthesizing shaping pulse waveforms of various durations under constraints on BER performance (correlation properties) and the peak-to-average power ratio (PAPR) of the radiated oscillations [10, 11]. The use of optimal signals ensures a proximity to the Shannon limit. Evaluations of these performance metrics have been considered for channels with constant parameters and limited frequency bandwidth under additive white Gaussian noise (AWGN) with power spectral density $N_0/2$. However, evaluations of the spectral and energy efficiency of optimal signals have not been performed for communication channels involving Doppler frequency shift (for example, low-Earth orbit satellite communication systems). This work fills this gap, and **its aim** is to analyze the spectral and energy performance of a radio communication system using optimal APSK signals in the presence of Doppler shift.

Representation of optimal signals with APSK

In general form, a sequence of N APSK signals of duration $T_a = LT$, $L \in \mathbb{N}$ with amplitude A_0 and carrier frequency f_0 , can be written as [7, 8, 10]:

$$y(t) = \text{Re} \left\{ A_0 \sum_{k=0}^{N-1} c^{(k)} a(t - k\xi T) \exp \left(j2\pi \left\{ f_0 + \Delta f(f_{s(f)}, t) \right\} t \right) \right\}, \quad (1)$$

where $0 \leq t \leq NT$, $a(t)$ is shaping pulse function, $c(k)$ is the channel alphabet symbols transmitted at symbol rate $R = 1/\xi T$, $0 < \xi \leq 1$, $\Delta f(f_{s(f)}, f)$ is the Doppler frequency shift.

The Doppler frequency shift $\Delta f(f_{s(f)}, f)$ is determined by the position of the low-Earth orbit (approximately 500 km) small satellite (CubeSat) relative to the ground station and depends both on the satellite velocity and on the bandwidth (shape) of the spectrum $S(f)$ of the shaping pulse.

As shown in [7, 8, 10], the shaping pulse $a(t)$ can be chosen as an optimal function obtained according to the criterion of a fixed out-of-band emission decay rate under constraints on BER performance (correlation properties). We can write the functional as:

$$\arg \min_{a(t)} J, \quad J = \frac{1}{2\pi} \int_{-\infty}^{\infty} g(f) |S_a(f)|^2 df, \quad g(f) = f^{2n}, \quad n = 1, 2, 3, \dots, \quad (2)$$

$$S_a(f) = \int_{-\frac{T_a}{2}}^{\frac{T_a}{2}} a(t) \exp(-j2\pi ft) dt,$$

where $g(f)$ is function, which assigns a certain weighting coefficient to each part of the spectrum. Obviously, the values of function should be as small as possible within the required frequency band and as large as possible outside it. The most convenient choice for the nuisance function is an even-degree

parabola $g(f) = f^{2n}$, where $n = 1, 2, 3, \dots$ is a parameter determining the degree of out-of-band emission suppression.

The function $a(t)$ can be represented on a symmetric time interval using a limited Fourier series:

$$a(t) = \frac{a_0}{2} + \sum_{k=1}^{m-1} a_k \cos\left(\frac{2\pi}{T_a} kt\right). \quad (3)$$

The following constraints must be taken into account:

- Boundary conditions on the pulse shape:

$$a^{(k)}(t) \Big|_{t=\pm T_a/2} = 0, \quad k = 1 \dots (n-1);$$

- Normalized energy constraint:

$$\int_{-T_a/2}^{T_a/2} a^2(t) dt = 1;$$

- BER performance constraint (K_0 is the threshold cross-correlation coefficient, η is determined by the modulation scheme):

$$\eta \max_{k=1 \dots (L-1)} \left\{ \int_{k\xi T}^{LT} a(t) a(t - k\xi T) dt \right\} < K_0.$$

The shapes of optimal amplitude pulses and their corresponding energy spectra (Fig. 1) were obtained using an iterative optimization technique [7, 8, 10]. The optimal pulses were designed for 64APSK modulation, pulse duration $8T$, out-of-band decay rate $n = 2$, symbol rate $R = 2/T$, and coding rate $4/5$. The correlation coefficient constraint ranged from $K_0 = 0.001$ to $K_0 = 0.050$. The time-domain and frequency-domain representations of RRC pulses ($\beta = 0.35$) are shown for comparison in Fig. 1.

The symbol rate for optimal signals is twice as high. Obviously, the spectrum width of such optimal signals is also wider than that of signals based on RRC pulses. However, the out-of-band emission level is controllable for optimal signals and turns out to be lower compared to RRC signals. This feature is important for multi-channel satellite communication systems with frequency-division multiplexing of several information channels.

It is necessary to choose a criterion for determining the occupied frequency bandwidth ΔF to evaluate the degree of spectral efficiency approaching the Shannon limit. It should be noted that the quantitative results of the proximity to the Shannon curve depend significantly on the choice of this parameter. One option is the energy concentration criterion in the frequency domain, e.g., at the 85% or 99% level.

Table 1 presents the estimated occupied bandwidth ΔF . Table 2 shows the corresponding spectral efficiency $R_b/\Delta F$ values for the cases of bandwidth determination by 85–99% energy concentration. The estimates were obtained for 64APSK modulation without error-correcting coding and pilot symbols.

As can be seen from Table 2, there is a significant dependence of spectral efficiency on the choice of occupied frequency bandwidth. Optimal signals provide the maximum difference in spectral efficiency equal to 12.7% relative to RRC signals in case of bandwidth determination by the 99% energy concentration level. At the same time, the BER performance in channels with constant parameters and AWGN is approximately the same [7].

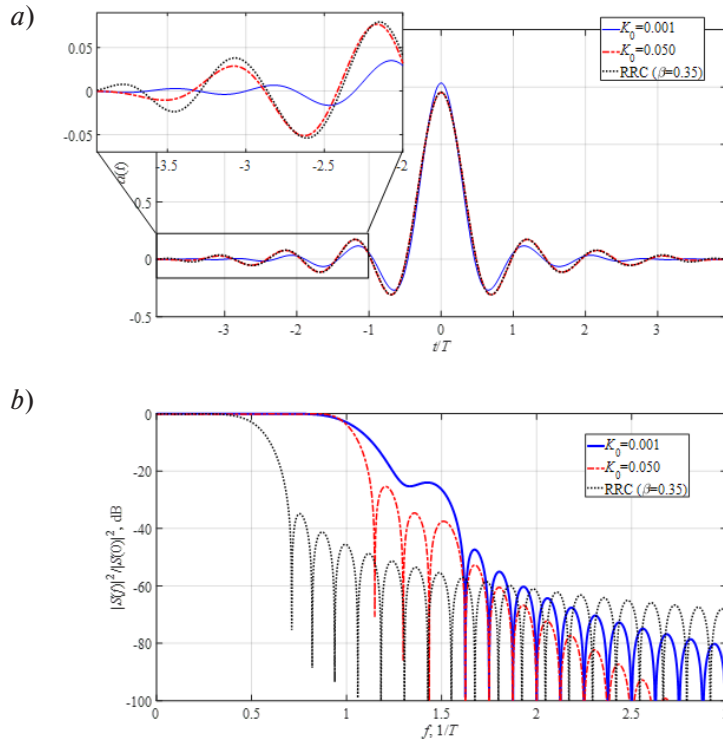


Fig. 1. Optimal pulses (a) and corresponding energy spectra (b)

Table 1

 Occupied frequency bandwidth ΔF by energy concentration level

	RRC, $R = 1/T$	Optimal signals, $R = 2/T$				
		$K_0 = 0.001$	$K_0 = 0.010$	$K_0 = 0.025$	$K_0 = 0.032$	$K_0 = 0.050$
$\Delta F_{99\%}, 1/T$	1.155	2.203	2.065	2.059	2.059	2.049
$\Delta F_{95\%}, 1/T$	1.024	1.973	1.912	1.907	1.905	1.895
$\Delta F_{90\%}, 1/T$	0.935	1.826	1.798	1.793	1.791	1.784
$\Delta F_{85\%}, 1/T$	0.867	1.709	1.698	1.694	1.692	1.686

Table 2

 Spectral efficiency $R_b/\Delta F$ for ΔF determined by energy concentration

	RRC, 64APSK, $R = 1/T$	Optimal signals, 64APSK, $R = 2/T$				
		$K_0 = 0.001$	$K_0 = 0.010$	$K_0 = 0.025$	$K_0 = 0.032$	$K_0 = 0.050$
$R_b/\Delta F_{99\%}, (\text{bit/s})/\text{Hz}$	5.195	5.447	5.811	5.828	5.828	5.857
$R_b/\Delta F_{95\%}, (\text{bit/s})/\text{Hz}$	5.859	6.082	6.276	6.293	6.299	6.332
$R_b/\Delta F_{90\%}, (\text{bit/s})/\text{Hz}$	6.417	6.572	6.674	6.693	6.700	6.726
$R_b/\Delta F_{85\%}, (\text{bit/s})/\text{Hz}$	6.920	7.022	7.067	7.084	7.092	7.117

Another option for determining ΔF is the criterion based on the normalized energy spectrum level. Table 3 presents the bandwidth values calculated at the -60 dB and -70 dB levels of the normalized energy spectrum of optimal signals for various values of the cross-correlation coefficient K_0 . As can be seen from comparing Tables 1 and 3, when the bandwidth is determined by the energy spectrum level, the bandwidth values are more than twice as large as those obtained using the energy concentration criterion.

Table 3

Occupied frequency bandwidth ΔF by levels of the normalized energy spectrum

	RRC, $R = 1/T$	Optimal, $R = 2/T$				
		$K_0 = 0.001$	$K_0 = 0.010$	$K_0 = 0.025$	$K_0 = 0.032$	$K_0 = 0.050$
$\Delta F_{-60 \text{ dB}}, 1/T$	$3.74/T$	$3.84/T$	$5.30/T$	$4.92/T$	$3.74/T$	$3.56/T$
$\Delta F_{-70 \text{ dB}}, 1/T$	$6.72/T$	$4.54/T$	$6.90/T$	$6.16/T$	$4.436/T$	$3.98/T$

Table 4 presents the spectral efficiency values for ΔF determined by the energy spectrum level. Comparing the spectral efficiency values (Tables 2 and 4), it is evident that the numerical spectral efficiency decreases by a factor of 2–3 when the bandwidth is determined by the energy spectrum levels.

Table 4

Spectral efficiency $R_b/\Delta F$ for ΔF determined by levels of the normalized energy spectrum

	RRC, 64APSK, $R = 1/T$	Optimal, 64APSK, $R = 2/T$				
		$K_0 = 0.001$	$K_0 = 0.010$	$K_0 = 0.025$	$K_0 = 0.032$	$K_0 = 0.050$
$R_b/\Delta F_{-60 \text{ dB}}, (\text{bit/s})/\text{Hz}$	1.60	3.13	2.26	2.43	3.21	3.37
$R_b/\Delta F_{-70 \text{ dB}}, (\text{bit/s})/\text{Hz}$	0.89	2.64	1.73	1.94	2.69	3.01

Computer simulation model for CubeSat with Doppler frequency shift

We evaluate the spectral and energy efficiency of data transmission in the presence of Doppler frequency shift using a model of signal transmission from a CubeSat to a ground receiving station. The block diagram of the model is shown in Fig. 2. The model is based on the DVB-S2X digital television signal transmission standard [12, 13].

At the transmitting module, information bits enter the coding block, where concatenated coding is performed using BCH codes with parity bits and LDPC codes at a coding rate of 4/5. This coding rate is chosen as a compromise between error-correction capability and the requirement to achieve high data rates (exceeding 1 Gbit/s). The encoded bits are fed to the bit interleaving blocks and bit-to-symbol mapping blocks. The 64APSK constellation is used because further increasing the channel alphabet size significantly raises the requirements for receiver synchronization algorithms and the link budget. The subsequent blocks (Fig. 2) insert pilot symbols into the message packet preamble for synchronization and perform scrambling to ensure uniform energy distribution across symbols.

Further processing in the transmitting module consists of forming the optimal signal according to the specified symbol rate $R = 1/\xi T$, where ξ is the time-domain compression factor, and the selected shaping pulse (RRC or optimal).

The channel simulation block accounts for Doppler frequency shift. The threshold signal-to-noise ratio is chosen as 15 dB, meaning that the required BER = 10^{-6} must be achieved at $E_b/N_0 < 15$ dB. The satellite position is described by the elevation angle φ (Fig. 3).

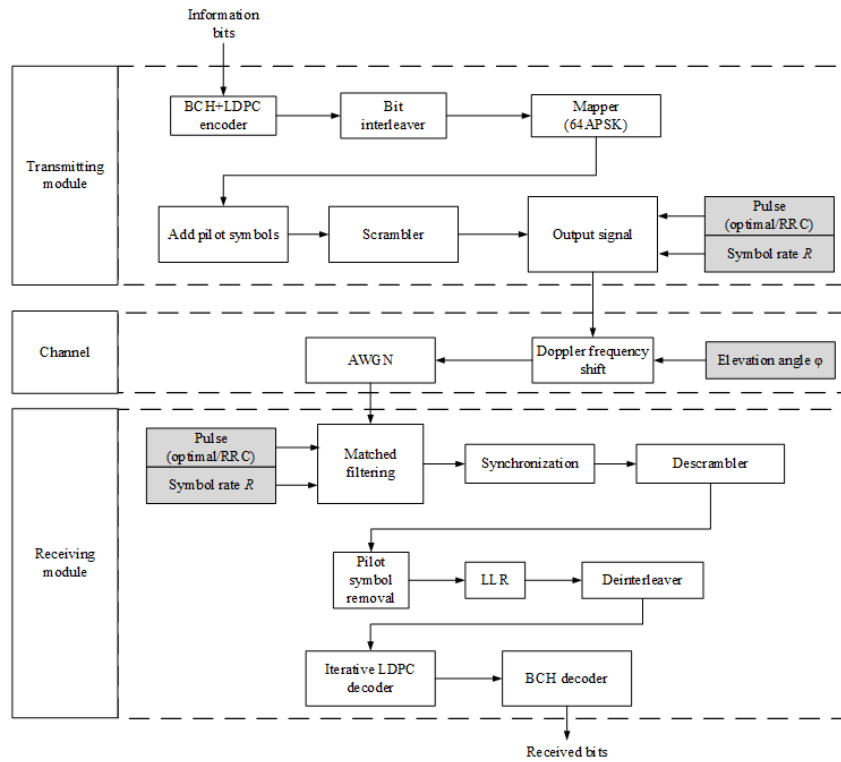


Fig. 2. Block diagram of the computer simulation model

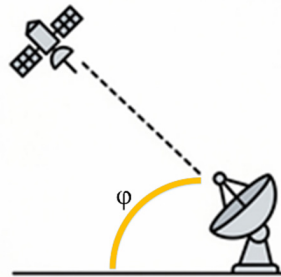


Fig. 3. Illustration of the CubeSat elevation angle

It should be noted that applying a Doppler frequency shift model based on a single frequency offset for all spectral components is insufficient when analyzing high-speed transmission systems based on the DVB-S2X protocol. Therefore, the motion of the satellite transmitter relative to the ground receiver must be modeled by time-scale transformation, equivalent to a change in the signal waveform (compression or stretching of the time representation) [14–17].

Mapping between the transmitter time scale and the receiver time scale is established based on modeling the distance variation between the receiver and transmitter. The corresponding arrival time at the receiver side is determined for a given transmission instant. Then the inverse problem is solved: for each sample on the uniform receiver time grid, the corresponding time instant at the transmitter side is found.

The received signal value is reconstructed by linear interpolation between adjacent samples of the transmitted realization since the receiver samples are formed on a uniform time grid and the corresponding time instants at the transmitter side generally do not coincide with the original samples.

The computer simulation model accounts for frequency instabilities of the transceiver module oscillators: carrier frequency offset, carrier frequency instability, and transmission start time offset.

The received signal is fed to the DVB-S2X demodulator block. The input signal processing employs matched filtering according to the selected pulse shape and symbol rate. Subsequently, symbol synchronization is performed using the Gardner algorithm. Next blocks are frame synchronization to locate the pilots, coarse and fine frequency synchronization. After descrambling and pilot symbol removal, soft log-likelihood ratio (LLR) estimates are computed. The obtained LLR stream is fed to the iterative LDPC decoding block. No more than 20 decoding iterations are used to enable processing speeds exceeding 1 Gbit/s [18, 19]. The received information bits are assembled after BCH decoding. Table 5 lists the parameters of the computer simulation model.

Table 5

Parameters of the computer simulation mode

Satellite orbit altitude	500 km
Carrier frequency	8 GHz
Satellite elevation angle	$\varphi = 0$ to $\varphi = 90^\circ$ (corresponds to Doppler shift from 180 kHz to 0, respectively)
Modulation scheme	64APSK
Coding rate	4/5
Number of decoding iterations	20
Pulse type	optimal / RRC
Carrier frequency offset	2 MHz
Carrier frequency instability	2 ppm
Time offset	31 samples

BER performance of optimal signals in the presence of Doppler frequency shift

Let us consider the results of BER performance evaluation in the presence of Doppler frequency shift based on computer simulations. As an example, we evaluate the BER performance using optimal signals for an elevation angle $\varphi = 60^\circ$ between the satellite and the ground station (Fig. 4). At least 10^8 information bits were transmitted for each signal-to-noise ratio point for BER computation. RRC signals were generated with symbol rate $R = 1/T$, while optimal signals were generated with symbol rate $R = 2/T$.

The following conclusions can be drawn from Fig. 4. First, for signals based on RRC pulses, achieving $\text{BER} = 10^{-6}$ requires value of signal-to-noise ratio of no more than $E_b/N_0 = 10.3$ dB. At the same time, the required value E_b/N_0 for optimal signals ranges from 13.1 to 14.5 dB depending on the choice of the correlation coefficient K_0 . Second, the energy losses for optimal signals amount to approximately 3–4 dB relative to RRC-based signals. These losses are caused by the need for a wider passband of the receiving station input filters, especially in the presence of carrier Doppler shift and spectral distortions.

The signal-to-noise ratio required to achieve the target error probability also changes as the elevation angle changes. Table 6 presents the values of E_b/N_0 (dB) required to achieve $\text{BER} = 10^{-6}$ for elevation angles ranging from 0 to 90 degrees (Fig. 3). These values lie within a 3.35 dB range (from 12.65 to 16.00 dB).

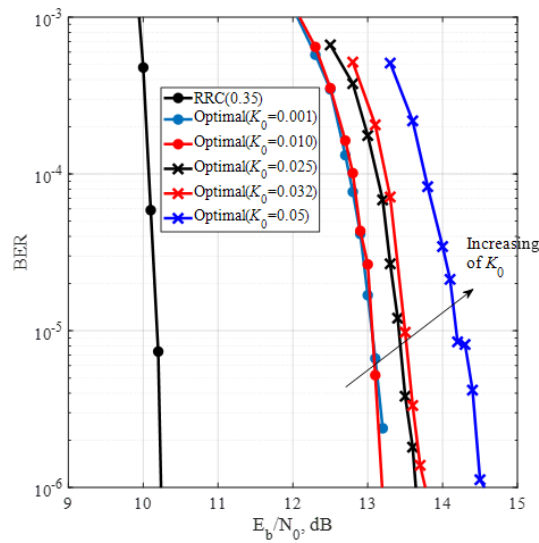
Fig. 4. BER performance of optimal signals for elevation angle $\varphi = 60^\circ$

Table 6

Values E_b/N_0 (dB) for BER = 10^{-6}

	$\varphi = 0^\circ$	$\varphi = 30^\circ$	$\varphi = 60^\circ$	$\varphi = 75^\circ$	$\varphi = 89^\circ$
$K_0 = 0.050$	13.85	14.05	14.55	14.85	16.00
$K_0 = 0.032$	13.08	13.32	13.80	14.05	15.10
$K_0 = 0.025$	13.03	13.18	13.65	13.86	14.75
$K_0 = 0.010$	12.68	12.92	13.20	13.40	14.01
$K_0 = 0.001$	12.65	12.91	13.19	13.40	14.00

Conclusions

The use of optimal APSK signals with doubled symbol rate $R = 2/T$ provides a spectral efficiency gain of approximately 12.7% compared to the case of RRC pulse usage for case of frequency bandwidth determination by the 99% energy concentration level.

It is shown that quantitative estimates of spectral efficiency critically depend on the method of determining the frequency bandwidth ΔF . When the bandwidth is determined by the energy spectrum levels, the spectral efficiency of optimal signals appears to be more than 2–3 times higher than that of RRC-based signals.

The energy efficiency of optimal signals in the presence of Doppler frequency shift is lower than that of RRC-based signals by 3–4 dB. This difference is explained by the fact that optimal signals require a wider passband of the receiving ground station input filters, especially in the presence of carrier Doppler shift and spectral distortions. The required E_b/N_0 for optimal signals ranges from 13.1 to 14.5 dB depending on the chosen correlation coefficient K_0 , which confirms their applicability in radio communication systems using small satellites.

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ADAPTIVE PAPR REDUCTION USING TONE RESERVATION AND CLIPPING IN OFDM TRANSMISSION OVER FADING CHANNELS

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Abstract. The high peak-to-average power ratio (PAPR) inherent in orthogonal frequency-division multiplexing (OFDM) signals forces the high-power amplifier (HPA) to operate with substantial input back-off (IBO) value, severely degrading transmitter power efficiency. This paper investigates the joint application of adaptive tone reservation (TR) and clipping for PAPR reduction in OFDM transmission over frequency-selective fading channels. The adaptive TR scheme employs channel state information to dynamically allocate reserved tones to subcarriers that experience poor signal-to-noise ratio (SNR) and are therefore of limited utility for data transmission. Four configurations have been systematically compared: a baseline without PAPR reduction, clipping only, adaptive TR only, and the proposed joint adaptive TR and clipping scheme. Simulations for the case of a measurement-based underwater acoustic channel with a hard-limiter HPA model demonstrate that adaptive TR alone achieves a 2.8 dB SNR gain over the baseline at a target bit error rate of 10^{-3} , without introducing in-band distortion. The joint scheme yields a total SNR gain of 4.6 dB, combining the benefits from distortionless peak suppression by TR with the aggressive clipping action. Relative to clipping-only operation, the joint scheme decreases out-of-band emission by 3.5 dB and compresses the 99.5% occupied bandwidth by 40%. These results confirm that the combination of SINR-based adaptive TR and clipping provides simultaneous improvements in power efficiency and spectral containment, making it a compelling solution for communication systems subject to both power and spectral mask constraints.

Keywords: PAPR, tone reservation, power allocation, adaptive systems, out-of-band emission suppression

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Научная статья

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АДАПТИВНОЕ СНИЖЕНИЕ ПИК-ФАКТОРА КОЛЕБАНИЙ С ПОМОЩЬЮ РЕЗЕРВИРОВАНИЯ ТОНОВ И КЛИППИРОВАНИЯ ДЛЯ СИГНАЛОВ С OFDM В КАНАЛАХ С ЧАСТОТНО-СЕЛЕКТИВНЫМИ ЗАМИРАНИЯМИ

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Аннотация. Высокий пик-фактор, присущий сигналам с ортогональным частотным уплотнением (OFDM), вынуждает выбирать рабочую точку усилителя вдали от насыщения его передаточной характеристики, что существенно снижает энергетическую эффективность передатчика. В данной работе исследуется совместное применение адаптивного резервирования тонов и клиппирования для снижения пик-фактора в системах связи с OFDM при работе в частотно-селективных каналах с замираниями. В предлагаемой адаптивной схеме при резервировании тонов используется информация о состоянии канала для динамического выделения поднесущих частот с низким отношением сигнал/шум, которые малоприспособлены для передачи данных, для излучения служебного сигнала коррекции пик-фактора. В работе сравниваются четыре конфигурации: базовый вариант без снижения пик-фактора, только клиппирование, только адаптивное резервирование тонов и предлагаемая совместная схема с адаптивным резервированием тонов и клиппированием. Моделирование, выполненное для гидроакустического канала с моделью усилителя с жестким ограничением, показывает, что адаптивное резервирование тонов обеспечивает выигрыш в помехоустойчивости по отношению сигнал/шум в 2,8 дБ по сравнению с базовым вариантом при целевой вероятности битовой ошибки 10^{-3} , не внося дополнительных искажений. Совместная схема дает суммарный выигрыш по отношению сигнал/шум в 4,6 дБ, сочетая подавление пиков с помощью резервирования тонов и клиппирования. Совместная схема снижает уровень внеполосных излучений на 3,5 дБ и сокращает занимаемую полосу частот по уровню 99,5% мощности на 40% по сравнению с отдельным использованием клиппирования. Полученные результаты подтверждают, что комбинация адаптивного распределения тонов и клиппирования обеспечивает одновременное повышение энергетической эффективности и улучшение спектральных характеристик, что делает предлагаемое решение привлекательным для систем связи, работающих в условиях ограничений как по мощности, так и по уровню внеполосного излучения.

Ключевые слова: пик-фактор, резервирование тонов, распределение мощности, адаптивные системы, подавление внеполосного излучения

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Introduction

Orthogonal frequency-division multiplexing (OFDM) has been widely adopted in modern wireless communication standards due to its robustness against multipath fading and high spectral efficiency. Nevertheless, one of the inherent drawbacks of OFDM signals is the high peak-to-average power ratio (PAPR), which forces the high-power amplifier (HPA) to operate with a large value of input back-off (IBO), thereby degrading the overall power efficiency of the transmitter.

To mitigate this issue, numerous PAPR reduction techniques have been extensively investigated. Clipping is a straightforward and effective approach; however, it causes in-band distortion and out-of-band (OOB) radiation [1–3]. In contrast, tone reservation (TR) is a distortionless technique that reserves a subset of subcarriers for a peak-canceling signal [1, 4, 5]. While effective, TR comes at the cost of spectral and power efficiency due to the allocation of reserved tones.

Recent literature has explored both hybrid combinations and adaptive strategies for these techniques. A combination of TR based on the projected conjugate gradient (PCG) algorithm with conventional clipping is proposed in [6]. While this work demonstrates the viability of joint PAPR reduction, the TR component operates statically and does not exploit channel state information (CSI). On the other hand, research on adaptive TR has gained traction in multi-user and resource-constrained scenarios in fading channels. An adaptive TR scheme provides PAPR reduction subject to throughput constraints by allocating reserved tones within resource blocks. In [7], authors investigated joint optimization of subcarrier allocation and TR for OFDM access, further highlighting the benefits of adaptive tone selection. However, these adaptive TR studies [2, 3] focus exclusively on PAPR reduction without considering the impact of additional non-linear operations such as clipping on system performance.

A distinct yet complementary direction was explored in [4], where the focus of TR was shifted from pure PAPR reduction towards improving bit error rate (BER) performance. Specifically, the authors demonstrated that adaptively selecting the reserved tones based on the signal-to-interference-plus-noise ratio (SINR) of the fading channel yields significant gains in error robustness. Nevertheless, the work does not address PAPR reduction itself, nor does it evaluate the combined effect of TR with clipping distortion.

From the above review, a clear research gap emerges. Hybrid TR-clipping schemes have been proposed in [1], and adaptive TR schemes exist for PAPR reduction [4–8] and for BER improvement [9]. However, none of these works has investigated the joint operation of SINR-based adaptive TR and clipping specifically for PAPR reduction over fading channels. Consequently, the potential power efficiency gains – as well as the spectral containment benefits – achievable by combining channel-aware TR with controlled non-linear distortion remain unexplored.

The primary objective of this work is to enhance the power efficiency and spectral containment of OFDM transmission over fading channels through the intelligent combination of adaptive TR and clipping. Unlike conventional approaches that apply PAPR reduction agnostically to channel conditions, we aim to demonstrate that exploiting SINR knowledge for TR allocation yields a more favorable trade-off between PAPR suppression, error rate degradation, and OOB radiation. By cascading distortionless peak suppression (adaptive TR) with a subsequent clipping stage, we target a simultaneous reduction in required HPA IBO and OOB radiation [10].

To evaluate the extent of this improvement, we benchmark the proposed joint scheme and three reference configurations under identical frequency-selective fading conditions:

- 1) *No PAPR reduction*: Baseline OFDM transmission without PAPR mitigation.
- 2) *Clipping only*: Conventional amplitude clipping applied to the OFDM signal.
- 3) *Adaptive TR only*: SINR-based TR as proposed in [4], applied for peak power reduction.
- 4) *Proposed joint scheme*: adaptive TR combined with subsequent clipping.

The analysis specifically quantifies the reduction of BER. Simulation results confirm that the proposed joint scheme transmission with higher power efficiency.

PAPR reduction techniques

The problem of high PAPR in OFDM systems is well explained in the literature [1–5]. The large envelope fluctuations of multicarrier signals force the HPA to operate with a significant power back-off, severely degrading transmitter power efficiency. A comprehensive review of PAPR mitigation

strategies can be found in [1] and references therein. Among the available techniques, this work focuses on TR and clipping, described in detail below.

TR

The concept of TR emerged from the observation that, in frequency-selective fading channels, certain subcarriers experience such poor SINR that they become unusable for reliable data transmission. Rather than leaving these degraded subcarriers idle, TR repurposes them to carry a peak-canceling signal, thereby improving the PAPR characteristics of the transmitted waveform without sacrificing useful data throughput [11, 12].

Formally, TR is a distortionless PAPR reduction technique wherein a subset of subcarriers is exclusively allocated to carry a peak-canceling signal rather than user data. Let R denote the set of reserved tone indices, and let D denote the complementary set of data-bearing subcarriers, such that

$$R \cap D = \emptyset; \quad R \cup D = [0, 1, \dots, N-1], \quad N_R + N_D = N, \quad (1)$$

where N is the total subcarriers number in OFDM symbol, N_R and N_D are reserved and data set sizes, respectively. The transmitted frequency-domain symbol is then

$$x_k = \begin{cases} d_k, & k \in D \\ c_k, & k \in R \end{cases}, \quad (2)$$

where d_k is the data symbol drawn from a modulation constellation (e.g., QAM), and c_k is the peak-canceling coefficient on k -th subcarrier.

The objective of TR is to find the optimal correction vector C that minimizes the peak magnitude of the resulting time-domain signal $IFFT(x_k)$. The optimization problem is formally stated as:

$$\min_C \max_k |IFFT(x_k)|^2, \quad \text{subject to } \sum_{k=0}^{R-1} c_k \leq P_{TR}, \quad (3)$$

where the constraint limits the total power injected into the reserved tones to a predefined power budget P_{TR} .

Adaptive TR

Conventional TR allocates reserved tones at fixed, predetermined positions (typically equally spaced across the available spectrum) without regard for the underlying channel conditions. This static assignment, while simple to implement, is inherently suboptimal in frequency-selective fading environments, as demonstrated in [9].

The core principle of adaptive TR is to exploit CSI to select which subcarriers should serve as reserved tones. The key insight, introduced in [9], is that subcarriers experiencing poor SINR are of limited utility for data transmission, as they would require excessive power or low-order modulation to achieve reliable communication. Rather than wasting the degraded subcarriers on unreliable data, they can be repurposed for peak cancellation.

In this work, we adopt the SINR-based allocation strategy of [9]. The adaptive TR scheme employed in this work departs from the conventional approach in two fundamental respects. First, the number of reserved tones N_R is not fixed a priori but is determined dynamically based on the instantaneous channel state. Second, the selection of which subcarriers serve as reserved tones follows directly from a bit-loading procedure [13] rather than from a predefined rule.

This adaptive allocation strategy ensures that spectrally efficient subcarriers are preserved for user data, while the peak-canceling function is offloaded to subcarriers that would otherwise contribute little to the overall system throughput.

Clipping

Clipping is a memoryless non-linear operation that limits the envelope of the time-domain OFDM signal to a predefined threshold. Despite its conceptual simplicity, clipping remains one of the most widely studied PAPR reduction techniques due to its low computational complexity and deterministic peak suppression capability.

Mathematically, the clipping operation is defined as:

$$\bar{x}_n = \begin{cases} x_n, & |x_n| \leq A \\ A \exp(j\phi(x_n)), & |x_n| > A \end{cases}, \quad (4)$$

where x_n is the n -th sample of the discrete-time baseband OFDM signal, A is the clipping threshold, and $\phi(x_n)$ is the phase of x_n .

The deep of clipping is conventionally parameterized by the clipping ratio (CR), defined as the ratio of the clipping threshold to the root mean square (RMS) amplitude σ of the OFDM signal:

$$CR = \frac{A}{\sigma}. \quad (5)$$

In a practical transmitter chain, the clipped signal is subsequently fed to an HPA. The operating point of the HPA is characterized by the IBO, which quantifies the margin between the average input power and the amplifier saturation threshold A_{sat} .

$$IBO = \frac{A_{sat}^2}{\sigma^2} \text{ or } IBO_{dB} = 10 \log_{10} \left(\frac{A_{sat}^2}{\sigma^2} \right). \quad (6)$$

The CR and IBO parameters are inherently coupled. When the clipping threshold A is set below the amplifier saturation level A_{sat} , the clipper effectively enforces a more stringent amplitude limit than the HPA itself. In this configuration, the clipping stage reduces the PAPR of the signal before it reaches the HPA. Consequently, for a fixed saturation level A_{sat} , a lower clipping threshold (smaller CR) allows the HPA to operate with reduced IBO while maintaining the same level of nonlinear distortion. The selection of appropriate CR and IBO values is therefore a joint design problem that directly determines the trade-off between PAPR reduction, BER degradation, and power efficiency. In this work, the clipping threshold is parameterized directly in terms of the target IBO reduction rather than an abstract CR value.

Unlike TR, clipping is not a distortionless technique. The hard amplitude limitation introduces two distinct categories of impairment:

- 1) In-band distortion: The non-linear operation corrupts the transmitted constellation, raising the error vector magnitude (EVM) and introducing an error floor in the BER performance [14].
- 2) OOB radiation: The sharp amplitude truncation broadens the power spectral density (PSD) of the transmitted signal, causing interference to adjacent frequency channels. In practical systems, regulatory spectral masks impose strict limits on such emissions, making OOB radiation a critical design constraint [15].

A standard approach to mitigate OOB radiation is to apply linear filtering after the clipping stage. However, filtering modifies the signal envelope and inevitably causes peak regrowth – a partial restoration of the peaks that clipping was designed to suppress [1]. This cyclical trade-off between peak suppression, in-band distortion, and OOB containment constitutes the fundamental limitation of

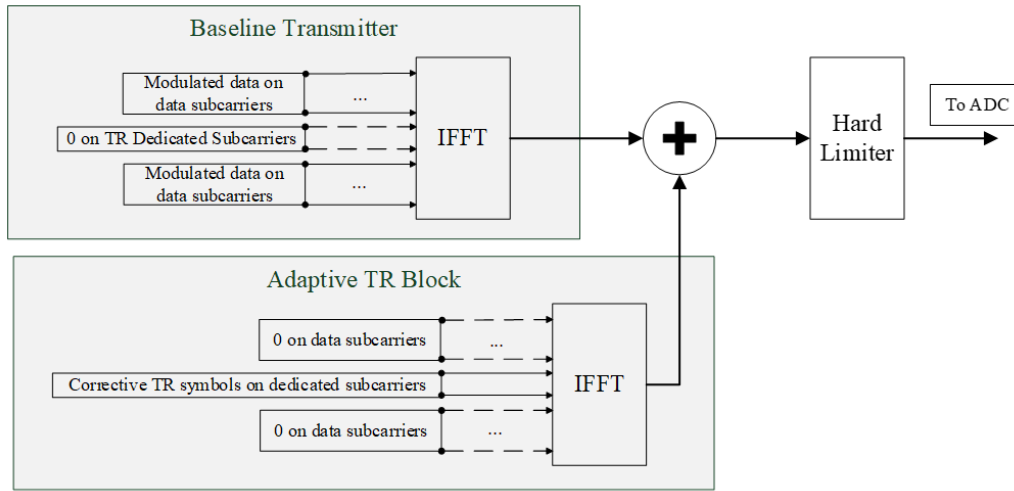


Fig. 1. Joint PAPR reduction scheme

standalone clipping and motivates its combination with distortionless techniques such as adaptive TR, as explored in this work.

Joint adaptive TR and clipping

The preceding subsections have established that adaptive TR and clipping offer complementary mechanisms for PAPR reduction. Adaptive TR is distortionless but provides limited peak suppression, constrained by the number of reserved tones.

The concept of combining TR with clipping to improve PAPR reduction performance was discussed in [6], which proposed a hybrid scheme that cascades TR based on the PCG algorithm with conventional amplitude clipping.

However, the TR component employed in [6] operates statically: the reserved tones are allocated to fixed, predetermined subcarrier positions without any consideration of the underlying channel conditions. The present work extends this concept by introducing channel awareness into the TR stage. Specifically, the fixed TR allocation of [6] is replaced by the SINR-based adaptive TR strategy.

The resulting joint scheme combines these two techniques in a cascaded architecture, as illustrated conceptually in Fig. 1. The signal processing chain proceeds as follows.

Both the adaptive TR block and the clipping block are active, arranged in cascade. The signal is first preconditioned by the adaptive TR stage, and the resulting peak-reduced signal is then clipped. The benefits of this cascade directly address the limitations of each individual technique:

1) *Enhanced PAPR reduction beyond standalone TR*: adaptive TR alone is constrained in its peak suppression capability by the number of reserved tones N_R and the allocated correction power budget P_{TR} . In practice, this means that a residual fraction of high-amplitude peaks remains after the TR stage. By cascading a clipping stage after the TR block, these residual peaks are forcibly limited, achieving a PAPR reduction that is substantially greater than what TR can deliver in isolation. This is the primary motivation for including the clipping stage: it compensates for the inherent peak suppression ceiling of the TR method.

2) *Suppressed OOB radiation compared to standalone clipping*: clipping alone introduces significant OOB spectral regrowth due to the frequent and sharp amplitude truncations. In the joint scheme, the TR preconditioning stage reduces the number and amplitude of signal samples that exceed the clipping threshold A . Consequently, the clipper is activated less frequently and on peaks of lower amplitude, leading to an adjacent channel leakage ratio (ACLR) measurably superior to that of clipping only.

System model

System overview

The performance of the proposed PAPR reduction schemes is evaluated using a Monte Carlo simulation of a complete OFDM communication link operating over frequency-selective fading channel. The simulation chain models passband OFDM modulation, application of one of the four PAPR reduction configurations, high-power amplification with a hard-limiter characteristic, transmission through a multipath fading channel, and receiver processing including equalization and symbol detection.

A key enabler for the adaptive TR scheme is the availability of CSI at the transmitter. In this study, perfect CSI is assumed at the transmitter side. The CSI is used as input to the greedy bit-loading algorithm, which determines the modulation assignment and, consequently, the reserved tone set c_k for each channel realization. This assumption isolates the performance gains attributable to the adaptive allocation strategy from any degradation due to channel estimation errors.

The main simulation parameters are summarized in Table 1.

Table 1

Communication system parameters

Parameter	Value
Mapper constellations	QPSK, QAM-16
FFT size	8192
Payload per OFDM symbol, bit	304
Number of data subcarriers (without TR)	152
Equalizer type	Zero-Forcing
Target BER	10^{-3}
Channel encoding type / code rate	Convolutional / 0.5

Channel overview

The performance of the proposed PAPR reduction schemes is evaluated over a frequency-selective underwater acoustic (UWA) communication channel. This propagation environment is chosen for two reasons directly relevant to the present study.

First, UWA channels are characterized by strong and persistent frequency-selective fading caused by multipath propagation arising from surface and bottom reflections [16, 17]. The low speed of sound in water (approximately 1500 m/s) results in delay spreads that are orders of magnitude larger than those encountered in terrestrial radio channels, producing deep spectral nulls on a subset of OFDM subcarriers. This creates precisely the conditions under which a bit-loading algorithm will identify a subset of subcarriers as unsuitable for data transmission and therefore available for TR.

Second, the UWA channel exhibits quasi-static behavior over the duration of a typical transmission packet. While the channel varies over longer time scales due to surface motion and platform displacement, the coherence time is typically much longer than the duration of an OFDM packet, particularly for moderate carrier frequencies (tens of kilohertz) and short packet lengths [16]. This stability is essential for the adaptive TR scheme: the CSI obtained at the start of a packet remains valid throughout its duration, allowing the reserved tone assignment to be fixed for all OFDM symbols within that packet without re-estimation [18].

The channel parameters are derived from experimental measurements reported in the UWA communications literature [13].

The channel is assumed to be quasi-static: the impulse response $h(t)$ remains constant for the duration of one transmission packet (comprising all OFDM symbols).

Signal-to-noise ratio metric

In the presence of clipping and hard-limiter amplification, the conventional E_b/N_0 metric – which is based on the average signal power – becomes dependent on the PAPR reduction scheme and the operating IBO. To enable fair comparison across all four configurations, we adopt a scheme-independent signal-to-noise ratio (SNR) reference based on the maximum available transmit power.

Let $P_{\max} = A_{\text{sat}}^2$ denote the saturation power of the HPA, and let N_0 denote the single-sided noise PSD. The reference SNR is defined as:

$$SNR_{\text{ref}} = \frac{P_{\max}}{N_0} = \frac{A_{\text{sat}}^2}{N_0}. \quad (7)$$

This metric represents the best-case SNR achievable when the HPA operates at saturation. For a given IBO, the actual average transmit power is:

$$P_{\text{avg}} = P_{\max} \cdot 10^{-\text{IBO}/10}. \quad (8)$$

The conventional E_b/N_0 can be recovered from SNR_{ref} as:

$$\frac{E_b}{N_0} = \frac{SNR_{\text{ref}}}{\log_2 \bar{M}} \cdot 10^{-\text{IBO}/10}, \quad (9)$$

where $\bar{M}$ is the average modulation order across data-bearing subcarriers. For the baseline case with uniform bit loading $\log_2 \bar{M} = 2$.

Performance metrics

Two categories of performance metrics are employed to evaluate the proposed schemes: link-level reliability and spectral containment. The primary metric for assessing end-to-end communication

quality is the BER as a function of the reference SNR ratio $SNR_{\text{ref}} = \frac{P_{\max}}{N_0}$.

In addition to link reliability, the spectral properties of the transmitted signal are of critical importance in practical systems subject to regulatory spectral masks. Two complementary metrics are employed to quantify spectral containment:

1. Peak OOB emission level is defined as the maximum value of the PSD measured outside the assigned signal bandwidth.
2. Occupied bandwidth at 99.5% energy is defined as the frequency interval that contains 99.5% of the total transmitted power.

Simulation results

Before evaluating the comparative performance of the four PAPR reduction configurations, it is necessary to establish a fair operating point for the clipping-based schemes. The clipping threshold A – equivalently expressed through the HPA IBO – governs the trade-off between peak suppression and signal distortion.

The use of SNR_{ref} rather than the conventional average-power-based SNR is deliberate. In a practical transmitter, the HPA must be designed to accommodate the maximum signal excursion, not the average signal level. When no clipping is applied (or when clipping is conservative, corresponding to a high IBO), large-amplitude peaks force the amplifier to operate with substantial back-off. Consequently, for a fixed HPA saturation power, the average transmitted power is low compared to the peak,

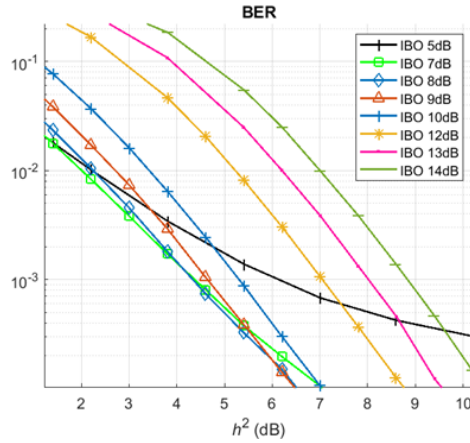


Fig. 2. BER performance for clipped OFDM without TR for different IBO value

and the additive white Gaussian noise (AWGN) floor at the receiver dominates. As clipping becomes more aggressive (lower IBO), these peaks are suppressed, allowing a higher average power to be transmitted within the same peak power constraint – which, in turn, improves the effective SNR at the receiver.

Fig. 2 presents the BER of the clipping only configuration as a function of SNR_{ref} for several candidate IBO values.

The resulting curves reflect two competing mechanisms:

1) High IBO regime (e.g., IBO = 10 dB and above): clipping is conservative. Large signal peaks remain largely unsuppressed, forcing the HPA to operate with a high back-off. For a given peak power constraint P_{max} , the average transmitted power is low, and the resulting SNR_{ref} yields a degraded BER. In this regime, the dominant impairment is not clipping distortion, but poor power efficiency: the HPA operates far from saturation, the low average transmitted power yields a reduced SNR at the receiver, thereby elevating the BER.

2) Low IBO regime (e.g., IBO = 5 dB): Clipping is aggressive. Signal peaks are effectively suppressed, enabling the HPA to operate closer to saturation and deliver higher average power for the same P_{max} . However, the severe amplitude truncation introduces substantial in-band distortion, which manifests as an elevated irreducible error floor at high SNR_{ref} .

The optimal IBO is the value that balances these two effects. In the present simulations, the curve corresponding to IBO = 8 dB achieves the lowest BER across the measured SNR_{ref} range. At this operating point, the peak suppression is sufficient to allow efficient HPA utilization, while the clipping-induced distortion remains within acceptable limits.

Based on this result, IBO = 8 dB is selected as the operating point for all subsequent simulations involving clipping.

Fig. 3 presents the BER vs SNR_{ref} curves for the four PAPR reduction configurations, evaluated with IBO = 8 dB at the HPA. The required SNR_{ref} values to achieve the target BER of 10^{-3} are extracted from the curves and summarized in Table 2.

First, the adaptive TR only configuration (Case 3) achieves a substantial 2.8 dB SNR gain over the baseline. This result confirms that SINR-based adaptive tone allocation, originally proposed for BER improvement in [4], is effective as a standalone PAPR reduction technique. By repurposing low-SINR subcarriers for peak cancellation, the scheme reduces the PAPR without introducing any in-band distortion, and this distortionless nature translates directly into an improved BER.

Second, the joint adaptive TR and clipping configuration (Case 4) yields an additional improvement, achieving a total SNR gain of 4.6 dB over the baseline. Compared to clipping only (Case 2),

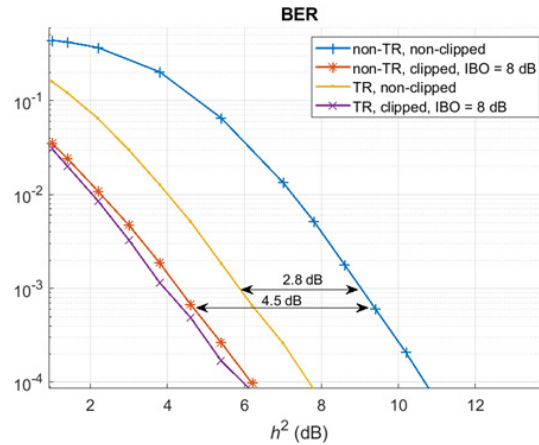


Fig. 3. BER performance for OFDM system with and without clipping and adaptive TR

Table 2

Communication system parameters

System configuration	Required $P_{\max}/N_0$ (dB)	SNR Gain vs Baseline (dB)
(1) non-TR, non-clipped (Baseline)	10.6	—
(2) non-TR, clipping only	6.1	4.5
(3) adaptive TR, non-clipped	7.8	2.8
(4) joint (adaptive TR and clipping)	6.0	4.6

the joint scheme delivers a modest 0.1 dB SNR gain. This incremental improvement is consistent with the physical mechanism: the TR preconditioning stage reduces the dynamic range of the signal prior to clipping, thereby lowering the frequency of clipping events and the associated distortion. While the BER gain over pure clipping is small, the true benefit of the joint scheme becomes apparent when spectral containment is examined, as discussed in the following subsection.

Fig. 4 presents the PSD of the transmitted signal for the four configurations, measured at the HPA output. The PSD curves reveal the spectral containment properties of each scheme.

The following observations are drawn from Fig. 4.

Clipping increases OOB radiation: The clipping only curve exhibits a pronounced spectral broadening, with the OOB emission level rising significantly above the baseline. This behavior is an inherent consequence of the clipping non-linearity: the abrupt amplitude truncation at the threshold A introduces high-frequency components into the signal, which manifest as spectral regrowth in the adjacent bands.

TR mitigates clipping-induced OOB radiation: a comparison of the joint scheme (Case 4) with clipping only (Case 2) reveals a measurable 3.5 dB reduction in OOB emission when the adaptive TR preconditioner is active. The physical explanation follows directly from the cascaded architecture: the TR stage reduces the number of signal samples that exceed the clipping threshold, thereby decreasing the frequency of clipping events. Quantitatively, the occupied bandwidth — measured as the frequency interval containing 99.5% of the total radiated power — is reduced by approximately 40% in the joint scheme compared to clipping only.

In summary, the spectral analysis demonstrates that the joint scheme offers a dual benefit: it retains the aggressive PAPR suppression of clipping while meaningfully mitigating its principal drawback OOB spectral regrowth.

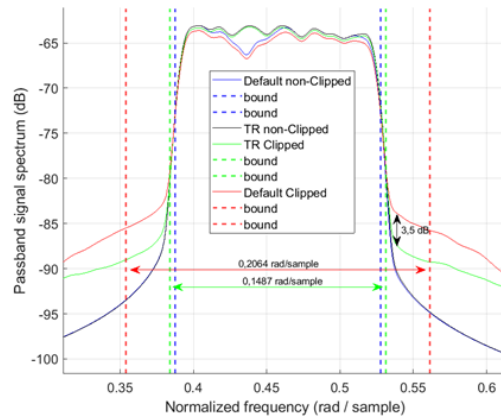


Fig. 4. Transmitted signal spectrums

Conclusion

This paper investigated the joint application of adaptive TR and clipping for PAPR reduction in OFDM systems operating over frequency-selective fading channels, with a particular focus on the UWA propagation environment. Motivated by the SINR-based TR allocation strategy proposed in prior works [7, 9], the study extended the analysis to evaluate the combined effect of this adaptive technique with conventional amplitude clipping. Four transmission configurations were benchmarked in terms of BER performance and spectral containment.

The simulation results confirm the efficacy of adaptive TR as a standalone PAPR reduction technique. By dynamically allocating reserved tones to subcarriers with low SINR — as determined by a greedy bit-loading algorithm — adaptive TR alone achieves a 2.8 dB SNR gain at a target BER of 10^{-3} compared to the non-reduced baseline, without introducing any in-band distortion.

The proposed joint adaptive TR and clipping scheme achieves the best overall performance, yielding a total SNR gain of 4.6 dB over the baseline. While the incremental BER improvement over clipping only is modest (0.1 dB), the joint scheme offers significant practical advantages in the spectral domain. Specifically, the TR preconditioning stage reduces the frequency of clipping events, leading to a 3.5 dB reduction in peak OOB emission and a 40% reduction in the 99.5% occupied bandwidth compared to clipping only. This enhanced spectral containment is of particular value in systems governed by stringent spectral mask regulations.

The results obtained for the UWA channel validate the proposed approach in a realistic propagation scenario where the adaptive allocation of reserved tones is both feasible and beneficial. The availability of perfect CSI at the transmitter, assumed in this study, is consistent with practical UWA communication systems that employ channel estimation during the preamble phase of each transmission packet.

Future work will extend the analysis to channels with mobility-induced Doppler spread, where the coherence time of the channel limits the validity period of the reserved tone assignment, and to scenarios with imperfect CSI, where channel estimation errors may degrade the performance of the SINR-based allocation strategy.

ABBREVIATIONS:

- ACLR — adjacent channel leakage ratio;
- AWGN — additive white Gaussian noise;
- BER — bit error rate;

- CR – clipping ratio;
- CSI – channel state information;
- HPA – high-power amplifier;
- IBO – input back-off;
- OFDM – orthogonal frequency-division multiplexing;
- OOB – out-of-band;
- PAPR – high peak-to-average power ratio;
- PCG – projected conjugate gradient;
- PSD – power spectral density;
- RMS – root mean square;
- SINR – signal-to-interference-plus-noise ratio;
- SNR – signal-to-noise ratio;
- TR – tone reservation;
- UWA – underwater acoustic.

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APPLICATION OF ASYNCHRONOUS DATA BYPASS TO INCREASE PERFORMANCE OF IN-ORDER SUPERSCALAR RISC-V PROCESSOR CORE

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Abstract. RISC-V is an open-source architecture that does not require license fees from processor core vendors. This allowed RISC-V to become widely distributed first in the microcontroller-class processor core market and subsequently in the market of higher-performance devices. Currently RISC-V processor cores with in-order execution, which combine mid-range performance, compactness, and energy efficiency are attracting the most interest from customers. This makes the task of continuing to improve them a highly relevant. This paper explores the application of a microarchitectural modification, asynchronous data bypass, to increase the performance of in-order superscalar RISC-V processor core. Asynchronous data bypass has been made for two pairs of functional blocks: between arithmetic-logic unit (ALU) and ALU, between ALU and branch unit. The main obstacle of implementing asynchronous data bypass is the creation of an extremely long logical path, which leads to violations of timing constraints. To overcome this obstacle, an approach was proposed that involves completely excluding a subset of instructions from asynchronous bypass and separating the logic of the remaining instructions into groups based on the length of the logical path. This approach made it possible to keep the logical path of asynchronous bypass no longer than the longest path of a single execution unit. The results showed that the use of asynchronous bypass can significantly increase the performance of in-order superscalar processor core. At the same time, the area overhead is very low.

Keywords: processor core, superscalarity, in-order, asynchronous data bypass, logical path

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ИСПОЛЬЗОВАНИЕ АСИНХРОННОЙ ПЕРЕСЫЛКИ ДАННЫХ ДЛЯ УВЕЛИЧЕНИЯ ПРОИЗВОДИТЕЛЬНОСТИ СУПЕРСКАЛЯРНОГО RISC-V ПРОЦЕССОРНОГО ЯДРА С ИСПОЛНЕНИЕМ КОМАНД В ПРЯМОЙ ОЧЕРЕДНОСТИ

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Аннотация. RISC-V является открытой процессорной архитектурой и не требует лицензионных отчислений от разработчиков процессорных ядер. Такой подход позволил RISC-V широко распространиться сначала на рынке процессорных ядер микроконтроллерного класса, и впоследствии выйти на рынок более производительных устройств. К настоящему моменту наибольший интерес у потребителей вызывают RISC-V процессорные ядра с исполнением команд в прямой очередности, сочетающие в себе производительность среднего уровня, компактность и энергоэффективность. Данное обстоятельство делает актуальной задачу их дальнейшего усовершенствования. В данной статье исследовано применение микроархитектурной модификации, асинхронной пересылки данных, для увеличения производительности суперскалярного RISC-V ядра с исполнением команд в прямой очередности. Рассмотрено внедрение асинхронной пересылки данных для двух пар функциональных блоков: между арифметико-логическим устройством (АЛУ) и АЛУ, между АЛУ и блоком обработки переходов. Главным препятствием при введении асинхронной пересылки является возникновение чрезмерно длинного логического пути, приводящего к нарушению временных ограничений. Для преодоления данного обстоятельства предложен подход, заключающийся в полном исключении части инструкций из асинхронной пересылки и разделении логики оставшихся инструкций на группы по длине логического пути. Данный подход позволил сделать логический путь пересылки не длиннее, чем самый длинный путь одиночного исполнительного блока. Полученные результаты показывают, что применение асинхронной пересылки данных может ощутимо увеличить производительность суперскалярного процессорного ядра с исполнением команд в прямой очередности. При этом затраты по площади являются незначительными.

Ключевые слова: процессорное ядро, суперскалярность, прямая очередность, асинхронная пересылка данных, логический путь

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Introduction

The RISC-V architecture had been developed in 2010, and in 2011 the first version of its base instruction set was published¹. Open source and the absence of licensing fees for using the architecture were declared to be the main principles of this architecture [1]. These conditions, which provide greater independence for processor core developers, allowed RISC-V to gain attraction in the market for energy-efficient microcontrollers and subsequently expand into the market for higher-performance cores [2–4].

Most of the implemented RISC-V processor cores has in-order execution [5]. In-order processor core executes program instructions strictly in the order in which they are located in the execution flow. If the current instruction cannot be executed, the entire core pipeline stops and waits until that instruction is completed. On the other hand, out-of-order processor cores analyze the dependencies between instructions and reorder them to achieve maximum performance. In-order processor cores have less performance than out-of-order processor cores. However, they are simpler to design, take up less area and consume less energy [6, 7].

RISC-V in-order microcontroller-class processor cores are currently widely available on the market^{2,3,4}. They are low-performance cores designed for maximum compactness and autonomous operation. They are used in the Internet of Things (IoT), various sensors, meters and simple Bluetooth devices [8, 9]. The other fast-growing class is higher-performance in-order cores. They are intended for use as coprocessors in data storage devices, energy-efficient components in systems on a chip, in automotive security systems, in industrial machine tools, in communication systems, and for devices that require an operating system: network routers and gateways, database servers, industrial terminals and access panels with an advanced graphical user interface [10–15].

Compared to microcontrollers, these processor cores typically feature an additional instruction execution pipeline (superscalar architecture), a greater number of pipeline stages, improved branch predictors and cache [16–18]. At the same time, improving the cores in this class remains a priority. Of particular interest are modifications that increase performance without significantly increasing the core area.

In this paper, we investigate a microarchitectural modification: asynchronous data bypass. It will be implemented for some execute units of the RISC-V in-order superscalar core. It is assumed that the introduction of this data pass-through will help eliminate some of the stalls in the core caused by dependencies between instructions entering the core's pipeline in a single clock cycle. This modification is expected to increase the core's performance while only slightly increasing its area.

Materials and methods

The microprocessor core used in this work belongs to a class of cores that offer higher performance than microcontrollers and are capable of running an operating system. It is an in-order superscalar processor core. The instruction execution pipeline of this core is shown in Fig. 1.

The instruction execution pipeline includes the following execution units:

- The arithmetic-logic unit (ALU) performs arithmetic and logical operations in a single clock cycle. The instruction execution subsystem contains two ALUs each in the E0 and CM stages. ALU pairing allows two ALU instructions to be executed in a single clock cycle. Additional ALUs at the CM stage enable ALU instructions to be sent to the CM stage and help avoid some of the stall time caused by dependencies.

¹ About RISC-V International. [online] Available: <https://riscv.org/about/> (Accessed 28.09.2026)

² PicoRV32 – A Size-Optimized RISC-V CPU. [online] Available: <https://github.com/YosysHQ/picorv32> (Accessed 28.09.2026)

³ A FPGA friendly 32 bit RISC-V CPU implementation. [online] Available: <https://github.com/SpinalHDL/VexRiscv> (Accessed 28.09.2026)

⁴ FEMTORV32 / FEMTOSOC: a minimalistic RISC-V CPU. [online] Available: <https://github.com/BrunoLevy/learn-fpga/tree/master/FemtoRV> (Accessed 28.09.2026)

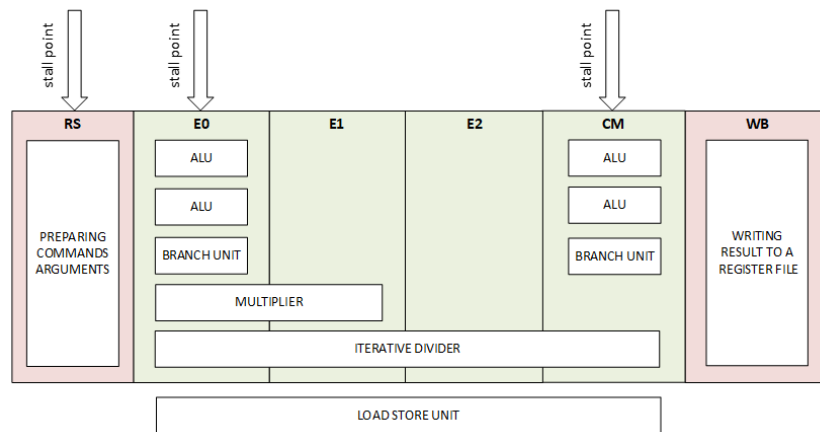


Fig. 1. Schematic of instruction execution pipeline

- The branch unit executes conditional branch instructions, in a single clock cycle. The instruction execution subsystem contains two BPUs each at the E0 and CM stages.
- The multiplier performs multiplication operations in two clock cycles. There is no duplication of this unit in the pipeline.
- The iterative divider performs division operations. The number of cycles required to complete the division depends on the number of bits in the dividend. This unit is not duplicated in the pipeline.
- The load store unit executes instructions that require interaction with memory.

The presence of two execution paths and two ALUs at the stages makes it possible to execute two ALU instructions simultaneously. However, for in-order cores, a stall occurs when two ALU instructions with Read after Write (RAW) dependency enter the pipeline as shown in Fig. 2, *a*. Two instructions have entered the pipeline, and there is a dependency between them. The result of the first instruction in the execution order (slot 0) is an argument for the second (slot 1). Because of this dependency, the instruction in slot 1 stalls for one clock cycle until the result of the instruction in slot 0 becomes ready.

We propose implementing asynchronous data bypass between ALUs. This allows two dependent instructions to move on to the E0 stage together, as shown in Fig. 2, *b*. In this case, the instruction in slot 1 receives data from the instruction in slot 0 directly during execution through the bypass.

An asynchronous bypass can also be added for ALUs on the CM stage. The case of sending ALU instructions to the CM stage is shown in Fig. 3. The instruction in slot 0 depends on the load from memory instruction (lw) and gets sent to the CM stage. At the same time, the asynchronous bypass allows the instruction in slot 1 to also be sent to the CM stage and receive data from instruction in slot 0.

Implementing direct connection between ALUs adds a new logical path to the system. This path could potentially become the longest in the system in terms of signal propagation time through the logic gates (critical path) and lead to a violation of timing constraints (Fig. 4, *a*). To avoid violating timing constraints, the following condition was set when organizing bypass: the logical path between two ALUs must not be longer than the longest path of a single ALU.

It was determined that the following instructions have the longest logical path in the single ALU of the original core:

- cpop – counts the number of logical ones in the register;
- clz – counts the logical zeros in the register up to the first logical one, starting from the most significant bit;
- ctz – counts the number of logical zeros in the register up to the first logical one, starting from the least significant bit.

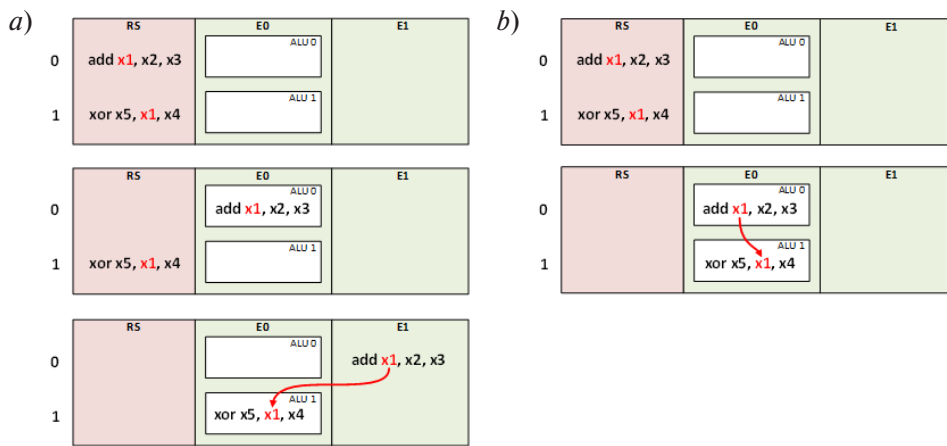


Fig. 2. Execution of two ALU instruction with dependency: without asynchronous bypass (a); with asynchronous bypass (b)

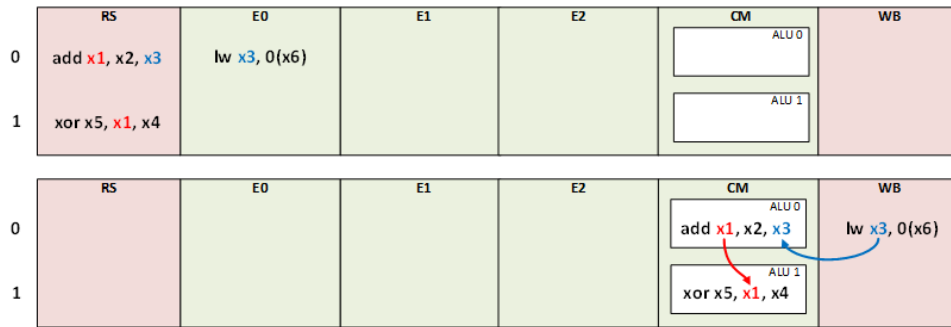


Fig. 3. Execution of two ALU instruction with dependency with asynchronous bypass on CM stage

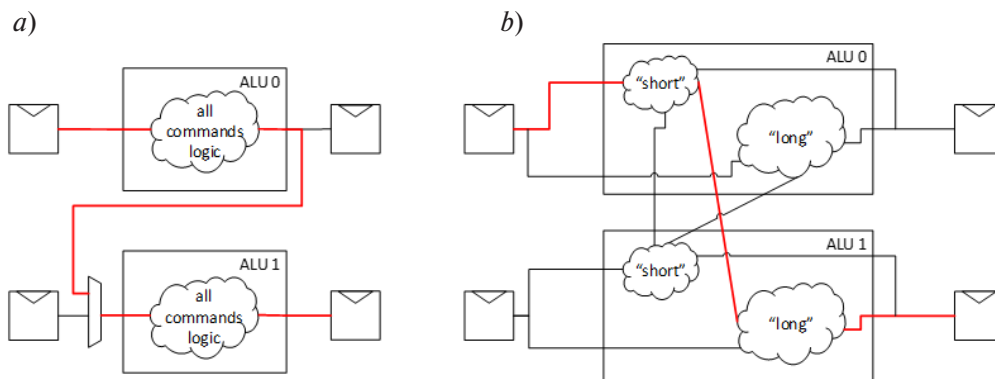


Fig. 4. Critical path of asynchronous bypass between ALUs: direct connection of two ALUs (a); critical path optimization by separating commands logic (b)

Adding these instructions would inevitably result in failure to meet the specified condition and violate timing constraints. Therefore, these instructions were completely excluded from the asynchronous data bypass. All other instructions executed on the ALU were separated into two groups depending on their logical path length: "short" and "long," and the asynchronous data bypass was organized as shown in Fig. 4, b.

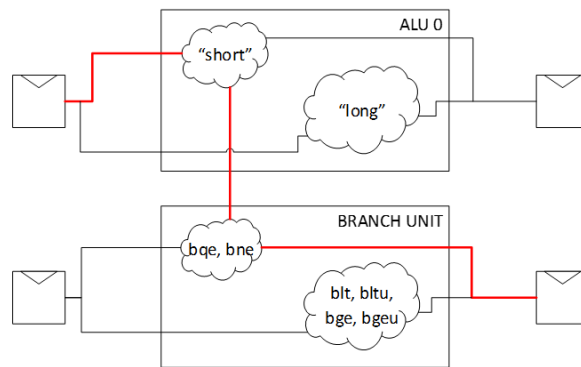


Fig. 5. Critical path of asynchronous bypass between ALU 0 and branch unit

The following instructions were classified as “short”:

- Logical instructions: and, or, xor, their versions with a constant argument – andi, ori, xori, their versions with an inverted argument – andn, orn, xorn.
- Single-bit instructions: set bit – bset, clear bit – bclear, invert bit – binv, get bit value – bext.
- Data extension instructions: sext.b – signed extension of the lower 8 bits, sext.h – signed extension of the lower 16 bits, zext.h – unsigned extension of the lower 16 bits.
- Byte instructions: orc.b – logical OR for all bits in a single byte, rev8 – reversing the byte order, brev8 – reversing the bit order within a single byte.
- Conditional assignment instructions: czero.eqz, czero.nez.

The remaining operations performed on the ALU were classified as “long”: addition, subtraction, comparisons, shifts. Their logic path is much longer than that of the “short” operations, but significantly shorter than that of the cpop, clz, and ctz operations.

We also tested the use of asynchronous data bypass between ALU 0 and branch unit. This time, it will allow for the simultaneous execution of an ALU instruction in slot 0 and a dependent conditional branch instruction in slot 1. The result of the instruction from ALU 0 is passed to one of the arguments of the conditional branch operation in the branch unit.

In this case, to meet timing constraints, the next condition was set: logical path between ALU 0 and the branch unit must not be longer than the longest path in the single branch unit. To satisfy this condition, only the following were added to the asynchronous data bypass:

- ALU 0 new “short” instructions: logical, data extension, byte instructions.
- Branch unit conditional branch instructions with an absolute equality condition: beq, bne, beqz, bnez.

The remaining instructions executed by the ALU and the branch instructions with longer logical paths (blt, bltu, bge, bgeu) were excluded. Thus, the asynchronous bypass between ALU 0 and branch unit was organized as shown in Fig. 5.

Results and discussion

After implementing the asynchronous bypass, performance measurements were taken relative to the original processor core. The following tests were used to measure performance: Coremark, Dhrystone, integer tests from the SPEC2006 and SPEC2017 collections. The results are shown in Fig. 6.

The test results show a noticeable performance gain when an asynchronous bypass is implemented. It can be seen that the results for Dhrystone increased more than the others. This is probably associated with the limited variety of operations in Dhrystone and its relatively small size. Due to

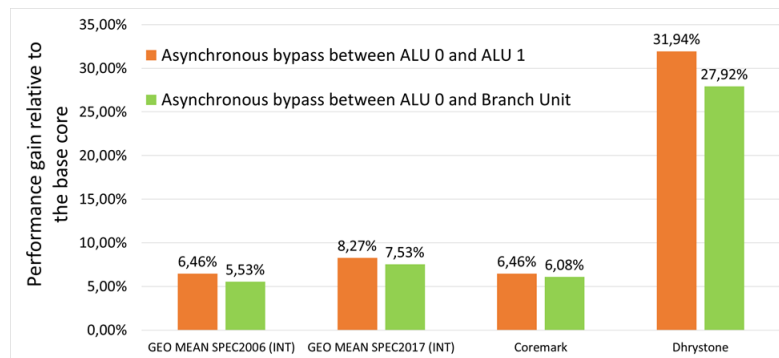


Fig. 6. Processor core performance gain after implementing of an asynchronous bypass

these factors, the acceleration of basic operations may be more pronounced in this test. Moreover, the introduction of an asynchronous bypass between ALU 0 and ALU 1 increased performance more significantly than the bypass between ALU 0 and the branch unit.

We also evaluated the increase in processor core area resulting from the introduction of an asynchronous bypass. A simulation-based synthesis was performed to estimate the processor core area with an approximation to its actual fabrication on a chip. The increase of the core area compared to the base one is shown in Table 1.

Table 1

Comparison of area increase relative to the base processor core

Modification	Core area increase
Asynchronous bypass between ALU 0 and ALU 1	2.35%
Asynchronous bypass between ALU 0 and branch unit	0.56%

The introduction of an asynchronous bypass between ALU 0 and ALU 1 resulted in a greater increase in area. This is because a significantly larger number of instructions were included in this asynchronous bypass. First, this put more pressure on the logic path of the bypass, increasing the area cost during simulation synthesis. Second, it led to increased area costs for data multiplexing and the formation of the bypass context.

Conclusion

In this work, we investigated the use of asynchronous data bypass. This microarchitectural modification was implemented to increase the performance of a superscalar in-order RISC-V processor core.

As part of this work, an asynchronous data bypass was implemented between the following execution units: ALU 0 and ALU 1, ALU 0 and branch unit. To meet the specified timing constraints, the following approach was proposed: instructions with the longest logical paths were excluded from the asynchronous bypass, and the logic of the remaining instructions was separated into groups based on logical path length. A greater performance gain was achieved by introducing a bypass between ALU 0 and ALU 1 than by introducing a bypass between ALU 0 and the branch unit. However, this also required a greater increase in core area: 2.35% against 0.56%, respectively.

Overall, the asynchronous data bypass succeeded in increasing the performance of higher-performance class core that already incorporated previously known modifications. At the same time, the area costs were relatively minor. This modification can be used to increase the performance of other similar cores as well.

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MULTI-LAYER HASH ANCHORING METHOD WITH WATERFALL CONSENSUS FOR FACT-ORIENTED BLOCKCHAIN

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Abstract. The paper proposes a method based on the ideas of classical Proof-of-Work (PoW) for building a distributed registry (Multi-Layer Hash Anchoring, MLHA) based on redundancy of PoW block headers. Each block contains links to the last blocks of all layers, determined by the number of leading hash zeros, which allows you to highlight the sparse skeleton of the waterfall chain. The properties of the waterfall are investigated: uniqueness, determinism, and logarithmic growth of average length. The criterion for the safe deletion of blocks not included in the waterfall is proved, and the possibility of a trustless audit of deleted data is shown. A consensus mechanism based on a lexicographic comparison of waterfall vectors is proposed, consistent with the principle of maximum performance. A single security window has been introduced linking the network hashrate, the minimum mining complexity and the allowable probability of an attack; an upper bound on this probability has been obtained. The simulation results confirm the theoretical estimates. The method does not require a trusted installation, has post-quantum stability and can be used in lightweight decentralized systems.

Keywords: Proof-of-Work, blockchain, data compression, logarithmic growth, consensus, waterfall, MLHA

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МЕТОД МНОГОСЛОЙНОЙ ПРИВЯЗКИ ХЕШЕЙ С ВОДОПАДНЫМ КОНСЕНСУСОМ ДЛЯ ФАКТО-ОРИЕНТИРОВАННЫХ БЛОКЧЕЙНОВ

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Аннотация. В работе предложен базирующийся на идеях классического Proof-of-Work (PoW) метод построения распределенного реестра (Multi-Layer Hash Anchoring, MLHA), основанный на избыточности заголовков блоков PoW. Каждый блок содержит ссылки на последние блоки всех слоев, определяемых количеством ведущих нулей хеша, что позволяет выделить разреженный скелет цепочки – водопад. Исследованы свойства водопада: единственность, детерминированность и логарифмический рост средней длины. Доказан критерий безопасного удаления блоков, не входящих в водопад, и показана возможность бездоверительного аудита удаленных данных. Предложен механизм консенсуса на основе лексикографического сравнения водопадных векторов, согласованный с принципом наибольшей работы. Введено единое окно безопасности, связывающее хешрейт сети, минимальную сложность майнинга и допустимую вероятность атаки; получена верхняя граница этой вероятности. Результаты имитационного моделирования подтверждают теоретические оценки. Метод не требует доверенной установки, обладает постквантовой стойкостью и может найти применение в легковесных децентрализованных системах.

Ключевые слова: Proof-of-Work, блокчейн, сжатие данных, логарифмический рост, консенсус, водопад, MLHA

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Introduction

The object of the study is the Fact-Oriented Blockchain (FOB), a distributed ledger that stores atomic facts (indivisible, self-sufficient units of information) in a chronological chain of blocks secured under the Proof-of-Work (PoW) concept [1]. Blockchain technologies are used in medicine [2], agronomy [3], and numerous other sectors of critical importance to government and industry. Traditional PoW blockchains require full nodes to store the entire block history, a volume that grows monotonically [4]. This steadily reduces the reach of users with the technical means to maintain a node, thereby threatening decentralization.

The problem is compounded by critical limitations in existing approaches [5]. For instance, pruning, while widely adopted, results in the irretrievable loss of historical block bodies across the entire network. Although the header chain preserves cryptographic coherence, the complete erasure of the source data makes it impossible for nodes to physically prove or verify the authenticity of the history from the genesis block itself. At the same time, compact proof protocols such as Non-Interactive Proofs of Proof-of-Work (NiPoPoW) [6] only facilitate synchronization of light clients but do not reduce storage requirements on full nodes, nor address consensus-level problems, preservation of auditability for erased data, or node synchronization within the proposed paradigms. Thus, until now,

the problem of building a PoW blockchain remains open, in which each full node stores data growing sublinearly (ideally logarithmically) with the total number of blocks created, while retaining the capacity for a complete trustless audit of any historical fact using only hash functions.

The problem of uncontrolled data growth and auditability attracted the attention of many researchers, giving rise to a variety of methods. Each of them, however, has fundamental limitations [7–9] in the context of the task at hand.

Classical pruning and sharding methods are designed to reduce the load on individual nodes [10]. Pruning, however, destroys the local completeness of historical data, making it impossible to audit remote transactions offline without re-requesting them again from other network participants. Sharding distributes data across nodes but does not enable each validator to audit the full history, significantly complicates cross-shard interaction and reduces the security of individual segments (shards). Neither approach allows an individual node to maintain complete independence when verifying history without linear accumulation of data.

Compact proof protocols such as NiPoPoW and FlyClient use probabilistic block samples and Merkle structures to create super-light clients that can verify consensus with a logarithmic amount of transmitted data. However, these protocols address the problem exclusively for light clients: full nodes are still required to store the entire linear volume of blocks, and auditing a specific historical transaction requires a request to a full node, which does not eliminate the storage problem on the proof source itself.

Approaches based on zero-knowledge recursive proofs (Incremental Verifiable Computation, IVC) compress the proof of correctness of the entire history of state transitions to a constant size (for example, the Mina blockchain). However, this architecture does not address data availability for independent audit of historical facts. A mathematical proof guarantees only the validity of the current state of the network, but to confirm the existence of a particular old block or transaction, an archive node is still required storing the original transaction history. Without access to these historical block bodies, a node is unable to extract and audit facts locally. In addition, most compact zk-SNARK systems are based on elliptic curves vulnerable to quantum attacks [8, 11], which imposes long-term security risks compared with systems that rely solely on cryptographic hash functions.

Editable blockchains based on chameleon hash functions (for example, PADHA [1]) permit history modification given a special key. This requires trusted key management, which contradicts the principles of full decentralization, and does not resolve the problem of complete data deletion without losing verifiability.

Thus, all known approaches either sacrifice auditability for compression, require trusted parties, or fail to reduce the load on a full node. None of the existing solutions simultaneously offers the following properties:

- a full node stores data that grows sublinearly or logarithmically with the total number of blocks created;
- trustless cryptographic audit of any historical fact without external compact proofs;
- complete decentralization of consensus without trusted keys or installations;
- post-quantum persistence based solely on standard hash functions.

The identified gap [12] necessitates the development of a fundamentally new method of organizing the blockchain, one that exploits the structural redundancy inherent in PoW to construct a sparse, but cryptographically complete chain skeleton that can replace the full history with minimizing losses in PoW.

Taking into account the gap identified in the literature review – the lack of a method for organizing a PoW blockchain that simultaneously provides logarithmic growth of stored data on full nodes, trustless audit of any historical fact, complete decentralization of consensus, and post-quantum stability based on standard hash functions – the aim of this study is to develop and formally justify a new

paradigm for building a distributed registry, called the Multi-Layer Hash Anchoring (MLHA) method with waterfall (skeleton) consensus.

To achieve this aim, the following objectives are addressed:

1. To construct a formal MLHA model that includes:
 - 1.1. A definition of layers based on the number of leading zeros in a block's PoW hash, together with an analysis of their probability distribution depending on the base of the number system L ;
 - 1.2. A block structure with redundant references $\text{prevHash}[0...N]$ and rules for constructing new blocks that ensure all previous layers remain connected.
2. To introduce the concept of a skeletal waterfall (WF) as a minimal cryptographically connected chain skeleton and strictly prove its key properties:
 - 2.1. uniqueness;
 - 2.2. determinism;
 - 2.3. logarithmic growth of the average WF length from the total number of blocks created;
 - 2.4. monotonic non-decrease of the lexicographic vector of layers over time.
3. To develop an algorithm for secure block deletion based on the invariant of continuity of neighbors after deletion, and show that, provided the deletion criterion is satisfied, complete auditability is preserved: any deleted block can be unambiguously verified through a continuous chain of blocks to the nearest WF block on the right without involving external cryptographic evidence.
4. To design a consensus protocol based on lexicographic comparison of WFs and justify its resistance to attacks of reorganization and forgery of historical references, assuming an honest majority.
5. To perform a simulation to confirm the logarithmic growth of WF.

The solution of these problems forms the MLHA theory, which is expected to overcome the fundamental contradiction between data compression and trustless auditing in decentralized PoW systems.

Materials and methods

Formal MLHA model

The MLHA method is based on using the natural heterogeneity of PoW results to build a distributed registry with controlled growth. The basic cryptographic primitive is a standard hash function $H: \{0,1\}^* \rightarrow \{0,1\}^{512}$ (since Secure Hash Algorithm 512), modeled as a random oracle. The hash length in hexadecimal representation is 128 characters or 512 bits in binary. For applications that require a different balance between the compression ratio and the size of service information, an arbitrary base of the number system L and any cryptographically strong hash function can be used, where L is a power of two ($L = 2, 4, 8, 16, \dots$). In this paper, all statements are formulated for the general case, and, if necessary, they are specified, for example, to $L = 2$, which corresponds to the binary representation of the hash, or $L = 16$, which corresponds to the usual form of hash function results.

Definition 1: Block layer. Let $h = H(m)$ be the hash of the block represented in the number system with the base L . The block layer $\ell \in \{0, 1, \dots, N\}$ (where $N = 512/\log_2 L$ for SHA-512) is the number of leading zero digits in this representation:

$$\ell = \max \left\{ k \in [0, N] \mid \forall i \in [0 \dots k-1]: h[i] = 0 \right\}.$$

In other words, ℓ is the length of the maximum hash prefix consisting of zeros only.

The probability distribution of the layer value ℓ for a random hash obeys the geometric distribution law. For the base of the number system L , the probability that the block belongs to layer k is:

$$P_r(\ell = k) = \begin{cases} ((L-1)/L) \cdot (1/L)^k, & 0 \leq k < N \\ (1/L)^N, & k = N \end{cases}.$$

This distribution is a key for subsequent analysis of WF properties and consensus security.

Definition 2: MLHA block structure. Block B in the MLHA system is a tuple:

$$B = (h, prev, data, t, \eta),$$

where $h = H(prev||t||\eta||data)$ is the cryptographic hash of the block; $prev = (prev[0], prev[1], \dots, prev[N])$ is an array of length $N+1$ containing references to the last blocks of each layer; the $prev[j]$ element stores the hash of the block that was the last block of layer j at the time of creating this block (or null if this block didn't exist yet); $data$ is the set of atomic facts included in the block; t is the timestamp; η is a nonce used to achieve the required PoW complexity.

Constructing a new block. Let B_{prev} be the last block of the chain at the time of mining. The new B_{new} block is constructed as follows:

1. A copy of the $prev$ array from B_{prev} is created.
2. In this copy, the element $prev[\ell]$, where $\ell = \text{layer}(B_{prev})$, is replaced with $\text{hash}(B_{prev})$.
3. The current timestamp t and the initial value $n = 0$ are set.
4. The hash $h = H(prev||t||\eta||data)$ is calculated. If the resulting hash satisfies the network complexity (has at least D leading zeros), the block is considered ready; otherwise, η changes (for example, it is incremented) and the hash is recalculated until the condition is reached.

Thus, each new block “remembers” the last blocks of all layers at the time of its creation, while updating the reference for the layer of its immediate predecessor. Link redundancy is a central element of MLHA, which provides the ability to restore connectivity later after deleting a part of the history.

Initial block validation. Block B is considered valid if the following conditions are met:

1. $h = H(prev||t||\eta||data)$ is the hash that matches the calculated one.
2. Hash h satisfies the current PoW complexity requirement ($\ell \geq D$).
3. If the block is not a genesis block, then it must be constructed based on the specific previous block B_{prev} immediately preceding it in the chain. For such a block, the equality $prev[\ell(B_{prev})]$ must be $= \text{hash}(B_{prev})$, where $\ell(B_{prev})$ is the layer of the previous block. In other words, each non-genesis block must explicitly refer to its direct predecessor through the cell of the $prev$ array that corresponds to the layer of this predecessor.
4. The timestamp in the block is larger than the timestamp in the previous block.
5. If the block is located in the temporary security window and the block is not extreme to the border of the security window on the left, then it is verified whether all links from the predecessor are inherited correctly.
6. The content of blocks does not contradict the rules of a specific FOB instance (verified by an external block validation function. Allows you to customize the FOB for specific use-cases).

These conditions define the protocol for creating and first verifying blocks in MLHA. The next section is devoted to selecting and analyzing the WF chain skeleton, which is formed based on the entered layers and validation of the entire chain.

WF concept and properties

The redundant $prev$ link introduced in the MLHA block structure makes it possible to form an MLHA “skeleton” (WF) in any MLHA chain – a skeleton that preserves cryptographic connectivity with all blocks that have ever existed while growing at a rate significantly slower than that of the full history. Conceptually, the WF comprises exactly those blocks that cannot be deleted without losing the ability to restore the full history, and which at the same time serve as the minimal carrier of PoW for the entire chain. Formally, whether a block belongs to a WF is determined using the *isIndexInWaterflow* predicate ($WF(i)$), which implements a simple rule: a block remains in the skeleton if no later block has a strictly larger layer.

Definition 3: WF.

Let us assume a chain of blocks $B = (B_0, B_1, \dots, B_{m-1})$ that is valid according to the MLHA rules. For the index $i \in \{0, \dots, m-1\}$, we define the predicate WF:

$$WF(i) = \begin{cases} \text{true}, & \nexists j > i : \ell(B_j) > \ell(B_i) \\ \text{false}, & \exists j > i : \ell(B_j) > \ell(B_i) \end{cases},$$

where $\ell(B)$ is the layer of block B .

The WF of the chain B is the set of indices $W = \{i \in [0, m-1] | WF(i) = \text{true}\}$. Blocks with indices from W are WF blocks (B_W).

Lemma 1: WF criteria and properties.

For any blockchain built in accordance with the MLHA protocol, the following statements are true:

1. WF criteria. A block B_i is a WF block if and only if, among all blocks with indices $j > i$, there is not a single block with a layer strictly larger than $\ell(B_i)$, i.e., $WF(i) \Leftrightarrow \max_{j > i} \ell(B_j) \leq \ell(B_i)$.
2. Boundary blocks. Genesis-block B_0 and the most recent block B_{m-1} always belong to the WF: $B_0 \in WF$ and $B_{m-1} \in WF$.
3. Uniqueness and determinism. For a fixed chain B , the $WF(B)$ is defined unambiguously and does not depend on the order in which blocks are checked.

Statement 1 (WF criterion) is a direct consequence of the definition of the predicate WF.

Statement 2 on boundary blocks can be proved by the inverse method:

The genesis block. Let us assume that $WF(0) = \text{false} \rightarrow$ by the WF criterion, there must be an index $j > 0$, where $\ell(B_j) > \ell(B_0)$. However, the genesis block by definition has the maximum possible layer N (in binary representation, since its hash is artificially set to N zeros. No other block can have a layer greater than N (exceeding the hash bit limit). Hence, $\ell(B_j) > \ell(B_0)$ is impossible for any j . Contradiction, $\rightarrow WF(0) = \text{true}$.

The last block. Let us assume that the last block B_{m-1} is not included in the WF, i.e., $WF(m-1) = \text{false}$. Then there must exist an index $j > m-1$ with $\ell(B_j) > \ell(B_{m-1})$. However, the set of indices $j > m-1$ is empty, such a j does not exist. Contradiction, $\rightarrow WF(m-1) = \text{true}$.

Statement 3 on uniqueness and determinism is also proved by the inverse method:

Let us assume that the WF is not unique, i.e., there are two different sets $W_1 \neq W_2$, each of which satisfies the definition of a WF (it consists of indices whose blocks do not have blocks of a strictly larger layer on the right). Without limiting generality, we find the index $i \in W_1 \setminus W_2$. Since $i \notin W_2$, by definition there is an index $j > i$ such that $\ell(B_j) > \ell(B_i)$. But then the condition “there is no strictly larger layer on the right” for index i is violated, and i cannot belong to W_1 . This contradicts the choice of i . Similarly, we consider the case $i \in W_2 \setminus W_1 \rightarrow$ our assumption about the existence of two different WFs is false $\rightarrow$ WF is defined in a unique way and does not depend on any external factors, except for an ordered sequence of layers of blocks.

Next, we consider the size of WF and its asymptotic behavior.

Lemma 2: Logarithmic growth of the average WF length.

Let the block chain be built in accordance with the MLHA protocol. T is the total number of blocks created (including genesis), and L is the base of the hash number system. Then the mathematical expectation of the WF length $|W_T|$ satisfies the relation:

$$\mathbb{E}[|W_T|] = (L-1) \log_L T + 1 + o(1), \quad (T \rightarrow \infty).$$

In particular, for the binary representation ($L = 2$) at $T \rightarrow \infty$, the estimate $\mathbb{E}[|W_T|] \approx \log_2 T + 1$ is valid, and for the hexadecimal representation ($L = 16$) – $\mathbb{E}[|W_T|] \approx 15 \log_{16} T + 1$.

Consider a probabilistic model in which the hashes of all blocks are independent and evenly distributed in $\{0, 1\}^{512}$. The layer $k \in \{0, 1, \dots, N\}$ appears with probability:

$$p_k = \frac{L-1}{L} \cdot \frac{1}{L^k} (k < N), \quad p_N = \frac{1}{L^N}.$$

For $k < N$, the distribution function has the form $S_k = \Pr(\ell \leq k) = 1 - (1/L)^{k+1}$.

Genesis-block B_0 has a fixed maximum layer N and always enters the WF, adding +1 to its length.

Let us now consider the $T-1$ subsequent blocks $B_1, \dots, B_{T-1}$. A block B_i ($1 \leq i \leq T-1$) with a layer k falls into a WF if and only if none of the blocks $B_{i+1}, \dots, B_{T-1}$ has a layer strictly larger than k . For block B_i , there are $T-1-i$ blocks after it. The probability that they all have a layer $\leq k$ is $(S_k)^{T-1-i}$.

The mathematical expectation of the number of WF blocks in layer k among non-genesis blocks in the chain is:

$$E_k = p_k \sum_{i=1}^{T-1} (S_k)^{T-1-i} = p_k \sum_{m=0}^{T-2} (S_k)^m = p_k \left(\frac{1 - S_k^{T-1}}{1 - S_k} \right).$$

The last block B_{T-1} is always a WF block, with the multiplier $S_k^0 = 1$.

For layer N , the probability of p_N is negligible, and its contribution can be taken into account separately, but it does not change the asymptotes.

Thus, the full mathematical expectation of the WF length is:

$$\mathbb{E}[|W_T|] = 1 + \sum_{k=0}^{N-1} \frac{p_k}{1 - S_k} (1 - S_k^{T-1}) + \varepsilon_T,$$

where $\varepsilon_T \rightarrow 0$ for $T \rightarrow \infty$. Note that for all $k < N$, $\frac{p_k}{1 - S_k} = L - 1$ holds, since

$$\frac{p_k}{1 - S_k} = \frac{\frac{L-1}{L} \cdot \frac{1}{L^k}}{\frac{1}{L^{k+1}}} = L - 1.$$

For large T , the value of S_k^{T-1} decreases exponentially for all k for which $S_k < 1$, i.e., for $k < N$. For real T , layers with $k \geq \log_L T + c$ (for a certain constant c) give a negligible contribution, and the summation can be limited to the index $K_{\max} \approx \log_L T$. Let us estimate the sum $\sum_{k=0}^{N-1} (L-1)(1 - S_k^{T-1})$ asymptotically.

$K = \lfloor \log_L T \rfloor$. Let us split the sum into two parts:

$$\sum_{k=0}^{N-1} (L-1)(1 - S_k^{T-1}) = \sum_{k=0}^K (L-1)(1 - S_k^{T-1}) + o(1).$$

For $k \leq K$, we have $S_k = 1 - L^{-(k+1)}$, and $(1 - S_k^{T-1}) = 1 - (1 - L^{-(k+1)})^{T-1}$. For $T \gg L^{k+1}$, this expression is close to 1, and for $T \ll L^{k+1}$, it is close to 0. The boundary of the “maturation” of layer k is at $T \approx L^{k+1}$, i.e., $k \approx \log_L T - 1$. Hence, the sum $(L-1)(1 - S_k^{T-1})$ over k from 0 to K asymptotically behaves as $(L-1)$

multiplied by the number of layers for which $T \gg L^{k+1}$, plus the contribution from the transition layer. More strictly, using integral estimation, we can show that:

$$\sum_{k=0}^K (1 - S_k^{T-1}) = \log_L T + O(1), \quad (T \rightarrow \infty).$$

The mathematical expectation of the number of records in a sequence of independent random variables with a geometric distribution grows as $\log_L T$. Hence:

$$\mathbb{E}[\lceil W_T \rceil] = 1 + (L-1) \log_L T + O(1) = (L-1) \log_L T + 1 + o(1).$$

This completes the proof.

The above proof assumes that there is no minimum complexity. In a practical protocol with $D > 0$, the layer distribution is truncated from below: blocks with layer $k < D$ are not created. This leads to the fact that the mathematical expectation of the WF length is smaller, asymptotically preserving the form $(L-1) \log_L T + O(1)$. Thus, the lemma 2 gives an upper bound for the real system, which only strengthens the statement about logarithmic compression.

This reasoning demonstrates the scalability property of MLHA: the average size of the stored WF chain grows only logarithmically with the total number of blocks created, which is also confirmed experimentally.

Secure data deletion and audit

One of the central advantages of MLHA is the ability to selectively delete blocks that are not part of the WF, without losing the connectivity of the remaining chain and without compromising the ability to audit deleted data. This section introduces the safe deletion criterion and proves its correctness, as well as sets the auditability property for deleted blocks.

Let the chain $B = (B_0, B_1, \dots, B_{m-1})$ be valid according to the MLHA rules, and let i be the index of some block that is supposed to be deleted. $B_{Left} = B_{i-1}$ is the immediately preceding block (left), and $B_{Right} = B_{i+1}$ is the immediately following block (right). We restrict the boundary values i : $i \neq 0$ and $i \neq m-1$.

Definition 4: Secure deletion.

Deleting a B_i block is considered safe if all MLHA validation rules are successfully executed for each remaining block after it is removed from the chain.

Lemma 3: Safe deletion criteria.

Deleting the B_i block is safe if and only if the following conditions are met:

1. B_i is not a WF block, i.e., $WF(i) = \text{false}$.
2. B_{Right} block in its reference array in the hash slot of the B_{Left} block contains the hash of the B_{Left} block, i.e., $B_{Right}.prev[\ell(B_{Left})] = \text{hash}(B_{Left})$.
3. Deletion takes place outside the security windows (it will be considered when determining the validity of the MLHA chain).

If these conditions B_i are met, the chain remains valid after deleting B_i .

Proof:

The proof is carried out using the opposite method, establishing the necessity and sufficiency of each of the conditions.

Assume that deleting block B_i is safe, i.e., after it is excluded, the chain $B' = (B_0, \dots, B_{i-1}, B_{i+1}, \dots, B_{m-1})$ satisfies all MLHA validation rules.

- If condition 1 was violated, i.e., $WF(i) = \text{true}$, then block B_i would belong to the WF. By lemma 1, the WF of a chain is uniquely determined, and removing any element of it would destroy the uniqueness and determinism property of the WF for the chain, which would mean losing the full auditability property required from safe deletion. Hence, $WF(i) = \text{false}$.

- Suppose condition 2 was violated, i.e., $B_{Right}.prev[\ell(B_{Left})] \neq \text{hash}(B_{Left})$, however, after removing B_i block, the B_{Right} block must refer to B_{Left} as its immediate predecessor. However, according to the rules of primary block-level validation (see definition 2), each non-genesis block must contain *prev* the hash of its direct predecessor in $prev[\ell(\text{predecessor})]$. Since B_{Left} becomes the precursor of B_{Right} in B' , $B_{Right}.prev[\ell(B_{Left})] = \text{hash}(B_{Left})$ is necessary for B_{Right} to be valid, which contradicts the assumption that the condition is violated. So, condition 2 is true.

- Condition 3 (deletion outside security windows) will be explained later in the article.

Let conditions 1–3 be met. After deleting B_i , the chain B' differs from the valid chain B only by the absence of an element with index i . For each block $B_j \in B', j \neq i+1$, the *prev* reference array and hash of the previous block have not changed, and each block continues to satisfy the validation rules. It remains to check the block B_{i+1} (now immediately following B_{i-1}). Condition 2 holds $B_{i+1}.prev[\ell(B_{i-1})] = \text{hash}(B_{i-1})$, i.e., B_{i+1} correctly references the new predecessor through the required slot. Therefore, in the aggregate, B' is valid.

Corollary 1: Neighbor continuity invariant:

If you repeatedly apply safe deletion within the safe deletion criterion in any valid order, the resulting chain always retains the property: for any of its elements B_k (except B_0), B_k is executed $B_k.prev[\ell(B_{k-1})] = \text{hash}(B_{k-1})$, where B_{k-1} is the immediately preceding block in this resulting chain. In other words, the chain remains continuous in the sense of hash links connecting each block to its left neighbor through the layer of the latter.

Corollary 2: Auditability of data:

Let the block B_i be safely removed from the network, and let the local node B_i not remove block B_i . Then the local node has a sequence B' of locally preserved blocks, starting with B_i and ending with some WF block on the right (the WF of the local node is synchronized with the WF of the network), such that each subsequent block of the sequence B' contains in its *prev* array the hash of the previous one. This sequence can be found by using the optimal *prev* link traversal mechanism, resulting in a continuous chain with the beginning at B_i and the end B of the WF block closest to B_i on the right. Since WF blocks are stored by all full nodes of the network, any node that receives the sequence B' can independently verify the authenticity of B_i by sequentially calculating the hashes of the chain B' from B_i until the result of the hash is verified with the *prev hash of the WF block*. No external cryptographic proofs are required, except for the standard hash function used in the protocol.

Thus, lemma 3 and its consequences form the foundation on which to build: the ability to customize the cleaning policy (and therefore customize the individually defined data lifecycle at the application level) within the criteria of safe cleaning; data audit mechanisms; mechanisms for distributed storage of specific data blocks in specific MLHA nodes at the level of top-level requirements, etc.

Condition 3 regarding security windows will be integrated into the overall chain validation procedure at the network consensus level, which will complete the holistic definition of the secure deletion model.

Consensus protocol based on the lexicographic order of WF vectors

The proposed MLHA model provides a unique feature: a complete node stores only a WF chain skeleton, the size of which grows logarithmically, and yet it is able to independently and reliably select a canonical chain among several competing candidates. The central element of such a consensus is a strict lexicographic order relation on the set of WF vectors, which, as will be shown below, is monotonous with respect to adding new blocks and induces a preference equivalent to the classical principle of “greatest expected performance”.

Definition 5: WF vector.

Let B be a valid MLHA chain, $WF(B) = (B_0, \dots, B_{s-1})$ be its WF, where $i_0 = 0$ (genesis), $i_{s-1} = m-1$ (last block), and layers of WF blocks $\ell_t = \ell(B_t)$. The WF vector is the ordered set $v(B) = (\ell_0, \ell_1, \dots, \ell_{s-1})$.

By construction (lemma 1), the genesis always has a maximal layer N , and $v(B)$ is uniquely determined by the chain.

Definition 6: Lexicographic order.

For two vectors $u = (u_0, \dots, u_{a-1})$ and $v = (v_0, \dots, v_{b-1})$, we set $u < v$ if there exists an index $j < \min(a, b)$ such that $u_i = v_i$ for all $i < j$, and $u_j < v_j$, or if $a < b$ and $u_i = v_i$ for all $i < a$. Accordingly, $u \leq v$ means $u < v$ or $u = v$.

The algorithm for selecting the canonical max chain (hereinafter referred to as the max algorithm) for two valid chains A and B works as follows:

1. Select $WF(A)$ and $WF(B)$ and plot their vectors v_A and v_B .
2. If $v_A < v_B$, return B ; if $v_B < v_A$, return A .
3. If $v_A = v_B$ (the lengths and layers are exactly the same), to ensure determinism, compare the numerical values of the hashes of the first different blocks of chains (for example, as 512-bit integers); return the chain with a larger hash value.

Lemma 4: strict monotony of the WF vector

Let B be a valid MLHA chain, and B' is obtained from B by adding one new block B_{new} (followed by implicit updating of the set WF according to definition 3). Denote by $v = v(WF(B))$ and $v' = v(WF(B'))$ layer vectors of WF block chains B and B' , respectively. Then $v' > v$.

Proof:

Let $K = \ell(B_{new})$ be the layer of the new block. Consider how the WF changes after enabling B_{new} and redefining the WF set according to the criterion (no block with a strictly large layer on the right). There are two possible cases:

1. The new B_{new} block does not exclude other blocks from the WF . This means that after updating the WF , all blocks that were part of $WF(B)$ retain their status. Since $WF(B')$ contains all the elements of $WF(B)$ and another block B_{new} (located to the right of all the previous ones), the vector v' is obtained from v by appending the element K to the end. Thus, $|v'| = |v| + 1$ for all indices $i < |v|$ completed $v'_i = v_i$. By the definition of lexicographic order (the second condition in definition 6), $v' > v$.
2. The new block excludes $m \geq 1$ of the last WF blocks. Let $v = (v_0, v_1, \dots, v_{s-1})$ be the source vector, and let r be the index of the first of the excluded blocks ($0 \leq r \leq s-1$), so that the blocks $B_r, B_{r+1}, \dots, B_{s-1}$ cease to exist be a WF . By construction, all these blocks have layers strictly smaller than K : otherwise, a block with a larger or equal layer could not be excluded, since there would be no block to the right with a layer larger than its own. Hence, $v_r < K, v_{r+1} < K, \dots, v_{s-1} < K$. The new WF vector takes the form $v' = (v_0, v_1, \dots, v_{r-1}, K)$. Compare v and v' lexicographically. The first r elements match: $v'_0 = v_0, \dots, v'_{r-1} = v_{r-1}$. At position r , we have $v'_r = K > v_r$. Since the vector v' has a higher value on the first element that differs, the strict inequality $v' > v$ is satisfied.

Both cases exhaust possible changes to the WF when adding a new block. In all cases $v' > v$. The lemma is proved.

Corollary 3: Consistency with the classical PoW principle.

Lemma 4 states that when a new block is added, the WF vector of the chain progresses strictly lexicographically. Thus, the max algorithm will never prefer a shorter chain. Now we show that such a lexicographic order is in full agreement with the PoW fundamental principle: the chain representing the largest amount of computational work is recognized as canonical.

Each WF block of layer k is an objective proof that on average L^k hash operations were spent to create it. Although the specific sum $\sum L^{\ell(B_i)}$ along the WF does not have to be monotonic (statistical fluctuations can lead to the fact that a chain of many low layers formally gives a larger sum than a chain with one very high layer), the lexicographic order on the vectors adequately reflects exactly the expected costs. The reason is that a higher layer at the first different position means an exponentially rarer event that requires an exponentially larger number of attempts, and the probability that a chain

with such a vector was built with less total effort decreases rapidly with the growth of the layer difference. Consequently, of the two competing chains, the one with the lexicographically larger WF vector was overwhelmingly likely to require more computational resources.

Thus, the MLHA consensus inherits the main property of the classic PoW: an honest chain supported by the majority of computing power will have the lexicographically largest WF vector in the long run and will therefore be accepted by all nodes of the network.

Hashrate estimation via WF

Since each WF block of layer k requires on average L^k hash operations, the value $\sum L^{\ell(B_i)}$ calculated from a sufficiently long sliding time window Δt , which includes N WF blocks (each block has a timestamp), can be considered as an estimate of the expected work performed by the network for the corresponding time interval Δt . This estimate, although not strictly unbiased, can serve as an indicator of the current hashrate for the purpose of dynamically adapting the minimum mining complexity, especially when normalized to the average fraction of WF blocks or when used in relative (differential) mode. Dividing this amount by Δt , we get a practical estimate of the current network hashrate:

$$\hat{H} = \frac{1}{\Delta t} \sum_{i=1}^N L^{\ell(B_i)}.$$

This estimate relies exclusively on WF, does not require storing remote blocks, and naturally averages random fluctuations, making it a convenient tool for dynamically adapting security parameters.

Threat model and security parameterization

The WF and lexicographic consensus properties set out above ensure that with a fair majority, the canonical chain accumulates the most expected work. However, in a real decentralized network, it is necessary to additionally protect against two fundamentally different classes of attacks that exploit the features of the MLHA architecture: immediate link forgery attacks and deep reorganization attacks.

Attack vector I: link forgery with instant deletion.

The attacker creates a B_{adv} block, in which he intentionally specifies incorrect values in the *prev-Hash* fields for low layers, and distributes it over the network. As the last block of the chain, B_{adv} temporarily enters the WF and can be accepted by nodes if its layer allows you to win the race. Malicious links are not checked by the consensus protocol, because they belong to layers below the block layer itself. If a new block that intercepts the WF appears shortly after, the B_{adv} is no longer WF and can be erased from local storage according to the safe deletion criterion. As a result, history auditing becomes impossible for some blocks, because links to deleted blocks are invalid.

Attack vector II: deep reorganization (selfish mining).

The attacker secretly builds an alternative chain, starting with a block located much deeper than the current tip of the honest chain. Over a long period of time, he can accumulate a WF vector that exceeds the honest one if he managed to find blocks with abnormally high layers. When publishing such a fork, nodes that use the max algorithm may be forced to switch to it, rolling back already confirmed facts and breaking the stability of the registry.

Solution:

To neutralize attack I, it is necessary that the block remains available for verification by all nodes for some time before being deleted. During this period, each node of the network, when receiving a candidate chain, must check the correctness of *prev data* within the framework of the *prev* array copying principle in window A . Deleting any block will automatically break the validation of the principle of copying *prev data* from block to block.

To neutralize attack II, it is necessary to limit the maximum depth of automatic reorganization: a node must reject forks that have a common ancestor with the local chain older than a certain threshold T .

These two solutions, at first glance, contradict each other: for the reliability of the audit, it is desirable to increase A , while to minimize the damage from reorganizations, it is desirable to reduce T . However, both defense mechanisms, A and T , regulate the same fundamental parameter: the time during which the system remains vulnerable to attacks based on its instability. Auditing requires that the block is online long enough before it can be deleted; preventing deep reorganizations requires that the block cannot be undone after it has already been verified. Therefore, it is technically justified to put $A = T = \Delta$. The single window Δ defines the instability horizon: all blocks that go beyond the left window Δ are considered finalized – blocks and link validity are verified by the network, and attempts to cancel them are rejected by the switching policy. Inside the window Δ , there is a probabilistic consensus, in which a race at the tip of the chain is acceptable, and any damage from it is limited by the depth Δ .

We can now formulate a central MLHA security statement linking the *network hashrate*, the *security window* Δ , and the required *mining difficulty* D .

Theorem 1: Upper bound on the probability of a successful attack.

Let the attacker control a fraction of $q < 0.5$ of the total network hashrate, and let the honest network have the hashrate H_{hon} . Assume that the minimum mining difficulty is D leading zeros, and the single security window is Δ . Then the probability that an attacker will be able to carry out an attack of the first or second type (i.e., replace historical links or impose a deep reorganization) does not exceed

$$P_{attack} \leq \sum_{k=D}^N \left(1 - e^{-H_{att}L^{-k}\Delta}\right) \cdot e^{-H_{hon}L^{-k}\Delta},$$

where $H_{att} = q \cdot H_{hon} / (1-q)$ is the attacker's hashrate, N is the maximum layer, and L is the base of the number system.

Rationale: Both types of attacks require that the Δ attacker create at least one block with a sufficiently high layer that will give his fork a lexicographic advantage, while an honest network should not create any blocks with a comparable or larger layer. The processes of generating layer blocks $\geq k$ by an attacker and an honest network can be approximated by independent Poisson flows with intensities $H_{att}L^{-k}$ and $H_{hon}L^{-k}$, respectively. Summing over all layers $k \geq D$ the probabilities that an attacker will get at least one success, and an honest network-none, we get the upper bound of the desired probability (union bound).

Corollary 4: Parameterization of minimal complexity.

To ensure that the probability of a successful attack of any type does not exceed the specified threshold P_{max} , the minimum mining difficulty D must satisfy the inequality

$$D \geq \log_L \left(\frac{H_{att} \cdot \Delta}{P_{max}} \right),$$

where $H_{att} = q \cdot H_{hon} / (1-q)$ is the attacker's hashrate.

The formula provides a simple and measurable criterion for configuring the protocol: knowing the current hashrate H_{hon} (estimated through a WF) and choosing an acceptable risk level P_{max} (for example, 10^{-9}), the network can dynamically adjust the required number of leading zeros D , maintaining security even if the attacker uses the optimal strategy of secret mining and timestamp manipulation.

Results and discussion

Comparative analysis with analogs

Table 1 shows that MLHA occupies a unique niche: unlike NiPoPoW/FlyClient, which address the problem only for light clients, MLHA radically reduces the amount of data stored on each full node.

Table 1

MLHA comparison with key approaches to blockchain compression and auditing

Criteria	MLHA criterion (this paper)	NIPoPoW / FlyClient	Mina (IVC, zk SNARK)
Data growth at the full node	$O(\log_L T)$ – logarithmic of the number of blocks created	$O(T)$ (the full node stores the entire history)	$O(1)$ (constant, ~22KB)
Trustless history audit	Yes, through a WF and a continuous chain of headers	Requires requests to the full node and additional Merkle-proofs	No, the audit requires an archive node with intermediate proofs
Post-quantum persistence	Yes (hashes)	Yes (hashes)	None (based on elliptic curves)
Trusted setup	No	No	Universal (require heavy calculations)
Consensus mechanism	WF consensus mechanism (lexicographic comparison of skeletons), equivalent to PoW	Classic PoW (longest chain)	Ouroboros (Proof of Stake)
Compression configuration flexibility	Is high (choice of base L and cleaning policies)	Fixed (defined by the protocol)	Maximum compression (constant), but without the ability to store history

Compared to Mina, MLHA does not require heavy calculations, has post-quantum stability, and retains the ability to independently audit history without external archivists. Thus, MLHA provides simultaneous fulfillment of all four requirements formulated in the introduction: logarithmic growth of stored data, trustless auditing, decentralization, and post-quantum persistence.

Prototype results

For experimental verification of the developed theoretical propositions, a software prototype of MLHA in Java was created using the SHA-512 hash function in binary representation (base of the number system $L = 2$). The simulation was performed on a machine running Arch Linux with an Intel i7-10850H processor (12 cores, up to 5.1 GHz) and 32 GB of RAM. All results were averaged over an ensemble of 1000 independently evolving blockchains, which made it possible to almost completely eliminate random fluctuations and identify stable patterns.

Fig. 1 shows the system's behavior when using the “no more than 1000 blocks” cleanup policy, which allows non-WF blocks to accumulate until the total number of blocks in the chain exceeds the threshold of 1000, after which the safe deletion mechanism (size containment within 1000) is triggered. The abscissa axis shows the total number of created blocks T (from 0 to 11500), and the ordinate axis shows the chain size in blocks. The four curves reflect, respectively:

1. The actual average (over time and over 1000 implementations) number of blocks in the chain.
2. The actual global maximum of the chain size for the entire history.
3. The actual average length of the WF.
4. The theoretical updated (adjusted) average length of the WF.

Fig. 1 shows that the average chain size increases monotonically at the initial stage, after which it asymptotically approaches the 1000 block mark. The global maximum quickly reaches the threshold value and then does not change, which confirms the correct operation of the cleaning policy and the correct restriction of unlimited chain growth. Against this background, the behavior of a WF is particularly remarkable: its average length remains extremely small and does not depend on how many non-WF blocks are accumulated in the chain. The actual and theoretical curves for the WF merge into one line, which clearly demonstrates the high accuracy of the refined analytical model even at relatively short time intervals.

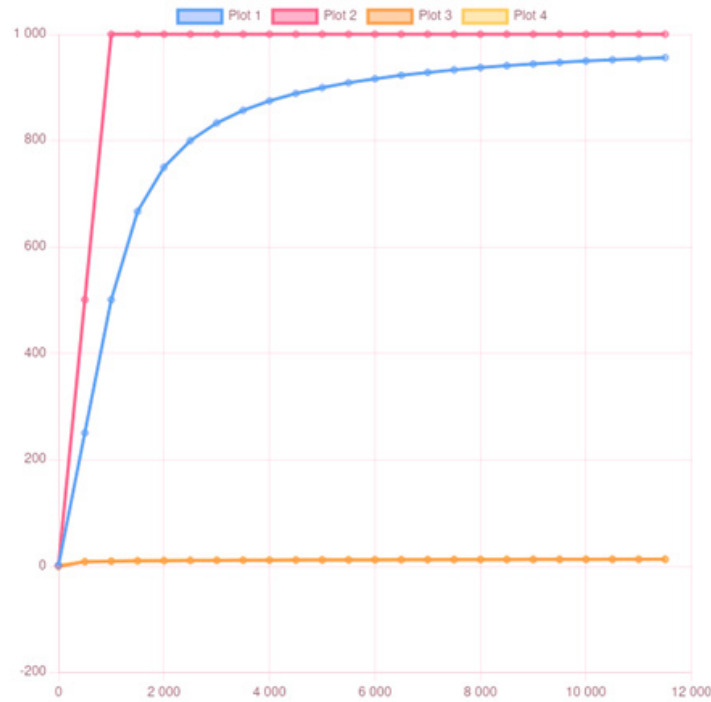


Fig. 1. Dynamics of the chain size under the “no more than 1000 blocks” restriction policy

Fig. 2 shows in detail the scalability of MLHA over the interval up to $T = 20000$ created blocks in the binary number system. Here, only the WF characteristics are plotted along the ordinate axis:

1. The actual average for all blockchains and all time points.
2. Global maximum WF length among 1000 chains.
3. Theoretical approximate value of $\log_2 T$.
4. A theoretical refined value that takes into account +1 and the exponentially decaying tail of the distribution.

The actual average and the refined theoretical curve are indistinguishable; their divergence is tenths of a block over the entire range studied. This is a direct experimental confirmation of lemma 2 on the logarithmic growth of a WF. The approximate formula $\log_2 T$ (removed the tail and 1) gives slightly lower values (especially at small T), which is explained by the neglect of the tail, but with increasing T , it quickly approaches the value of the exact curve -1 .

Special attention should be paid to the global maximum length of the WF. It has a characteristic step structure: each jump up occurs at the moment when one of the 1000 chains “delays” the appearance of a block with a new, higher layer, which should “displace” part of the chain. This step pattern is a visual representation of the probabilistic nature of MLHA consensus and is fully consistent with the predictions of the theory. It is important to note that the global maximum of 1000 chains does not even exceed 50 blocks with 20000 created, which emphasizes the practical compactness of the WF.

Fig. 3 shows the results of the simulation with the “no more than 1000 blocks” policy for the interval up to $T = 635'000$ blocks created. Four curves that characterize both the complete chain and its WF skeleton are combined on one field:

1. The actual average number of blocks in the chain.
2. The actual global maximum of the chain size.
3. The actual average number of blocks in the WF.
4. Theoretical refined value of the number of blocks in a WF, taking into account +1 and the exponentially decaying tail of the distribution.

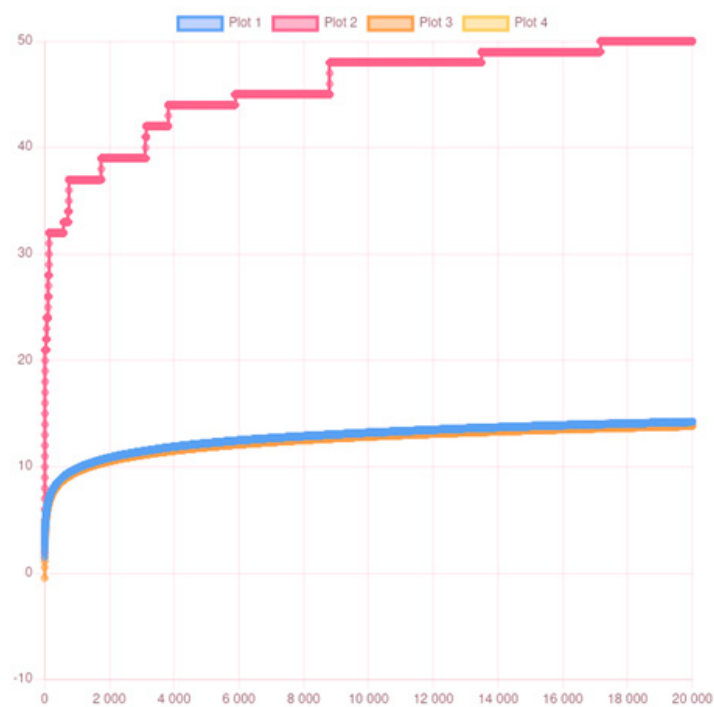


Fig. 2. Logarithmic WF growth and verification of the theoretical estimate



Fig. 3. Comparison of full chain and WF under controlled growth

The behavior of the complete chain (lines 1 and 2) demonstrates the rapid achievement of a near-equilibrium state. After a period of initial linear growth, the average number of blocks stabilizes near the specified threshold of 1000 blocks, and the global maximum, once touching this value, then

remains unchanged. This clearly demonstrates that the cleanup policy effectively limits the size of the chain, preventing its uncontrolled expansion.

Against the background of these two almost horizontal lines, the behavior of the WF (lines 3 and 4) looks particularly revealing. Despite the fact that the full chain constantly contains about 1000 blocks, its skeletal skeleton (WF) remains several orders of magnitude smaller. The actual and theoretical curves for the WF are indistinguishable, which once again confirms the high accuracy of the developed analytical model.

The scale of the graph makes this logarithmic growth of the WF visually almost invisible against the background of the stabilized size of the full chain. And it doesn't make sense to make a comparison chart with the classic PoW at this scale. This is the key advantage of MLHA: the main amount of data stored can be dictated by application policy (in this case, 1000 blocks), but the cryptographic skeleton that is critical for consensus and audit remains exponentially more compact. Even after more than half a million blocks have been created, it is enough to store only a few dozen WF blocks to fully verify and audit the entire network history. A long simulation horizon ($T = 635'000$) and averaging the result over 1000 parallel runs strongly proves that this property is a stable, not short-term effect, and that the system does not degrade over time.

Thus, Fig. 3 serves as a clear demonstration of the effectiveness of the proposed method: it demonstrates how the MLHA architecture allows you to completely separate chain size management from the fundamental requirements of consensus (WF storage), while ensuring strict mathematical predictability of the latter.

Thus, the experimental part of the work fully confirms the viability and scalability of the proposed method. The resulting graphs are a clear illustration of how the structural redundancy of PoW provides an efficient mechanism for controlled chain compression without loss of cryptographic completeness.

Synchronization mechanism and WF block addressing

The proposed WF structure makes it possible to implement an efficient full node bootstrapping procedure and a unified mechanism for addressing arbitrary blocks without storing the full history.

When a node connects to the network, it performs two actions:

1. Gets the current WF from peers.
2. Requests and receives all blocks located on the network within the security window Δ and not included in the WF.

After that, the node is able to independently verify the consensus state and participate in it, storing only $O(\log_L T)$ WF blocks and a small amount of data for validation, if the node's policy does not allow skipping primary synchronization and compressing the security window Δ .

WF addressing

Since each block B in MLHA is characterized by a layer $\ell(B)$ and a position in the chain, it can be uniquely identified by the vector $\langle c_{\ell_{\max}}, c_{\ell_{\max}-1}, \dots, c_0 \rangle$, where c_k is the sequence number of the block in the sequence of WF blocks of layer k containing B or associated with it. In other words, the address specifies the path in the hierarchy of layers from the rarest (genesis) to the most frequent (layer 0). This method of addressing allows you to search for blocks in logarithmic time, simplifies the work of decentralized auditing, and is itself a naturally routable unit of the network.

Thus, WF not only provides compact storage, but can also serve as a universal mechanism for navigating the entire history of the blockchain.

Conclusion

MLHA offers a unique combination of properties: it makes the blockchain compact for a regular node, but at the same time retains security, post-quantum stability, and does not require creating "master keys" or performing complex cryptographic ceremonies at launch. In other words, consensus-critical data now grows logarithmically, and individual archive nodes can be responsible for storing the full history.

The key scientific result is the development of a fundamentally new method for organizing the blockchain, in which the structural redundancy of PoW itself is used to build a sparse but cryptographically complete chain skeleton that can replace the full history with minimizing losses in PoW. It is shown that the structural redundancy of PoW-hashes can be effectively used to create optimizations both within the framework of the blockchain structure and for consensus algorithms. The novelty of the work is determined by the following main results:

- The concept of WF is introduced. The WF membership criterion, its uniqueness and determinism are proved (lemma 1).
- It is proved that the mathematical expectation of the WF length grows as $O(\log_L T)$, where L is the base of the hash number system, and T is the total number of blocks created (lemma 2). This result establishes the fundamental possibility of exponential compression of the blockchain's history.
- A criterion for secure block deletion (lemma 3) has been developed, which guarantees the preservation of cryptographic connectivity and the ability to audit any deleted block. It is shown that the audit does not require external cryptographic proofs or trusted archivists.
- A consensus protocol based on lexicographic comparison of WF vectors is proposed and its strict monotonicity is proved (lemma 4). This consensus is consistent with the principles of classical PoW (corollary 3).
- A probabilistic threat model covering different attack vectors is constructed. The concept of a single security window linking the network hashrate, minimum mining complexity, and acceptable attack probability is introduced. An upper bound on the probability of a successful attack is obtained (theorem 1) and the minimum complexity parameterization formula is derived (corollary 4).
- A method for estimating the current network hashrate is developed, based solely on WF blocks, which does not require storing the full history.

The results obtained are of fundamental importance for the theory of distributed ledgers, as they demonstrate the possibility of building a PoW blockchain in which each full node stores a sublinear amount of data, without sacrificing either decentralization, audibility of history, post-quantum stability, or processor power. The MLHA method opens up a new research area-structural compression of blockchains based on internal PoW statistics.

From a practical point of view, MLHA can become the basis for creating lightweight decentralized registries in areas such as the Internet of Things (IoT), distributed document management, certification and logging systems, where node resources are limited, but the requirements for long-term data verifiability are high. The ability to adjust the base of the L number system allows you to flexibly adjust the balance between compression ratio and overhead.

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