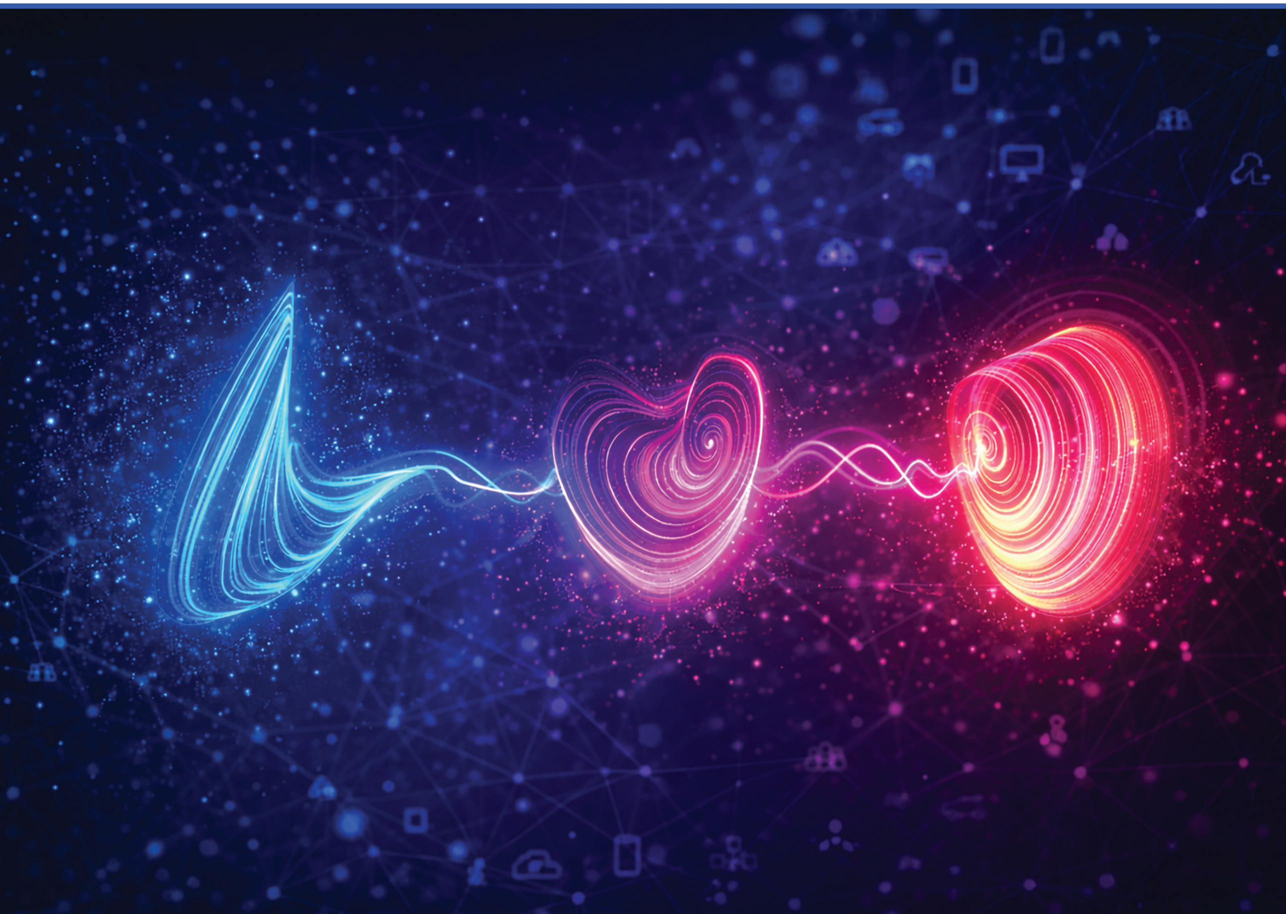
RIGA TECHNICAL
UNIVERSITY

Darja Čirjuļina

DESIGN AND PERFORMANCE EVALUATION OF CHAOS-BASED COMMUNICATION SYSTEMS UNDER NOISE AND MULTIPATH CONDITIONS

Summary of the Doctoral Thesis



RTU Press
Riga 2026

RIGA TECHNICAL UNIVERSITY
Faculty of Computer Science, Information Technology and Energy
Institute of Photonics, Electronics and Telecommunications

Darja Čirjuļina

Doctoral Student of the Study Programme “Electronics”

DESIGN AND PERFORMANCE EVALUATION OF CHAOS-BASED COMMUNICATION SYSTEMS UNDER NOISE AND MULTIPATH CONDITIONS

Summary of the Doctoral Thesis

Scientific supervisors:

Associate Professor Ph. D.
DENISS KOLOSOVS

Professor Dr. sc. ing.
DMITRIJS PIKUĻINS

Tenured Professor Ph. D.
XIAODAN PANG

RTU Press
Riga 2026

Čirjuļina, D. Design and Performance Evaluation of Chaos-Based Communication Systems under Noise and Multipath Conditions. Summary of the Doctoral Thesis. – Riga: RTU Press, 2026. – 50 p.

Published in accordance with the decision of the Promotion Council "RTU P-08" of 2 February 2026, Minutes No. 47.

Finansē Eiropas Savienība
NextGenerationEU

2027
Nacionālais attīstības plāns

The research was partially supported by research and development grant No. RTU-PA-2024/1-0064 under the EU RRF project No. 5.2.1.1.i.0/2/24/I/CFLA/003.

Cover image created using ChatGPT.
https://doi.org/10.7250/9789934372773
ISBN 978-9934-37-277-3 (pdf)

DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on 24 April 2026 at 11:00 at the Faculty of Computer Science, Information Technology and Energy of Riga Technical University, 12 Āzenes Street, Room 201.

OFFICIAL REVIEWERS

Associate Professor Dr. sc. ing. Aleksandrs Ipatovs
Riga Technical University

Professor Dr. Christos Volos
Aristotle University of Thessaloniki, Greece

Assistant Professor Ph. D. Lazaros Moysis
University of Nova Gorica, Slovenia

DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Darja Čirjuļina ______________________

Date: ______________________________

The Doctoral Thesis has been written in English. It consists of Introduction, four sections, Conclusions, 51 figures, eight tables, two appendices; the total number of pages is 97, not including appendices. The Bibliography contains 73 titles.

CONTENTS

ACRONYMS

ADP3450 Digilent's Analog Discovery Pro

AWGN additive white Gaussian noise

BER bit error rate

BJT bipolar junction transistor

CSK chaos shift keying

DC direct current

DCSK differential chaos shift keying

ETSI European Telecommunications Standards Institute

FM frequency modulation

FM-CSK frequency modulated chaos shift keying

FSK frequency shift keying

HPF high-pass filter

IF intermediate frequency

IoT Internet-of-Things

LPF low-pass filter

PCB printed circuit board

PLS physical layer security

PSD power spectral density

QAM quadrature amplitude modulation

QCSK quadrature chaos shift keying

RF radio frequency

SNR signal-to-noise ratio

WSN wireless sensor network

Z1TEST 0–1 test for chaos

INTRODUCTION

Rationale

The rapid expansion of Internet-of-Things (IoT) infrastructures is transforming conventional environments into interconnected smart ecosystems, enabling applications in healthcare, smart cities, industrial automation, and environmental monitoring. According to the Ericsson Mobility Report [1], the number of IoT-connected devices is expected to grow sharply in the coming years, driven by advances in 5G and beyond. This growth significantly increases the amount of sensitive data transmitted over wireless channels, heightening the importance of secure, reliable, and resource-efficient communication mechanisms.

Security in IoT networks is predominantly handled through cryptographic mechanisms operating at higher protocol layers, including link-, network-, and application-layer encryption and authentication techniques [2], [3]. These methods provide strong protection for data confidentiality and integrity once a communication link has been established; however, they often introduce considerable computational and energy overhead, which is problematic for resource-constrained IoT devices [4], [5]. Complementary architectural approaches, such as fog computing and software-defined networking, enable localized processing and centralized traffic control, potentially reducing latency and improving manageability, but at the cost of increased system complexity and new security challenges related to control-plane vulnerabilities and heterogeneous network architectures [6], [7]. Importantly, security mechanisms operating at higher protocol layers are inherently limited in mitigating attacks that exploit the wireless transmission medium itself, such as jamming, passive eavesdropping, or man-in-the-middle interference during signal propagation [8].

To address these limitations, physical layer security (PLS) has emerged as a complementary security measure that exploits inherent properties of the communication medium and device-specific characteristics rather than replacing cryptographic protection [9], [10]. By leveraging hardware imperfections and signal-level features, PLS enhances confidentiality and resilience without relying on computationally intensive cryptographic operations, making it particularly attractive for low-power and resource-constrained IoT devices. Techniques including artificial noise injection and radio-frequency fingerprinting further strengthen PLS by degrading an eavesdropper's reception quality or enabling device authentication at the signal level [11], [12].

Among the promising developments within PLS is the integration of chaos theory, which enhances security by exploiting the inherent unpredictability of chaotic signals. Chaos-based communication techniques offer a compelling solution for secure data transmission, particularly in IoT sensor networks where devices are constrained in terms of computational complexity and energy consumption. The reason is that these systems rely on relatively simple analog chaos oscillators rather than conventional encryption-based security mechanisms [8]. Chaotic systems such as the Lorenz and Chua circuits have been effectively utilized in chaos-based communication schemes to secure data transmission [13]–[15]. These systems generate wide-band, noise-like waveforms, being sensitive at the same time to initial conditions, which makes them well-suited for enhancing information security. In coherent chaos-based implementations, accurate data recovery requires precise synchronization between the transmitter and receiver chaotic oscillators, thereby introducing an additional security layer, since any disruption of synchronization renders the intercepted signal unreadable and significantly complicates unauthorized access [16].

A variety of chaos-based modulation techniques have been proposed to exploit these properties, including chaos shift keying (CSK), differential chaos shift keying (DCSK), and their extensions [16]–[19]. These schemes benefit from the inherent decorrelation and wide-band nature of chaotic signals, which enhances resilience to interception and narrow-band interference. Recent studies have also explored the integration of chaos-based signaling with multi-carrier and multiple-input multiple-output configurations to improve spectral efficiency and robustness while preserving security properties [17], [20].

Researchers are developing advanced chaotic models to overcome limitations of existing systems, such as high complexity and limited resilience to noise. Innovations such as the exponential chaotic model have introduced the concept of robust chaos, defined as a dynamical regime in which chaotic behavior persists over a continuous range of system parameters without the emergence of periodic windows or coexisting stable attractors. Therefore, small parameter perturbations do not suppress the chaotic attractor, which is particularly advantageous for secure communication systems operating under component tolerances and channel noise [21]–[23]. Beyond communication, chaos has found applications in multimedia security and the generation of random numbers [24]–[26]. Advanced image encryption algorithms based on dynamic chaotic systems provide robustness against statistical and differential attacks and ensure data integrity in IoT environments [12], [27]–[30].

Chaotic signals are generally wide-band, but they can be characterized by the fundamental (basic) frequency value. This frequency primarily depends on the nominal values of components chosen during circuit design [31]. Alternatively, in some cases, the frequency can be controlled by adjusting the operational amplifier gain value [32]. Most implementations of chaotic analog oscillators using discrete circuit components have a sub-MHz fundamental frequency, the increase of which is limited due to the use of an operational amplifier (if present) [31]. Some reports on chaotic oscillator implementations in ultrahigh-frequency ranges [33]–[35] are available, but they require more advanced high-frequency technologies, such as resonant tunneling diodes and integrated chaotic circuits. Changing the chaotic oscillator frequency can be beneficial in chaotic communication systems to increase the data transmission rate, differentiate between multiple user channels, or implement frequency-hopping modulation schemes.

Another critical aspect of chaos-based communication systems is synchronization, which enables reliable data transmission and receiving in IoT and wireless sensor network (WSN). At its core, chaotic synchronization ensures that the state variables of a receiver's chaotic oscillator replicate those of the transmitter's oscillator, enabling precise signal decoding. Techniques like the Pecora–Carroll method [36] and adaptive control [37], [38] are commonly used to achieve synchronization by coupling specific state variables between drive and response oscillators.

Research on the topic has consistently emphasized the critical role of synchronization stability in the performance of chaos-based systems [39]–[41]. For instance, studies on systems such as the Vilnius chaos oscillator emphasize the importance of stable synchronization methods to overcome noise, parameter deviations, and environmental variability [42]. This is particularly crucial in applications of chaos-based communication, where synchronization directly impacts the system's ability to securely and accurately transmit data [43]–[45].

In practical wireless deployments, chaos-based signaling must also be compatible with radio frequency (RF) transmission and resilient to multipath propagation. The integration of chaotic waveforms with conventional modulation techniques, such as quadrature amplitude modulation (QAM) and frequency modulation (FM), enables operation within regulated frequency bands and compatibility with existing transceiver hardware. At the same time, multipath-induced frequency-selective fading remains a dominant impairment in wireless sensor networks, motivating comparative studies between chaos-based and conventional communication schemes under realistic propagation conditions [46].

The Objective Statement and the Tasks

The **objective** of this Doctoral Thesis is to investigate the dynamical and synchronization properties of chaotic oscillators from a chaos-based communication system design perspective. The Thesis examines the impact of the oscillator's fundamental frequency on data rate and formulates a systematic methodology for developing chaos-based communication architectures that ensure noise-resilient transmission in additive white Gaussian noise (AWGN) and two-ray propagation channels.

The fulfillment of the objective is established through quantitative analysis of chaotic dynamics, synchronization quality, correlation properties, and bit error rate (BER) performance in both simulation and experimental implementations.

The following **tasks** are stated to achieve the previously defined objective:

- To analyze the influence of the fundamental frequency on the dynamical properties of chaotic oscillators, including spectral characteristics, oscillator signals cross-correlation, and aperiodicity, using LTspice simulations and hardware prototypes.
- To investigate the noise immunity of chaotic oscillator synchronization when different oscillator state variables are used as synchronization signals, and to quantify synchronization quality using correlation-based metrics.
- To study the impact of unequal correlation levels between received and synchronized oscillator's regenerated signals among state variables on CSK-based communication systems, and

to estimate the resulting error probability imbalance in correlation-based data detection.

- To develop a technique for optimal decision-making threshold calculation that ensures balanced symbol detection and error probability minimization in CSK-based communication systems.
- To design and implement chaos-based communication systems that employ advanced modulation techniques, including QAM and FM, enabling the radio-frequency transmission.
- To evaluate the noise immunity of the proposed chaos-based communication systems under AWGN and multipath propagation conditions, and to compare their performance with conventional modulation schemes.

The effectiveness of the proposed approaches is demonstrated through comparative simulation and experimental studies, focusing on synchronization quality, achievable data rates, and bit error rate metrics under various channel conditions.

Research Methodology

The research presented in this Doctoral Thesis follows a systematic methodology based primarily on numerical simulations and hardware measurements aimed at investigating chaotic oscillator dynamics, synchronization behavior, and their application in chaos-based communication systems. The work combines theoretical modeling and experimental validation to ensure consistency and reproducibility of the obtained results.

At the initial stage, an extensive review of the scientific literature on chaotic oscillators, chaotic synchronization, and chaos-based data transmission techniques was conducted. This review provided the background required to identify open research questions related to oscillator parameter variation, synchronization stability, and system-level performance in practical communication environments.

Accurate modeling is essential when analyzing nonlinear and chaotic systems. Therefore, the research begins with the development and validation of circuit-level models of chaotic oscillators. Two structurally distinct oscillators–the Colpitts and Vilnius chaotic oscillators–are selected to ensure generality of the observations. Their behavior is examined under variations of the fundamental frequency to analyze changes in spectral characteristics, the cross-correlation properties of generated signals, and time-lag behavior relevant to symbol duration selection.

The methodology is based on a structured research framework that integrates both sequential and parallel stages:

- Development and validation of chaotic oscillator models using circuit simulations and experimental prototypes.
- Analysis of oscillator dynamics under fundamental frequency variation, including spectral properties and generated signals' cross-correlation behavior.
- Investigation of chaotic synchronization properties in drive–response configurations under

additive noise conditions.

- Evaluation of multiple circuit nodes as potential synchronization signals using correlation-based metrics.
- Identification of synchronization quality when different state variables are used as synchronization signals and estimation of the impact of synchronization quality on correlation-based data detection.
- Expression of the optimal detection threshold to compensate for error probability imbalance and restore balanced symbol detection.
- Integration of chaotic baseband transmission with advanced modulation techniques, including QAM and FM.
- Performance evaluation of chaos-based communication systems in AWGN and two-ray propagation channels using simulation and experimental measurements.

Simulations are carried out using LTspice for chaotic oscillator modeling and MATLAB for signal processing, synchronization analysis, and bit error rate evaluation. Experimental validation is performed using custom-built hardware prototypes and commercially available modulation and measurement equipment. This combined approach ensures that both simulation and experimental proof support the conclusions drawn in this Thesis.

Scientific Novelty and Main Results

The scientific contributions of this Doctoral Thesis are based on original system-level analysis and design methodology, circuit-level simulations, and experimental investigations of chaos-based communication systems. Several of the proposed methods and observations are either introduced for the first time or represent a novel application of nonlinear dynamics and synchronization theory to practical communication system design. The main elements of scientific novelty are summarized as follows:

- For the first time, the relationship between the fundamental frequency of an analog chaotic oscillator and the achievable data rate of a chaos-based communication system is quantitatively established using a lag-based analysis of cross-correlation functions applied to simulated and experimentally measured signals.
- For the first time, it is experimentally demonstrated that different state variables of the same chaotic oscillator can exhibit significantly different correlation levels under identical coupling conditions, despite the use of a single synchronization signal.
- It is shown that unequal correlation levels between data-carrying chaotic signals lead to systematic imbalance in correlation-based detection, resulting in asymmetric symbol decision errors in chaos-based communication systems.
- For the first time, an error-probability-optimal compensation-based decision threshold for-

mulation is derived for correlation-based detection with correlated chaotic carriers, restoring decision symmetry without modifying the synchronization mechanism.

- The influence of synchronization signal selection on the bit error rate performance of chaos-based communication systems is experimentally demonstrated and quantified under additive noise and multipath propagation conditions.

In addition to the scientific contributions, this Thesis provides several important practical and methodological results that support the design and evaluation of chaos-based communication systems:

- A reusable evaluation workflow for chaos-based communication systems is established, combining LTspice circuit-level simulations, MATLAB-based signal processing, and hardware prototype measurements, enabling consistent analysis of chaotic oscillator dynamics, synchronization behavior, and communication performance. The developed simulation and signal processing codes are publicly available on GitHub.
- A systematic methodology for selecting synchronization signals in chaos-based communication systems is established, providing a structured workflow based on noise immunity, correlation properties, and practical signal accessibility to ensure balanced chaotic synchronization.
- A practical approach for integrating chaos shift keying with quadrature and frequency modulation is demonstrated, enabling chaotic baseband signals generated by analog oscillators to be upconverted to arbitrary carrier frequencies compatible with conventional RF transmission systems.
- An experimental procedure for assessing the noise immunity of quadrature chaos shift keying (QCSK) and frequency modulated chaos shift keying (FM-CSK) communication systems under AWGN conditions is provided, including detection, bit error rate estimation, and post-processing performed in MATLAB.
- A simulation-based methodology for evaluating the performance of chaos-based communication systems in multipath environments is presented using a two-ray propagation channel model, allowing direct and fair comparison with conventional modulation schemes under identical bandwidth and channel conditions.

Together, these results advance the understanding of how chaotic oscillator properties, synchronization signal selection, and modulation techniques influence the performance and reliability of chaos-based communication systems, providing a structured foundation for their application in practical wireless environments.

Theses to be Defended

1. In chaos shift keying communication systems based on chaotic oscillators, the symbol rate adjustment for Vilnius oscillator up to 55 kb/s and for Colpitts oscillator up to 166 kb/s can be

established through modification of the fundamental frequency of the oscillator.

2. In chaos shift keying communication system with non-equal correlation levels β_X, β_Y for the corresponding pairs of the received and synchronized oscillator's regenerated chaotic signals, the error probability minimizing optimal detection is achieved with threshold defined as:

$$\beta_{X'} \geq \beta_{Y'} + \frac{1}{2}\left(\beta_X - \beta_Y\right),$$

where $\beta_{X'}$ and $\beta_{Y'}$ are the correlation levels of the symbol-carrying chaotic pulses.

3. QCSK and FM-CSK communication systems based on Vilnius chaotic oscillator outperform correspondingly 4-QAM and 2-frequency shift keying (FSK) communication systems in a two-ray multipath channel with 3.25 dB notch at the carrier frequency, ensuring error probability of 3.29×10^{-3} and 1.52×10^{-3}, respectively.

Approbation and Practical Significance

The results presented in this Doctoral Thesis were obtained within the framework of applied research and experimental development activities carried out by the author during doctoral studies at Riga Technical University. The research evolved in close connection with ongoing academic, industrial, and applied research projects, ensuring both scientific relevance and practical applicability of the proposed chaos-based communication methods.

The scientific results of this Thesis have been published in peer-reviewed international journals and conference proceedings. The most significant publications directly reflecting the core contributions of this work are listed below. Publications in which the author is the first author are highlighted in **bold**. In one publication, the contribution was shared equally with the listed first author.

[45] D. Cirjulina et al. "Experimental Study on Frequency Modulated Chaos Shift Keying Communication System." In: *2022 Workshop on Microwave Theory and Techniques in Wireless Communications (MTTW)*. Riga, Latvia: IEEE, Oct. 2022, pp. 1–4. ISBN: 978-1-6654-6439-0. DOI: 10.1109/MTTW56973.2022.9942593

[46] R. Babajans et al. "Performance Analysis of Vilnius Chaos Oscillator-Based Digital Data Transmission Systems for IoT." en. In: *Electronics* 12.3 (Jan. 2023). Number: 3, p. 709. ISSN: 2079-9292. DOI: 10.3390/electronics12030709

[47] D. Cirjulina et al. "Fundamental Frequency Impact on Colpitts Chaos Oscillator Dynamics." In: *2023 Workshop on Microwave Theory and Technology in Wireless Communications (MTTW)*. Riga, Latvia: IEEE, Oct. 2023, pp. 19–23. ISBN: 9798350393491. DOI: 10.1109/MTTW59774.2023.10320021

[48] D. Cirjulina et al. "Experimental Study on Colpitts Chaotic Oscillator-Based Communication System Application for the Internet of Things." en. In: *Applied Sciences* 14.3 (Jan. 2024),

p. 1180. ISSN: 2076-3417. DOI: 10.3390/app14031180

[49] D. Cirjulina, R. Babajans, and D. Kolosovs. "Experimental Study on Quadrature Chaos Shift Keying Communication System." In: *2024 IEEE Workshop on Microwave Theory and Technology in Wireless Communications (MTTW)*. Riga, Latvia: IEEE, Oct. 2024, pp. 29–32. ISBN: 979-8-3315-3317-5. DOI: 10.1109/MTTW64344.2024.10742187

[50] D. Cirjulina et al. "Fundamental Frequency Impact on Vilnius Chaos Oscillator Dynamics." en. In: *16th Chaotic Modeling and Simulation International Conference*. Ed. by C. H. Skiadas and Y. Dimotikalis. Series Title: Springer Proceedings in Complexity. Cham: Springer Nature Switzerland, 2024, pp. 87–101. ISBN: 978-3-031-60906-0 978-3-031-60907-7. DOI: 10.1007/978-3-031-60907-7_8

[51] D. Cirjulina, R. Babajans, and D. Kolosovs. "Design Particularities of Quadrature Chaos Shift Keying Communication System with Enhanced Noise Immunity for IoT Applications." en. In: *Entropy* 27.3 (Mar. 2025), p. 296. ISSN: 1099-4300. DOI: 10.3390/e27030296

The research results of this Thesis were presented at international scientific conferences, workshops, and symposia, providing peer feedback and dissemination within the research community. The author presented the results of this Doctoral Thesis at the following international scientific conferences:

1. D. Cirjulina. "QCSK Communication System Performance in Multipath Propagation Channel," Days of Applied Nonlinearity and Complexity (DANOC 2026), Aristotle University of Thessaloniki, Thessaloniki, Greece, 23–25 January 2026.
2. D. Cirjulina. "Nonlinear Dynamics of the Colpitts Chaotic Oscillator Under Bias Voltage Tuning," RTU 66th International Scientific Conference, Riga Technical University, Riga, Latvia, 27 November 2025.
3. D. Cirjulina. "Synchronization Noise Immunity in the Vilnius Chaos Oscillator for Secure Communications in IoT," RTU 66th Student Scientific and Technical Conference, Riga Technical University, Riga, Latvia, 25 April 2025.
4. D. Cirjulina. "Experimental Study of a Quadrature Modulation Chaos Shift Keying-Based Data Transmission System," RTU 65th International Scientific Conference, Riga Technical University, Riga, Latvia, 11 October 2024.
5. D. Cirjulina. "Experimental Study on Quadrature Chaos Shift Keying Communication System," IEEE Workshop on Microwave Theory and Technology in Wireless Communications (MTTW 2024), IEEE Latvia COM/MTT/AP Joint Chapter, Riga, Latvia, 2–4 October 2024.
6. D. Cirjulina. "Experimental Study on Colpitts Chaotic Oscillator-Based Communication System Application for the Internet of Things," RTU 65th Student Scientific and Technical Conference, Riga Technical University, Riga, Latvia, 29 April 2024.
7. D. Cirjulina. "Experimental Study on Quadrature Chaos Shift Keying Communication System," Days of Applied Nonlinearity and Complexity (DANOC 2024), Aristotle University of

Thessaloniki, Thessaloniki, Greece, 12–14 January 2024.

8. D. Cirjulina. “Fundamental Frequency Impact on Colpitts Chaos Oscillator Dynamics,” RTU 64th International Scientific Conference, Riga Technical University, Riga, Latvia, 6 October 2023.
9. D. Cirjulina. “Fundamental Frequency Impact on Colpitts Chaos Oscillator Dynamics,” IEEE Workshop on Microwave Theory and Technology in Wireless Communications (MTTW 2023), IEEE Latvia COM/MTT/AP Joint Chapter, Riga Technical University, Riga, Latvia, 4–6 October 2023.
10. D. Cirjulina. “Fundamental Frequency Impact on Vilnius Chaos Oscillator Dynamics,” The 16th CHAOS 2023 International Conference, Technical University of Crete, Crete, Greece, 13–17 June 2023.
11. D. Cirjulina. “Experimental Study on Frequency Modulated Chaos Shift Keying Communication System,” IEEE Workshop on Microwave Theory and Techniques in Wireless Communications (MTTW 2022), IEEE Latvia COM/MTT/AP Joint Chapter, Riga, Latvia, 5–7 October 2022.

The research was conducted in parallel with participation in several national and institutional research projects, which supported the experimental validation, prototype development, and applied investigations addressed in this Thesis:

1. Digital Europe Programme (DIGITAL) “Microchip Competence Centre of the Republic of Latvia” 0B000-3.5.2-e/3 | 101217976 (01.10.2025–28.02.2027)
2. “Implementation of consolidation and management changes at RTU, LiepU, Rēzekne Academy of Technology and Latvian Maritime Academy and Liepāja Maritime College for progress towards excellence in higher education, science and innovation.” Grant No RTU-PA-2024/1-0064 under the EU RRF project No 5.2.1.1.i.0/2/24/I/CFLA/003 (01.01.2024–31.01.2026)
3. Internal funding of RTU “Exploring cyber-secure IoT data-driven agricultural management” 04000-1.3-e/24 | ZI-2024/7 (02.01.2024–31.12.2024)
4. Internal funding of RTU “Exploring the Next Generation IoT Network” 003000-3.1.2.1-e/14 | ZI-2023/3 (02.01.2023–31.12.2023)
5. SAM 8.2.2. “Strengthening of Ph. D. students and academic personnel of Riga Technical University and BA School of Business and Finance in the strategic fields of specialization” of the Specific Objective 8.2.2 “To Strengthen Academic Staff of Higher Education Institutions in Strategic Specialization Areas” of the Operational Program “Growth and Employment” and the RTU doctoral grant program. Project 03000-3.1.2.1-e/177 | 8.2.2.0/20/I/008. (01.12.2022–30.11.2023)
6. Internal funding of RTU “Frequency Modulated Chaos Manipulated Data Transmission System” 03000-3.1.1.1-e/145-1 | AM-2021/2 (07.06.2022–30.11.2022)
7. LZP fundamental and applied research project “Advanced wireless power transmission tech-

niques" 03000-3.1.2.1-e/4 | lzp-2021/1-0170 (03.01.2022–30.12.2024)

An essential practical outcome of the present Doctoral Thesis is the development and application of an integrated simulation and experimental framework for chaos-based communication systems. The framework combines circuit-level modeling of chaotic oscillators in LTspice with signal processing, synchronization analysis, modulation, and detection implemented in MathWorks ® MATLAB. This approach enables the consistent evaluation of chaotic dynamics, synchronization stability, and communication performance under conditions of additive noise and multipath propagation.

The developed models and analysis procedures were utilized for both research purposes and practical validation through experimental measurements. The gained scientific and engineering experience was directly applied in the author's teaching activities at Riga Technical University. In particular, the results and methodologies developed during the PhD studies were incorporated into study courses related to signal processing, communication systems, and electronics, contributing to the improvement of course content and practical assignments.

During the doctoral studies, the author has been involved in teaching the following study courses at Riga Technical University:

- DE0848 – Digital Optical Communication Systems (6 ECTS).
- RDE713 – Digital Optical Communication Systems (6 ECTS).
- SDD701 – Innovative Product Development and Entrepreneurship (4 ECTS).
- RR713 – Digital Signal Processing (study project) (3 ECTS).
- RTR825 – Fundamentals of Smart Radio (study project) (3 ECTS).
- ERA708 – Research Seminars in the Field of Electronics (3 ECTS).
- RRI324 – Digital Signal Processing (3 ECTS).

The development of this Doctoral Thesis was further supported by international academic and research mobility, enabling collaboration with external research institutions and access to advanced experimental infrastructure. During the doctoral studies, the author remained employed at Riga Technical University while completing the following mobility periods:

- KTH Royal Institute of Technology, Sweden (01.05.2023–31.05.2023).
- Infineon Technologies Austria (18.09.2023–22.09.2023).
- Central European Student and Young Professionals Congress, Cracow University of Technology (30.11.2023–03.12.2023).
- Keysight Technologies GmbH, Germany (13.08.2024–21.08.2024).
- Politecnico di Torino, Italy (18.11.2024–22.11.2024).
- Keysight Technologies GmbH, Germany (18.02.2025–27.02.2025).
- Keysight Technologies GmbH, Germany (13.06.2025–20.06.2025).
- Keysight Technologies GmbH, Germany (26.08.2025–04.09.2025).
- Aristotle University of Thessaloniki, Greece (30.11.2025–05.12.2025).

The scientific and academic contributions of the author during doctoral studies were recognized by the following awards:

- IEEE Student & Young Professional (SYP) Travel Grant, 19.08.2025.
- Best Presentation Award for Students, Days of Applied Nonlinearity and Complexity (DANOC'24), 14.01.2024.
- Gratitude from RTU Children and Youth University, 24.05.2024.

Overall, the results presented in this Doctoral Thesis were validated through peer-reviewed publications, international conference presentations, experimental prototypes, and applied research projects. The combination of simulation-based analysis, experimental measurements, and system-level validation confirms the scientific relevance and practical applicability of the proposed chaos-based communication methods.

Structure of the Thesis

This Doctoral Thesis follows an incremental research structure, where each section builds upon the results and conclusions obtained in the prior stages. While certain well-established concepts related to chaotic oscillators and communication systems are introduced where necessary, the focus is placed on the development, analysis, and experimental validation of original research contributions. Background material is included only to the extent required to support subsequent analysis and discussion.

The organization of the Thesis reflects the logical progression from the study of individual chaotic oscillators to the evaluation of complete chaos-based communication systems under different channel conditions. The content of each section is summarized as follows.

The first section investigates the properties of chaotic oscillators with an emphasis on the influence of the fundamental frequency. Two structurally different oscillators–the Colpitts and Vilnius chaotic oscillators–are analyzed using simulations and experimental prototypes. The section examines spectral characteristics, cross-correlation behavior, and time-lag properties relevant to symbol duration selection in chaos-based communication systems.

The second section focuses on chaotic synchronization in drive–response chaotic oscillator configurations. The noise immunity of synchronization is studied using different circuit nodes as synchronization signals. Correlation-based metrics are employed to quantify synchronization quality under additive noise, enabling a systematic comparison of potential synchronization signals for both chaotic oscillators.

The third section addresses the impact of unequal synchronization on correlation-based data detection. It demonstrates that imbalanced synchronization between different signals leads to biased symbol decisions. To compensate for this effect, a detection threshold is introduced to restore balanced decision-making in chaos shift-keying systems.

The fourth section focuses on the integration of advanced modulation techniques with chaos-based communication systems. It first introduces the use of QAM and FM for transmitting chaotic signals at a specified carrier frequency, describing the corresponding system architectures and signal processing chains. The noise immunity of the resulting chaos-based communication systems is then evaluated through both simulation and experimental prototype measurements, with performance assessed in terms of bit error rate under AWGN conditions. Subsequently, the impact of synchronization signal selection and chaotic oscillator topology on system performance is investigated. The section concludes with an analysis of system performance in a two-ray propagation channel, where QCSK and FM-CSK systems are evaluated under frequency-selective fading and compared with conventional modulation schemes to assess their performance in practical wireless environments.

The fifth section concludes the Thesis by summarizing the main research findings, discussing their implications for chaos-based communication system design, and outlining directions for future work.

Together, these sections provide a coherent framework that connects chaotic oscillator dynamics, synchronization behavior, detection strategy design, and system-level communication performance. The structure ensures a clear transition from circuit-level analysis to practical communication scenarios, supporting the overall objectives of the Thesis.

1 CHAOTIC OSCILLATORS

This section investigates two representative continuous-time chaotic oscillators—the Colpitts and Vilnius circuits—using simulation and hardware prototype studies, focusing on their mathematical models, tunability, and spectral and temporal characteristics evaluated via power spectral density (PSD), the Z1-test, and cross-correlation analysis. Low- and high-frequency configurations are examined (Colpitts at $f_0 \approx 96.86\,\mathrm{kHz}$ and $968.59\,\mathrm{kHz}$; Vilnius at $f_0 \approx 1.6\,\mathrm{kHz}$ and $160\,\mathrm{kHz}$) to assess frequency-scaling effects. The oscillators were selected for their complementary architectures: the Colpitts oscillator represents a minimal transistor-based chaotic circuit that combines gain and nonlinearity, whereas the Vilnius oscillator separates these functions using an operational amplifier and a diode, reflecting the two dominant chaotic oscillator design approaches. While more complex chaotic circuits, including memristor-based implementations, exist [52], they are typically limited to low-frequency operation and are less suitable for broadband communication [47], [50]. The central thesis demonstrated in this section is that the fundamental frequency of a chaotic oscillator directly determines the achievable data rate in chaos-based communication systems: bit duration is defined using the decay of the dominant cross-correlation peak [45], and increasing the fundamental frequency reduces the high-correlation lag region, enabling higher data rates, as confirmed by both simulation and prototype measurements.

1.1 Colpitts Chaotic Oscillator

This subsection introduces the nonlinear dynamics of the Colpitts chaotic oscillator. The Colpitts chaotic oscillator was chosen for this study because of its simple design and ability to adjust the fundamental frequency, as well as the sharp cross-correlation function of its generated signals. The primary objective is to evaluate the dynamics of a Colpitts chaotic oscillator in simulation and prototype.

Mathematical Model

The Colpitts oscillator considered in this work operates as a nonlinear dynamical system capable of generating chaotic signals. Its circuit diagram, shown in Fig. 1.1, consists of passive components (resistors, capacitors, and an inductor) and an active nonlinear element implemented using a bipolar junction transistor (BJT). Under appropriate operating conditions and component values, the circuit exhibits chaotic behavior [53].

The oscillator topology comprises a BJT, an inductor L_1, and a capacitive voltage divider formed by C_1 and C_2, which provides the feedback necessary for sustained oscillation. The resonant behavior of the circuit is determined by the LC network formed by L_1 and the equivalent capacitance of C_1 and C_2, while the transistor is biased using the voltage sources V_1 and V_2.

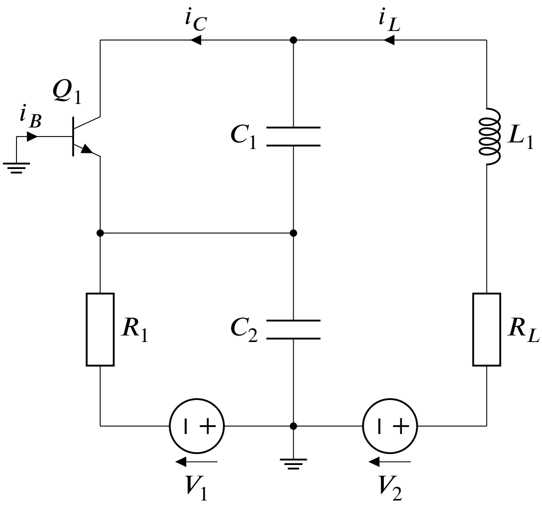


Fig. 1.1. Colpitts chaotic oscillator circuit diagram.

The dynamics of the Colpitts chaotic oscillator are described by a set of nonlinear differential equations derived from Kirchhoff's laws [54]:

$$\begin{cases} C_1 \dfrac{\mathrm{d}v_{C1}}{\mathrm{d}t} = i_L - i_C \\ C_2 \dfrac{\mathrm{d}v_{C2}}{\mathrm{d}t} = \dfrac{V_1 - v_{C2}}{R_1} - i_L - i_B \\ L_1 \dfrac{\mathrm{d}i_L}{\mathrm{d}t} = V_2 - v_{C1} - v_{C2} - i_L R_L \end{cases}, \tag{1.1}$$

where v_{C1} and v_{C2} denote the voltages across capacitors C_1 and C_2, respectively, i_L is the inductor current, and i_B and i_C are the base and collector currents.

The chaotic behavior of the oscillator arises from the nonlinear characteristics of the transistor. The voltage-controlled nonlinearity of the base-emitter junction is approximated by the following piecewise-linear model:

$$i_B = \begin{cases} 0, & \text{if } -v_{C2} \le V_{TH} \\ -\dfrac{v_{C2} + V_{TH}}{R_{ON}}, & \text{if } -v_{C2} > V_{TH} \end{cases}, \tag{1.2}$$

$$i_C = \beta_F \cdot i_B, \tag{1.3}$$

where V_{TH} is the threshold voltage, R_{ON} is the small-signal base-emitter resistance, and β_F is the forward current gain of the transistor.

Fundamental Frequency

The Colpitts chaotic oscillator includes a series RLC resonant circuit, whose fundamental frequency f_0 equals the resonator's natural oscillation frequency. This frequency is determined by the energy exchange between the inductor and the equivalent capacitance and can be expressed using Thomson's formula

$$f_0 = \frac{1}{2\pi \sqrt{L_1 \cdot C_{eq}}}, \tag{1.4}$$

where the equivalent capacitance C_{eq} is given by

$$C_{eq} = \frac{C_1 \cdot C_2}{C_1 + C_2}. \tag{1.5}$$

In the original study [54], the Colpitts chaotic oscillator was implemented with the parameters $R_L = 35\,\Omega$, $L_1 = 98.5\,\mu\text{H}$, $C_1 = C_2 = 54\,\text{nF}$, $R_1 = 40\,\Omega$, $V_1 = V_2 = 5\,\text{V}$, and a 2N2222 transistor. In this work, the inductance was approximated to $L_1 = 100\,\mu\text{H}$ due to component availability, resulting in a fundamental frequency of $f_0 = 96.86\,\text{kHz}$.

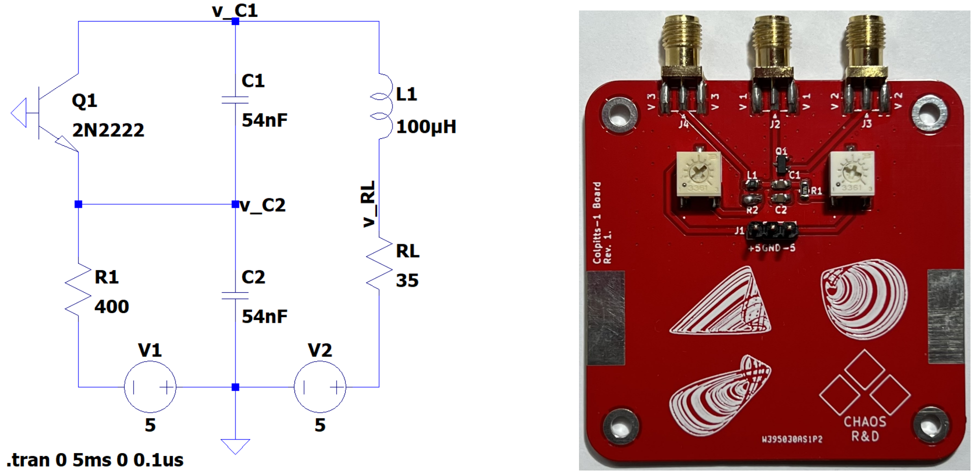
A tenfold increase in the fundamental frequency was achieved using reactive component values of $L_1 = 10\,\mu\text{H}$ and $C_1 = C_2 = 5.4\,\text{nF}$, yielding $f_0 = 968.59\,\text{kHz}$. Furthermore, chaotic behavior was also observed for $L_1 = 1\,\mu\text{H}$ and $C_1 = C_2 = 540\,\text{pF}$, corresponding to a fundamental frequency of $f_0 = 9.69\,\text{MHz}$ [47].

These results demonstrate that the Colpitts chaotic oscillator can operate over a wide range of fundamental frequencies by appropriately selecting reactive component values, which is advantageous for chaos-based communication systems that require different carrier frequencies.

Simulation and Experimental Study

A model of the Colpitts chaotic oscillator was constructed in the LTspice simulation environment, with simulated signals exported and processed in MATLAB (Fig. 1.2(a)). Two configurations with fundamental frequencies of 96.86 kHz and 968.59 kHz were investigated. To validate the simulation results, a hardware prototype was developed using an identical printed circuit board (PCB) layout for both configurations, with only the reactive component values adjusted. The fabricated PCB is shown in Fig. 1.2(b). Voltage signals from selected circuit nodes were measured using the Digilent's Analog Discovery Pro (ADP3450) portable mixed-signal oscilloscope, exported, and processed in MATLAB.

Chaotic behavior was verified using the 0–1 test for chaos (Z1TEST) [55], yielding values above 0.95 for both configurations. Power spectral density analysis confirmed broadband spectra centered around the fundamental frequency. Increasing f_0 from 96.86 kHz to 968.59 kHz resulted in a clear bandwidth expansion while preserving the overall spectral shape, demonstrating frequency-controlled bandwidth scalability.



(a) (b)

Fig. 1.2. Colpitts chaotic oscillator (a) LTspice simulation model and (b) fabricated PCB prototype.

Temporal relationships between oscillator variables were analyzed using cross-correlation functions to estimate the minimum bit duration [45]. An example for $f_0 = 96.86\,\text{kHz}$ is shown in Fig. 1.3. For all signal pairs, the cross-correlation functions exhibit a dominant peak near zero lag followed by rapid decay, which is characteristic of chaotic signals.

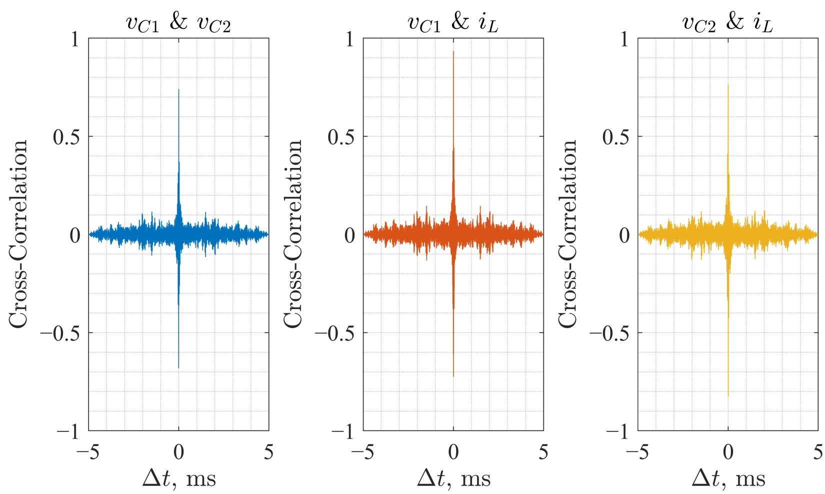


Fig. 1.3. Cross-correlation functions for v_{C1} and v_{C2}, v_{C1} and i_L, and v_{C2} and i_L in the Colpitts chaotic oscillator at $f_0 = 96.86\,\text{kHz}$.

The maximum value of the cross-correlation function does not occur exactly at zero lag but at a small, nonzero time shift, as illustrated by the close-up view in Fig. 1.4. This behavior is a consequence of the phase relationships between voltages across the capacitors and the current through the inductor, which are governed by the circuit differential equations.

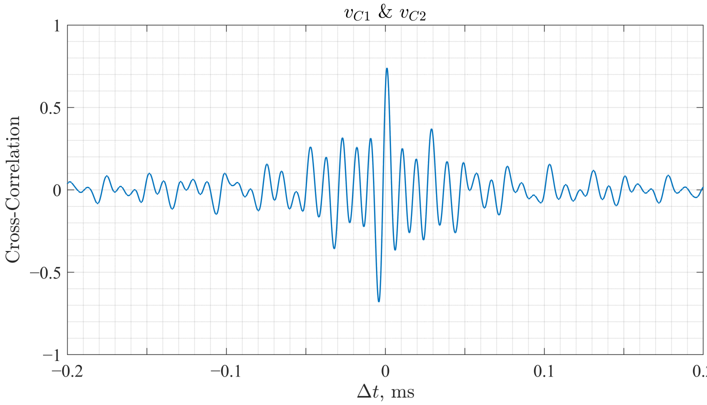


Fig. 1.4. Close-up view of the cross-correlation function between v_{C1} and v_{C2} in the Colpitts chaotic oscillator at $f_0 = 96.86$ kHz, highlighting the dominant correlation peak at a nonzero time lag.

The cross-correlation analysis was performed for both fundamental frequency configurations and repeated for experimentally measured prototype signals. In all cases, increasing the fundamental frequency reduces the extent of the high-correlation lag region. The minimum bit duration was defined as the time lag at which the cross-correlation amplitude decays from its dominant peak and settles into small fluctuations [45]. For simulated signals, this lag decreases from approximately 60 µs at 96.86 kHz to approximately 6 µs at 968.59 kHz, while for prototype measurements it decreases from approximately 78 µs to approximately 7.5 µs. These results confirm that increasing the fundamental frequency enables shorter bit durations and higher achievable data rates, providing a quantitative basis for selecting communication parameters in chaos-based transmission systems.

1.2 Vilnius Chaotic Oscillator

The Vilnius chaotic oscillator [56] is a simple nonlinear circuit widely used in studies of chaotic dynamics due to its reliable operation and ease of implementation [42], [50], [57], [58]. It was selected for this work because its straightforward structure enables good agreement between simulation and experimental results. Additionally, the oscillator supports operation over different frequency ranges through appropriate selection of reactive component values, making it suitable for chaos-based communication systems with varying bandwidth requirements.

Mathematical Model

The circuit of the Vilnius oscillator, shown in Fig. 1.5, consists of an operational amplifier, an RLC resonance circuit in a positive feedback loop, an additional capacitor, and a diode functioning as the nonlinear element. This configuration ensures chaotic dynamics with minimal components.

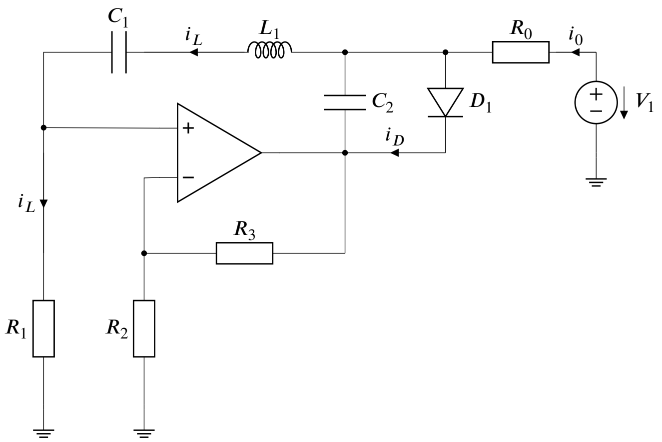


Fig. 1.5. Vilnius chaotic oscillator circuit diagram.

The behavior of the Vilnius chaotic oscillator is described by a system of differential equations combining the states of three variables: v_{C1}, the voltage across the capacitor C_1; i_L, the current through inductor L_1; and v_{C2}, the voltage across the supplementary capacitor C_2. The system is derived using Kirchhoff's circuit laws:

$$\begin{cases} C_1 \dfrac{\mathrm{d}v_{C1}}{\mathrm{d}t} = i_L \\ C_2 \dfrac{\mathrm{d}v_{C2}}{\mathrm{d}t} = i_0 + i_L - i_D \\ L_1 \dfrac{\mathrm{d}i_L}{\mathrm{d}t} = (k-1) \cdot R_1 \cdot i_L - v_{C_1} - v_{C_2} \end{cases}, \tag{1.6}$$

where i_D is the current of the diode D_1, i_0 is the current of the resistor R_0, and k is the closed-loop gain of the non-inverting operational amplifier.

The oscillator's nonlinearity is introduced by the diode's current-voltage characteristic, represented by the following equation:

$$i_D = i_S \cdot \left(\mathrm{e}^{\frac{v_D}{v_T}} - 1 \right), \tag{1.7}$$

where v_D is the voltage across the diode (due to parallel connection $v_D = v_{C2}$), i_S is the diode saturation current (approximately 2×10^{-14} A for a standard 1N4148 diode), and v_T is the thermal voltage (about 25.8 mV at room temperature, 298 K).

Fundamental Frequency

The Vilnius chaotic oscillator, first introduced in [56], is based on an RLC resonant circuit topology. In its original configuration, the component values are: $C_1 = 100\,\text{nF}$, $C_2 = 15\,\text{nF}$, $L_1 = 100\,\text{mH}$, $R_1 = 1\,\text{k}\Omega$, $R_2 = 10\,\text{k}\Omega$, $R_3 = 6\,\text{k}\Omega$, $R_0 = 20\,\text{k}\Omega$, $V_1 = 5\,\text{V}$, $k = 1.6$. The fundamental frequency f_0 of the oscillator can be estimated using the standard RLC resonance formula:

$$f_0 = \frac{1}{2\pi\sqrt{L_1 \cdot C_1}}. \tag{1.8}$$

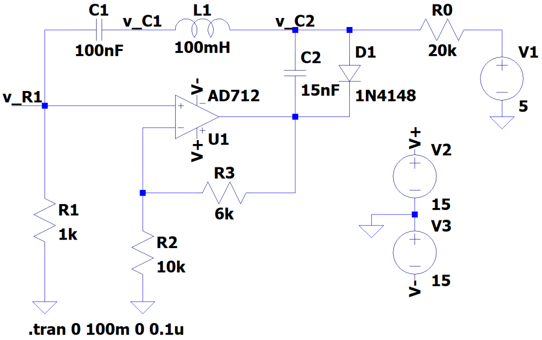
With these component values, the fundamental frequency is approximately 1.6 kHz.

The fundamental frequency can be increased by proportionally decreasing the values of the reactive elements. For instance, reducing C_1, C_2, and L_1 by a factor of 100–to $C_1 = 1\,\text{nF}$, $C_2 = 150\,\text{pF}$, and $L_1 = 1\,\text{mH}$–results in a fundamental frequency of approximately 160 kHz. Importantly, maintaining the same proportional relationship among these elements preserves the oscillator's chaotic behavior.

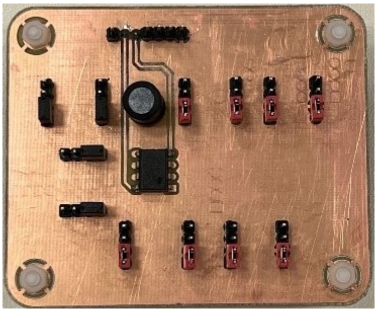
Simulation and Experimental Study

A Vilnius chaotic oscillator model was implemented in LTspice and evaluated for fundamental frequencies of 1.6 kHz and 160 kHz (Fig. 1.6(a)). Simulated signals were exported and processed in MATLAB. To validate the results, a hardware prototype was fabricated using the same PCB layout for both configurations, with only reactive component values adjusted. Voltage signals were measured using the ADP3450 mixed-signal oscilloscope and processed in MATLAB. The prototype PCB (top view) is shown in Fig. 1.6(b).

The frequency-domain characteristics were evaluated using the power spectral density (PSD), which exhibits broadband behavior centered around the fundamental frequency for both simulation



(a)



(b)

Fig. 1.6. Vilnius chaotic oscillator (a) LTspice simulation model and (b) fabricated PCB prototype (top view).

and prototype measurements. Increasing the fundamental frequency results in a corresponding expansion of the signal bandwidth, whereas experimentally measured spectra show only minor narrowing due to parasitic effects and component tolerances. The temporal properties of the chaotic signals were analyzed using cross-correlation functions to characterize inter-signal relationships and to estimate the minimum bit duration. Fig. 1.7 presents a representative cross-correlation result obtained from LTspice simulations at $f_0 = 1.6$ kHz.

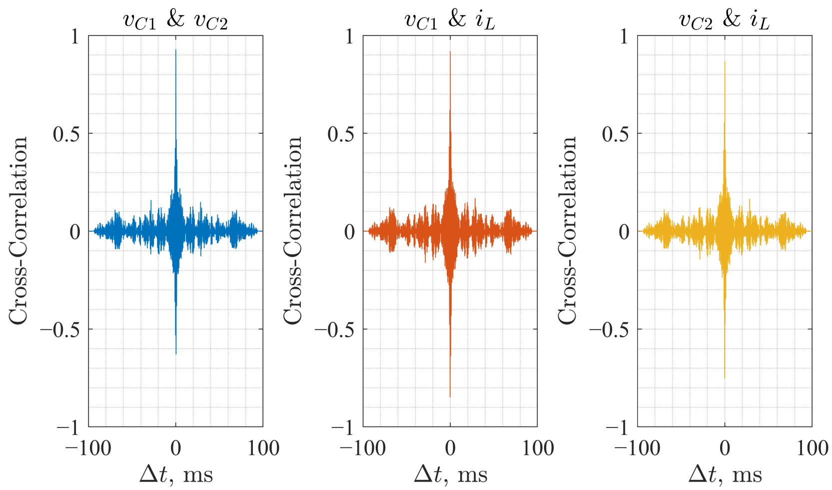


Fig. 1.7. Example cross-correlation functions for v_{C1} and v_{C2}, v_{C1} and i_L, and v_{C2} and i_L in the Vilnius chaotic oscillator at $f_0 = 1.6$ kHz (simulation).

For all signal pairs and both fundamental frequencies, the cross-correlation functions exhibit a dominant peak near zero lag followed by rapid decay, indicating short-term correlation and aperiodic, chaotic behavior. In both simulations and prototype measurements, the maximum correlation occurs at nonzero lags due to phase shifts introduced by the circuit's reactive elements. The minimum bit duration was defined by the lag at which the cross-correlation amplitude decays from its dominant peak and settles into small fluctuations [45]. For simulated signals, this lag is approximately 1.87 ms at $f_0 = 1.6$ kHz (535 b/s) and 18.1 µs at $f_0 = 160$ kHz (55.2 kb/s). Prototype measurements show the same trend, yielding bit durations of approximately 1.89 ms (529.1 b/s) and 18.81 µs (53.2 kb/s), respectively.

1.3 Discussion and Comparative Analysis

Both the Colpitts and Vilnius chaotic oscillators exhibited stable chaotic behavior in simulation and hardware, with Z1TEST values exceeding 0.90, broadband spectra, and rapid decorrelation confirmed by cross-correlation analysis. Minor reductions in achievable data rates were observed in prototype measurements due to circuit non-idealities.

In this work, the bit duration is defined by the time lag at which the cross-correlation amplitude decays from its dominant peak, providing a physically meaningful criterion for symbol separation. As summarized in Table 1.1, increasing the Colpitts oscillator fundamental frequency from 96.86 kHz to 968.59 kHz reduces the bit length and increases the data rate from 16.7 kb/s to 166.7 kb/s in simulation and from 12.82 kb/s to 133.3 kb/s in prototype measurements.

Table 1.1

Achievable data rates summary of the Colpitts chaotic oscillator

f_0, kHz	Simulation		Prototype	
	Bit length (μs)	Data rate (kb/s)	Bit length (μs)	Data rate (kb/s)
96.86	60	16.7	78	12.82
968.59	6	166.7	7.5	133.3

A similar frequency-scaling trend is observed for the Vilnius chaotic oscillator, as summarized in Table 1.2. Increasing the fundamental frequency from 1.6 kHz to 160 kHz reduces the characteristic cross-correlation lag and increases the achievable data rate from approximately 0.5 kb/s to over 50 kb/s in both simulation and prototype measurements.

Table 1.2

Achievable data rates summary of the Vilnius chaotic oscillator

f_0 (kHz)	Simulation		Prototype	
	Bit length	Data rate (kb/s)	Bit length	Data rate (kb/s)
1.6	1.87 ms	0.535	1.89 ms	0.529
160	18.1 μs	55.2	18.81 μs	53.16

While the Colpitts oscillator achieves higher maximum data rates, the Vilnius oscillator confirms the same fundamental relationship between oscillator frequency, cross-correlation lag, and bit duration using a different circuit topology. The achieved data rates fall within the operating ranges of established IoT communication standards. For example, LoRaWAN in the 868 MHz ISM band supports data rates from approximately 0.3 kb/s up to 50 kb/s under configurations defined by the LoRa Alliance [59]. Zigbee systems based on the IEEE 802.15.4 standard support data rates of up to approximately 20 kb/s at 868 MHz and 40 kb/s at 915 MHz [60]. In contrast, Sigfox systems operate at significantly lower rates, around 100 bit/s in the 868 MHz band, as defined by European Telecommunications Standards Institute (ETSI) EN 300 220-2 [61]. These comparisons indicate that chaos-based communication systems can be configured to operate within data-rate regimes relevant to contemporary IoT and WSN applications.

Overall, the results confirm that the fundamental frequency of a chaotic oscillator serves as a direct control parameter for achievable data rate, enabling scalable symbol-rate adjustment validated through both simulation and hardware experiments.

2 CHAOTIC SYNCHRONIZATION

Synchronization of chaotic oscillators is essential for chaos-based communication systems, as it enables reliable information transmission despite channel noise and hardware non-idealities. Among existing approaches, the Pecora–Carroll method [62] is widely used due to its simplicity and applicability to both analog and digital chaotic circuits [51], [63].

This section investigates the synchronization of the Colpitts and Vilnius chaotic oscillators introduced in the first section, considering the Colpitts oscillator at 968.59 kHz and the Vilnius oscillator at 160 kHz. The analysis focuses on synchronization configurations and their resilience to AWGN, which is a critical factor in the design of secure communication systems.

The section presents the theoretical basis and experimental implementation of chaotic synchronization, followed by a noise-immunity analysis of both oscillators, providing guidance on selecting synchronization signals and configurations for chaos-based communication systems.

2.1 Pecora–Carroll Synchronization

Chaotic synchronization enables the use of chaotic oscillators in secure communication systems by allowing reliable information transfer only between synchronized units [64]. Among available approaches, the substitution method, also known as Pecora–Carroll synchronization [65], is widely used due to its simplicity and applicability to both analog and discrete chaotic systems.

In this method, one state variable of the response oscillator is replaced by the corresponding signal from the drive oscillator, forcing the response system to follow the drive dynamics. Synchronization quality is commonly evaluated using Pearson's correlation coefficient β, defined as

$$\beta = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}}, \tag{2.1}$$

where x and y denote the signals of the drive and response oscillators, respectively, values of β close to unity indicate strong synchronization, whereas $\beta \approx 0$ implies uncorrelated behavior.

The synchronization scheme is implemented by feeding the selected drive signal into the response oscillator, as illustrated in Fig. 2.1. A unity-gain operational amplifier buffer is used to isolate the drive and response circuits and to prevent loading effects [66], [67]. The choice of synchronization node determines the synchronization configuration and direction. Since chaotic oscillators typically provide multiple accessible state variables, several synchronization options are possible.

For the Colpitts chaotic oscillator (Fig. 1.1), synchronization can be performed using v_{C1}, v_{C2}, or v_{RL} [48], while for the Vilnius oscillator (Fig. 1.5), the corresponding signals are v_{C1}, v_{C2}, or v_{R1}. This flexibility enables the evaluation of multiple synchronization configurations.

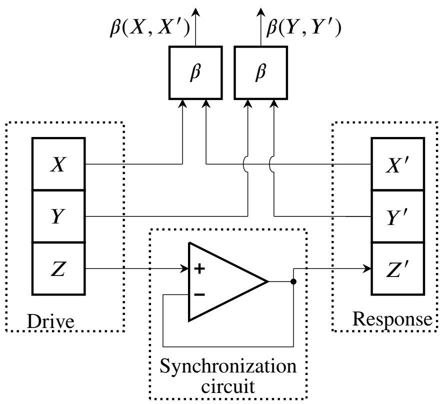


Fig. 2.1. Chaos oscillator synchronization block-scheme.

2.2 Chaos Oscillator Synchronization Noise Immunity Study Methodology

The noise immunity study follows the block diagram shown in Fig. 2.2, where X, Y, and Z denote the state variables of the drive chaotic oscillator and X', Y', and Z' their counterparts in the response oscillator.

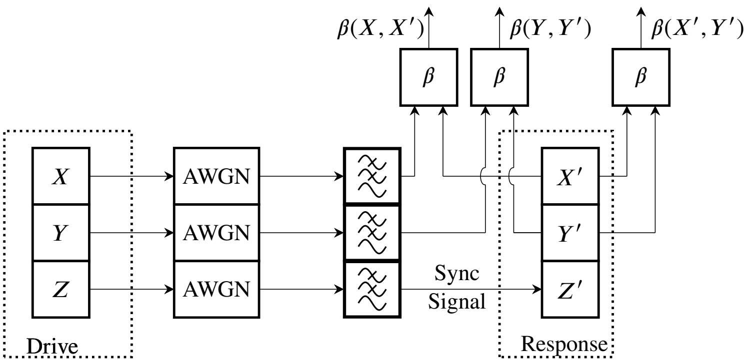


Fig. 2.2. Chaos oscillator synchronization noise immunity study block-scheme.

In this setup, Z is used as the synchronization signal and replaces Z' in the response oscillator, while the remaining drive signals would be used for CSK transmission. The signals propagate through an AWGN channel with the signal-to-noise ratio (SNR) varied from -20 dB to 30 dB and are filtered at the receiver using an low-pass filter (LPF) designed to preserve the dominant spectral components. Synchronization quality is then evaluated using Pearson correlation coefficients between corresponding state variables, quantifying the effect of channel noise.

The methodology is applied to both the Colpitts and Vilnius chaotic oscillators. Since each oscillator provides three state variables, all synchronization configurations listed in Table 2.1 are evaluated. For the Colpitts oscillator, synchronization is tested using v_{C1}, v_{C2}, and v_{RL}, while for the Vilnius oscillator, v_{C1}, v_{C2}, and v_{R1} are considered.

Table 2.1

Colpitts and Vilnius chaos oscillators configurations

Colpitts chaos oscillator			**Vilnius chaos oscillator**		
X	***Y***	***Z***	***X***	***Y***	***Z***
v_{C1}	v_{C2}	v_{RL}	v_{C1}	v_{C2}	v_{R1}
v_{RL}	v_{C1}	v_{C2}	v_{R1}	v_{C1}	v_{C2}
v_{C2}	v_{RL}	v_{C1}	v_{C2}	v_{R1}	v_{C1}

2.3 Chaos Oscillator Synchronization Noise Immunity Study Results

This study evaluates the synchronization noise immunity of the Colpitts and Vilnius chaotic oscillators for different drive–response configurations, aiming to identify synchronization signals that provide stable performance in noisy channels. Fig. 2.3 serves as a representative example of the applied analysis methodology, showing the correlation coefficient as a function of SNR. Each synchronization configuration is represented by a pair of curves corresponding to the correlations between X and X' and between Y and Y', as summarized in Table 2.1.

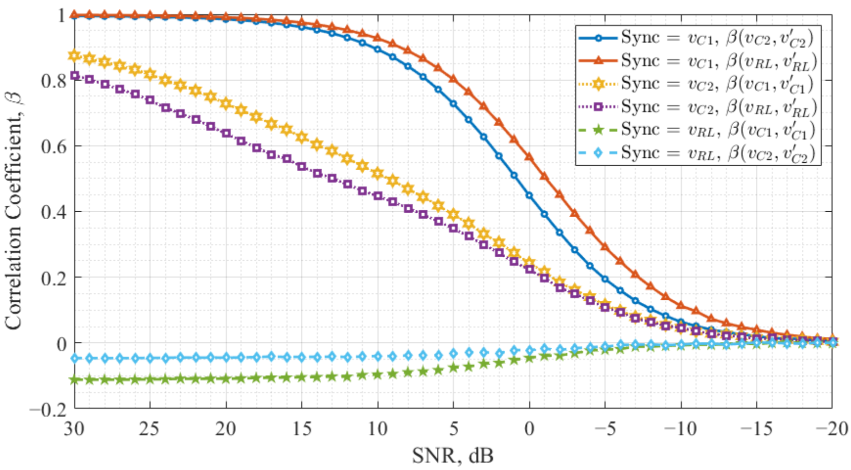


Fig. 2.3. Colpitts chaos oscillator synchronization noise immunity.

For the Colpitts oscillator, synchronization performance strongly depends on the selected synchronization signal. When v_{RL} is used, synchronization is not achieved over the investigated SNR range. Using v_{C1} enables synchronization of both response signals, though at different correlation levels, while v_{C2} achieves weaker synchronization only at higher SNR values. These results indicate a restricted synchronization capability resulting from the Colpitts oscillator topology and strong coupling between state variables.

In contrast, the Vilnius chaotic oscillator synchronizes across all tested configurations once the noise level is sufficiently low. The v_{C2} configuration exhibits the most resilient behavior, providing balanced synchronization and the lowest SNR threshold, whereas v_{C1} and v_{R1} lead to noticeable imbalance in the synchronization of the response signals.

A common observation across both oscillators is a synchronization imbalance in the response variables at identical SNR levels, which may lead to asymmetric bit detection and increased error rates. Therefore, configurations ensuring balanced correlation are preferred for communication applications. Overall, the Vilnius oscillator offers greater synchronization flexibility and resilience to noise. In contrast, the Colpitts oscillator provides reliable synchronization only in specific configurations, motivating further analysis of cross-correlation and data-detection performance.

2.4 Synchronization Signal Selection Methodology

The noise-immunity study demonstrates that selecting the synchronization signal is a key factor for stable synchronization in chaos-based communication systems. Due to differences in circuit topology and signal coupling, a systematic selection methodology is required for both the Colpitts and Vilnius chaotic oscillators.

The synchronization signal should be chosen based on the following criteria: (i) high and stable correlation between drive and response signals across a wide SNR range, (ii) balanced synchronization levels among all data-carrying response signals to avoid bit detection asymmetry, (iii) low sensitivity to noise-induced degradation, and (iv) low cross-correlation between data-carrying signals to improve symbol discrimination. Practical aspects such as node accessibility, signal amplitude, and resilience to parasitic effects should also be considered.

Applying these criteria to the experimental results leads to clear guidelines. In the Colpitts oscillator, the v_{C1} node provides the best synchronization performance, combining strong noise immunity with low cross-correlation between data-carrying signals. For the Vilnius oscillator, the optimal synchronization signal is v_{C2}, which achieves the most stable and balanced synchronization across the investigated noise range.

In practice, synchronization signal selection can be implemented by evaluating circuit nodes in a drive–response configuration under noisy conditions and comparing correlation and cross-correlation metrics. The signal that maintains strong, balanced synchronization with minimal noise sensitivity should be selected. This methodology provides a practical framework for synchronization design and directly motivates the subsequent analysis of detection imbalance and threshold optimization in the following section. It also forms the basis for evaluating the impact of synchronization strategies on the performance of chaos-based communication systems in Section 4.

3 DESIGN AND SIGNAL PROCESSING IN CHAOS-BASED COMMUNICATION

Chaos-based communication systems have attracted significant interest due to the wide-band spectral properties, inherent unpredictability, and security potential of chaotic signals [14], [15], [21], [22]. This section presents the key aspects of system design, including architectural choices, signal processing procedures, and the implementation of CSK as the modulation scheme. Considerations relevant to both simulation and hardware implementation are addressed, with particular emphasis on synchronization, signal processing, and threshold-based detection for reliable data transmission.

3.1 System Architecture

This subsection introduces the fundamental concept of a chaos-based communication system, in which chaotic signals are employed for information transmission and synchronization. Fig. 3.1 presents the general block diagram of such a system, illustrating the main components and signal flow.

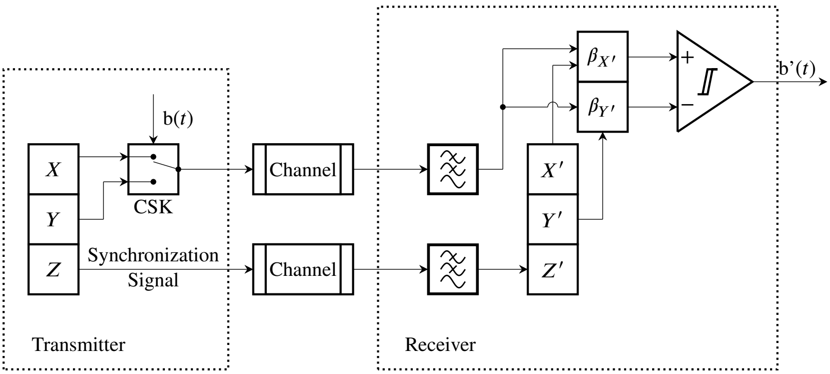


Fig. 3.1. Chaos-based communication system block scheme.

At the transmitter, an analog chaos oscillator operates in a drive–response configuration and generates chaotic state variables X, Y, and Z. One state variable (typically Z) is used for synchronization, while X and Y are used for information transmission. The information-carrying signal is formed by a binary information-signal-controlled switch that alternates between X and Y, mapping bit '1' to X and bit '0' to Y, corresponding to CSK.

At the receiver, a response chaos oscillator synchronizes with the transmitter by injecting the received synchronization signal, enabling reconstruction of X' and Y'. Information detection is performed by comparing the Pearson correlation coefficients between the received signal and X'

and Y', with the detected bit determined by the larger coefficient. Detection accuracy depends on the quality and balance of chaotic synchronization; unequal synchronization between state variables, particularly under noisy conditions, introduces detection bias, making accurate threshold selection essential for reliable and balanced detection.

3.2 Chaos Shift Keying Implementation

CSK is the modulation scheme used in the proposed system, enabling digital transmission by selecting between two chaotic signals based on the binary data stream. As shown in Fig. 3.1, the CSK block receives the data signal and chaotic signals X and Y, and outputs an information-carrying signal by switching between X and Y according to the input bit value.

In simulation, implementing CSK is straightforward due to the flexibility of numerical signal processing. The chaotic signals X and Y first have their mean values subtracted to remove the direct current (DC) offset. The amplitude of the Y signal is then adjusted to match that of X, ensuring uniform signal levels for both bit values. After preprocessing, the CSK operation is implemented using a logical switching function, where the output follows either X or Y based on the binary information signal. This approach simplifies signal processing and enables rapid evaluation under different operating conditions.

In the hardware prototype, the CSK implementation is realized using analog signal processing and switching circuitry. The DC offset is removed by passing the X and Y signals through high-pass filter (HPF) with low cutoff frequencies, implemented as simple RC filters. The signals are then amplified using non-inverting amplifiers with adjustable gain to equalize their amplitudes. The switching operation is performed using an analog electronic switch (ADG419), controlled by the digital data stream. The data stream is generated by the ADP3450 module and controlled via Python code, enabling flexible, precise modulation of the transmitted information.

3.3 Detection and Threshold Determination under Imperfect Synchronization

At the detector input, the received information-carrying signal is correlated within each bit interval with two reference signals regenerated by the synchronized response chaotic oscillator, yielding correlation coefficients used for bit decision and BER estimation. Under ideal balanced synchronization, detection can rely on a direct comparison of these coefficients; however, as shown in Section 2, noise-induced synchronization imbalance and nonzero cross-correlation introduce detection bias and degrade performance. To compensate for these effects, a nonzero adaptive detection threshold is required to ensure reliable and balanced bit detection.

The threshold for bit detection can be derived using a likelihood ratio approach. Assuming

AWGN, the likelihood that the received signal $s(t)$ is induced by the signal X is given by

$$\Lambda[X|s(t)] = \frac{1}{(\sigma\sqrt{2\pi})^K} \exp\left(-\frac{1}{2}\sum_{k=1}^{K}\frac{(s_k - x_k)^2}{\sigma^2}\right), \tag{3.1}$$

where σ is the noise standard deviation and s_k and x_k denote the kth samples of $s(t)$ and X, respectively. The logarithm of the likelihood ratio is

$$\ln \Lambda[s(t)] = \frac{\Lambda[X|s(t)]}{\Lambda[Y|s(t)]} = \sum_{k=1}^{K}\frac{s_k}{\sigma^2}(x_k - y_k) - \frac{1}{2}\sum_{k=1}^{K}\frac{(x_k^2 - y_k^2)}{\sigma^2}. \tag{3.2}$$

The decision boundary is defined by

$$\sum_{k=1}^{K} s_k(x_k - y_k) - \frac{1}{2}\sum_{k=1}^{K}(x_k^2 - y_k^2) \geqslant 0. \tag{3.3}$$

Assuming $s(t) = X + n(t)$, the mathematical expectation of the first term becomes

$$E\left[(x_k + n_k)(x_k - y_k)\right] = \sum_{k=1}^{K} x_k^2 - \sum_{k=1}^{K} x_k y_k, \tag{3.4}$$

where n_k denotes the noise samples. Substitution into (3.3) shows that increased cross-correlation between the state variables X' and Y' reduces the probability of correct detection.

Rewriting (3.3) yields the following decision rule:

$$\sum_{k=1}^{K} s_k x_k \geqslant \sum_{k=1}^{K} s_k y_k + \frac{1}{2}\left[\sum_{k=1}^{K} x_k^2 - \sum_{k=1}^{K} y_k^2\right]. \tag{3.5}$$

Expressed in terms of correlation coefficients, this criterion becomes $\beta_{X'} \geqslant \beta_{Y'} + \frac{1}{2}(\beta_X - \beta_Y)$, where a satisfied inequality corresponds to the detection of bit '1', and bit '0' otherwise.

This formulation enables adaptive threshold computation that accounts for synchronization imbalance, cross-correlation, and noise, thereby improving the detection balance in chaos-based communication systems.

3.4 Impact of Threshold Selection on BER

Under AWGN conditions, imperfect synchronization between the drive and response chaotic oscillators produces imbalanced correlation coefficients, introducing detection bias and increasing the bit error rate by favoring one symbol over the other. To compensate for this effect, a nonzero detection threshold was applied in the correlation-based decision process. Its effectiveness was evaluated through BER analysis over a range of SNR values. Table 3.1 summarizes the resulting BER and misdetection counts for a representative Vilnius oscillator configuration using υ_{R1} as the synchronization signal.

Table 3.1
Error count without and with the detection threshold in a system based on the Vilnius chaos oscillator using υ_{R1} as the synchronization signal

SNR, dB	Without threshold			With threshold		
	BER	**False '0'**	**False '1'**	**BER**	**False '0'**	**False '1'**
−15	0.4407	2287	2120	0.4370	2168	2202
−10	0.3249	1761	1488	0.3195	1598	1597
−5	0.1134	702	432	0.1053	519	534
0	0.0121	79	42	0.0107	57	50
2	0.0048	34	14	0.0043	21	22
4	0.0019	12	7	0.0014	7	7

As shown in Table 3.1, applying a detection threshold consistently improves performance across SNR values. Without the threshold, detection errors are unevenly distributed between symbols due to synchronization imbalance, particularly at higher SNR. Introducing the threshold balances the detection process, reduces the overall BER, and mitigates the impact of imperfect synchronization, confirming the effectiveness of threshold compensation in chaos-based communication systems.

3.5 Discussion

This section presents the key system design and signal processing aspects of chaos-based communication systems, outlining the roles of the drive and response chaotic oscillators, the CSK modulation block, and the detection process. The implementation of CSK was discussed for both simulation and hardware prototypes, highlighting the transition from flexible numerical processing to practical analog realization.

The analysis demonstrated that synchronization imbalance between chaotic state variables leads to biased correlation-based detection and increased error probability. To mitigate this effect, an adaptive detection threshold was derived and applied, explicitly compensating for unequal correlation levels. The results show that threshold-based detection significantly reduces the bit error rate and balances symbol errors, thereby validating the central thesis of this section. These findings emphasize the importance of adaptive detection strategies for reliable chaos shift keying communication under practical, imperfect synchronization conditions.

4 ADVANCED MODULATION TECHNIQUES FOR CHAOS-BASED COMMUNICATION

Chaos-based communication systems generate wideband baseband signals via chaotic dynamics and chaos-shift keying. While these signals enable secure transmission, practical WSN and IoT applications require operation within regulated RF bands, necessitating an additional modulation stage to translate chaotic waveforms to a carrier frequency while preserving their information and synchronization properties. This RF modulation also defines the spectral placement of the chaotic signal and directly impacts noise, interference, and multipath resilience.

This section introduces advanced modulation techniques for RF translation and spectral shaping of chaos-based signals. Two representative approaches are considered: QAM, a linear modulation technique, and FM, a nonlinear approach based on frequency deviation. Both schemes are integrated with the CSK framework, implemented in simulation and hardware prototypes, and evaluated under multipath propagation.

Accordingly, the thesis of this section is that combining chaos shift keying with advanced RF modulation–specifically QCSK and FM-CSK implementations using the Vilnius chaotic oscillator–improves resilience to frequency-selective multipath fading compared to conventional 4-QAM and 2-FSK systems under a two-ray channel model.

4.1 Modulation Schemes

Quadrature Chaos Shift Keying Communication System

The QCSK communication system integrates the principles of CSK and QAM, combining chaotic modulation with linear quadrature modulation to achieve spectrally efficient, coherent chaos-based communication. In this architecture, two orthogonal carrier components are used: the in-phase branch represents the synchronization signal, while the quadrature branch carries the information-carrying chaotic signal. This arrangement enables simultaneous transmission of synchronization and data over the same frequency channel.

Fig. 4.1 shows the block diagram of the QCSK system. At the transmitter, the drive chaos oscillator generates state variables that form the synchronization signal $I(t)$ and the information-carrying chaotic signal $Q(t)$. These signals are applied to orthogonal carriers $\cos(\omega_c t)$ and $\sin(\omega_c t)$, respectively, and combined to form a single quadrature-modulated waveform. The transmitted signal is expressed as

$$s(t) = I(t)\cos(\omega_c t) - Q(t)\sin(\omega_c t), \tag{4.1}$$

where ω_c denotes the carrier angular frequency. Owing to the linear nature of quadrature modulation, the spectral characteristics of the chaotic signals are preserved.

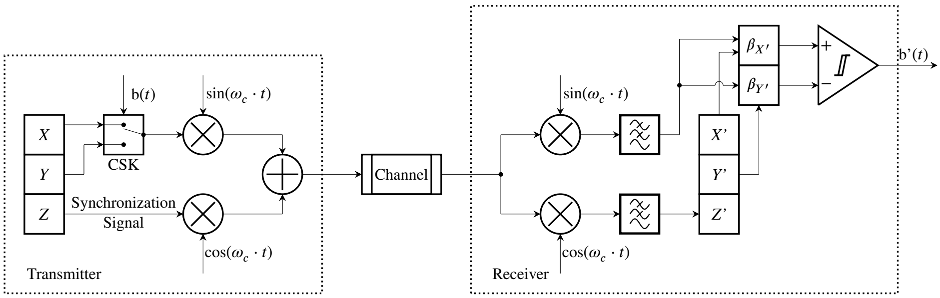


Fig. 4.1. Block diagram of the QCSK communication system combining chaos shift keying and quadrature modulation.

At the receiver, the incoming signal is coherently demodulated using synchronized orthogonal carriers. Multiplication with $\cos(\omega_c t)$ and $\sin(\omega_c t)$ yields

$$s(t)\cos(\omega_c t) = \frac{I(t)}{2} - \frac{I(t)}{2}\cos(2\omega_c t) + \frac{Q(t)}{2}\sin(2\omega_c t), \tag{4.2}$$

$$-s(t)\sin(\omega_c t) = \frac{Q(t)}{2} - \frac{I(t)}{2}\sin(2\omega_c t) - \frac{Q(t)}{2}\cos(2\omega_c t). \tag{4.3}$$

Low-pass filtering removes the high-frequency components at $2\omega_c$, resulting in the recovered baseband signals $I'(t)$ and $Q'(t)$.

The recovered synchronization signal $I'(t)$ is injected into the response chaos oscillator, enabling chaotic synchronization between transmitter and receiver. The reconstructed oscillator states are then used in a correlation-based detection process to recover the transmitted information from the quadrature chaotic signal. This architecture preserves the security properties of chaos-based modulation while exploiting the spectral efficiency and coherence of quadrature transmission.

Frequency-Modulated Chaos Shift Keying Communication System

The FM-CSK communication system integrates CSK with FM to enable resilient transmission of chaotic signals. In this architecture, the drive chaos oscillator generates multiple state variables, one of which serves as the synchronization signal, while the remaining two are used to form the information-carrying signal via data-dependent switching, corresponding to CSK. By embedding the chaotic waveforms into a frequency-modulated carrier, the system preserves the nonlinear properties of chaotic modulation while benefiting from the noise resilience of FM.

Fig. 4.2 illustrates the block diagram of the FM-CSK communication system. At the transmitter, the synchronization signal and the CSK-formed information-carrying chaotic signal are processed in parallel branches and used to frequency-modulate the carrier. The resulting composite waveform is transmitted through the communication channel. Since the information is conveyed through instantaneous frequency variations rather than amplitude, the transmitted signal is more resilient to additive noise and amplitude distortions.

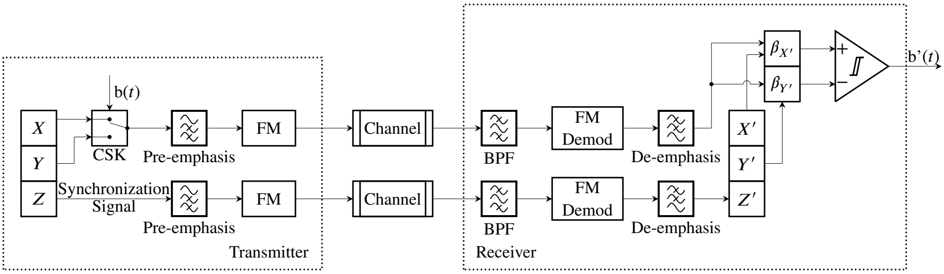


Fig. 4.2. Block diagram of the FM-CSK communication system combining chaos shift keying with frequency modulation.

At the receiver, the incoming signal is filtered and demodulated to recover the baseband synchronization and information-carrying chaotic signals. The recovered synchronization signal is injected into the response chaos oscillator to establish chaotic synchronization. Once synchronized, the reconstructed oscillator outputs are compared with the received information-carrying signal using correlation-based detection, allowing reliable recovery of the transmitted data. This architecture enables secure chaos-based communication while enhancing resilience against channel noise and distortions.

4.2 Performance Analysis of the QCSK System under Different Synchronization Signal Configurations

The performance of the QCSK communication system strongly depends on the choice of the synchronization signal used to couple the chaotic oscillators. As shown in Section 2, synchronization quality varies across circuit nodes, leading to different levels of correlation imbalance that directly affect detection accuracy and noise immunity. In this section, the influence of synchronization signal selection on QCSK performance is evaluated. For the Vilnius chaotic oscillator, all three signals analyzed in Section 2 were considered as synchronization candidates, enabling a direct comparison of different configurations. For the Colpitts chaotic oscillator, reliable synchronization was achieved only when using the v_{C1} node; therefore, only this configuration is included in the analysis.

Fig. 4.3 presents the BER as a function of E_b/N_0 for all tested QCSK configurations. The best performance is achieved for the Vilnius chaos oscillator when v_{C2} is used as the synchronization signal, as this configuration provides balanced correlation levels between X and Y, high noise immunity, and low cross-correlation of the information-carrying chaotic signals, resulting in the lowest observed BER.

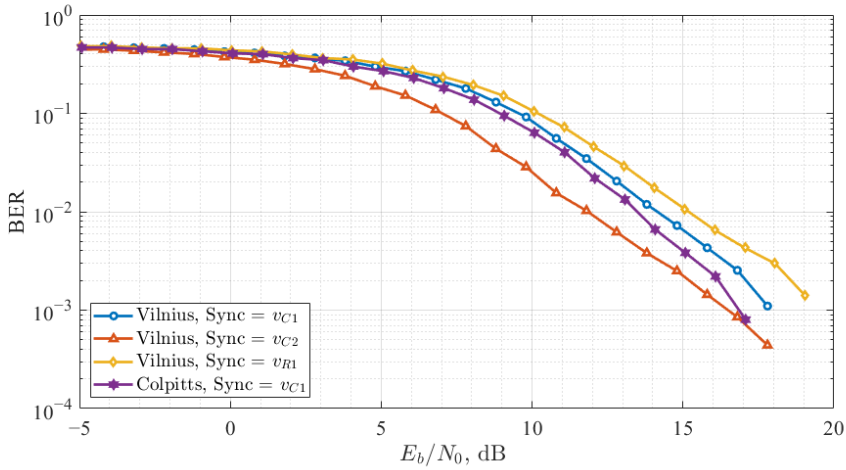


Fig. 4.3. BER versus E_b/N_0 curves of the QCSK data transmission system.

The QCSK system based on the Colpitts chaos oscillator achieved the second-best performance when synchronized via the v_{C1} node. While this configuration exhibited synchronization resilience comparable to the v_{C2}-based Vilnius system, unequal correlation levels between X' and Y' introduced detection imbalance, requiring compensation at the receiver.

The remaining Vilnius oscillator configurations followed trends similar to those observed in the synchronization noise-immunity study. The poorest performance occurred when v_{R1} was used as the synchronization signal, where increased noise sensitivity and broader spectral occupancy of the information-carrying signal degraded the BER performance [46].

4.3 QAM- and FM-Based Communication System Performance in Selective Fading Conditions

This subsection presents a comparative analysis of the QCSK and FM-CSK communication systems to assess their suitability for WSN applications. Since such systems must operate reliably in wireless environments, particular attention is given to multipath propagation, which introduces inter-symbol interference and selective fading. Building on the AWGN results from the previous section, system performance is evaluated in a two-ray propagation channel, followed by a comparison of the noise immunity of QCSK and FM-CSK under multipath fading conditions.

Study Setup

System performance under selective fading is evaluated using a MATLAB-based simulation framework designed explicitly for chaos-based communication systems, namely QCSK and FM-CSK. A common simulation setup is used to ensure a consistent comparison between the two architectures. A two-ray multipath channel is employed to emulate frequency-selective fading. The model consists of a direct path and a delayed reflected path, producing a spectral notch whose position depends on the path delay. In this study, the delay is selected such that the notch occurs at an intermediate frequency (IF) of 140 MHz. The multipath channel model is shown in Fig. 4.4. While the notch frequency is fixed, its depth is varied to assess system resilience under different fading conditions.

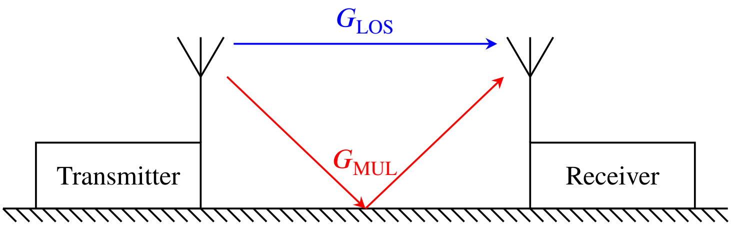


Fig. 4.4. Model of the emulated two-ray multipath channel.

Fig. 4.5 illustrates the effect of the two-ray channel on the spectra of the chaos-based transmission schemes. Fig. 4.5(a) shows the spectrum of the QCSK signal, while Fig. 4.5(b) presents the corresponding result for the FM-CSK signal. In both cases, the estimated channel amplitude transfer function $|K(f)|$ is overlaid to indicate the location and depth of the spectral notch.

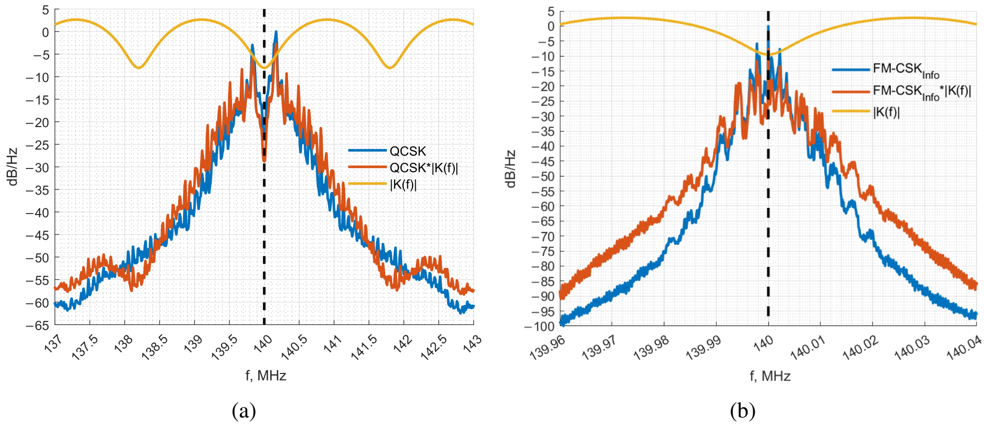


Fig. 4.5. Effect of a two-ray multipath channel on chaos-based transmission (a) QCSK and (b) FM-CSK.

After propagation through the multipath channel, AWGN is introduced at controlled SNR levels. The received signals are demodulated using the chaos-based receivers defined earlier in the Thesis, and the resulting BER is evaluated as a function of SNR and notch depth.

Performance Analysis in Selective Fading Conditions

Figures 4.6 and 4.7 compare the BER performance of the QCSK and 4-QAM systems in a two-ray frequency-selective fading channel for different spectral notch depths. The SNR axis is normalized such that a 0 dB notch corresponds to a BER of 10^{-3}, enabling direct comparison across fading conditions.

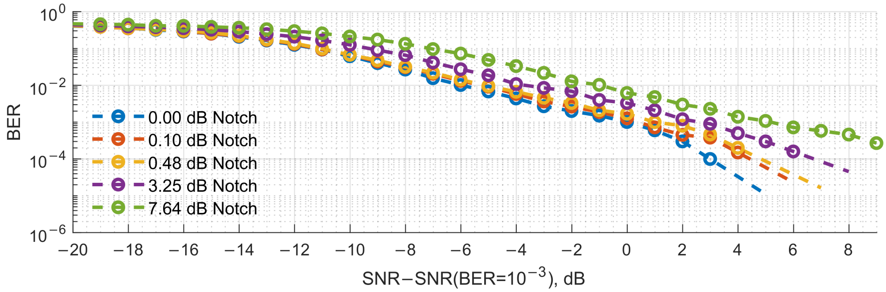


Fig. 4.6. QCSK communication system performance under two-ray selective fading.

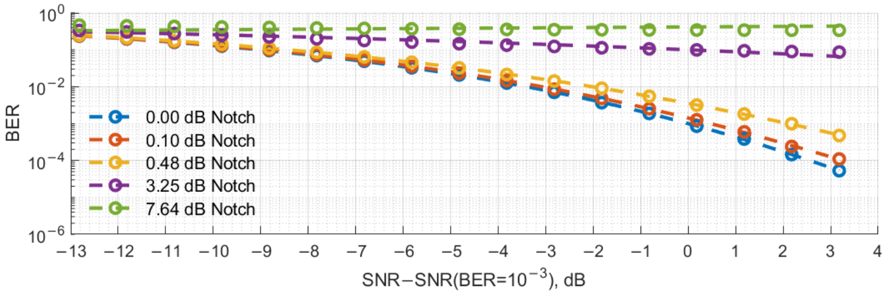


Fig. 4.7. 4-QAM communication system performance under two-ray selective fading.

For shallow spectral notches (below approximately 0.5 dB), QCSK and 4-QAM exhibit comparable performance, with a slight advantage for 4-QAM. However, as the notch depth increases, the performance trends diverge. At a representative notch depth of 3.25 dB, which corresponds to moderate frequency-selective fading, QCSK maintains a low BER on the order of 10^{-3}, whereas the BER of 4-QAM increases by nearly two orders of magnitude. Under deeper notches, the degradation of 4-QAM becomes severe, while QCSK exhibits only a gradual performance loss. This behavior indicates a substantially higher resilience of chaos-based quadrature transmission to notch-type fading.

The same evaluation was performed for FM-CSK and binary FSK (figures omitted for brevity), and similar trends were observed. Around the 3.25 dB notch depth, FM-CSK slightly outperforms FSK, achieving lower BER under moderate selective fading. For deeper notches, conventional FSK becomes more resilient than FM-CSK, while FM-CSK remains superior to 4-QAM in comparable fading conditions.

Comparing the two chaos-based systems, FM-CSK provides better resilience at moderate notch depths, including the critical 3.25 dB case, whereas QCSK exhibits improved resilience at some higher notch depths. Overall, both chaos-based schemes demonstrate significantly greater tolerance to frequency-selective fading than conventional linear modulation, confirming the advantages of integrating chaotic signaling into RF transmission architectures.

4.4 Discussion

This section investigated two chaos-based communication architectures, QCSK and FM-CSK, as representative extensions of advanced RF modulation applied to chaotic baseband signals. System modeling, prototype validation, synchronization analysis, noise immunity, and selective fading behavior were examined to evaluate how each modulation strategy affects overall system performance.

The QCSK system demonstrated reliable operation above the analog front-end sensitivity threshold, with performance strongly influenced by the choice of synchronization signal. Under two-ray selective fading, QCSK consistently outperformed its linear counterpart 4-QAM, particularly for deeper spectral notches, indicating that the combined CSK–quadrature structure preserves chaotic diversity under frequency-selective distortion.

In contrast, the FM-CSK architecture exhibited increased resilience to noise and fading, owing to information transmission via instantaneous frequency deviation. Simulation results showed that FM-CSK maintains lower BER than QCSK as notch depth increases, demonstrating stronger resilience to amplitude-related impairments and multipath-induced fading.

Quantitatively, in a two-ray channel with a 3.25 dB spectral notch at the carrier frequency, both chaos-based systems outperformed their conventional benchmarks. The QCSK system achieved a BER of 3.29×10^{-3}, while FM-CSK further reduced the error probability to 1.52×10^{-3}, exceeding the performance of 4-QAM and 2-FSK, respectively. These results confirm that chaotic modulation provides a measurable resilience advantage in frequency-selective multipath environments.

Overall, the two chaos-based architectures exhibit complementary strengths: QCSK is well suited for moderate noise and fading when optimal synchronization is used, whereas FM-CSK offers superior resilience under stronger fading and variable channel conditions. Collectively, the results demonstrate that chaos-based modulation can outperform conventional linear schemes in RF bands relevant to IoT and WSN applications when the modulation strategy is matched to channel characteristics.

CONCLUSIONS

This Doctoral Thesis is devoted to the analysis, design, and experimental evaluation of chaos-based communication systems operating under noise and multipath propagation conditions. The research focused on the influence of the fundamental frequency of the chaotic oscillator, synchronization stability, detection optimality, and advanced modulation techniques on the achievable performance of such systems. The proposed methods and system architectures were verified through circuit-level simulations and experimental measurements, demonstrating their practical feasibility and consistency with the theoretical considerations.

The main objective of the Thesis–to investigate and demonstrate how chaotic oscillator characteristics, synchronization strategies, and modulation techniques affect the performance of chaos-based communication systems–has been achieved. All research tasks formulated in the Introduction have been completed. The principal results obtained within the framework of this Doctoral Thesis are summarized as follows:

- It has been demonstrated that variation of the fundamental frequency of analog chaotic oscillators provides a practical mechanism for adjusting the achievable data rate of chaos-based communication systems. A lag-based analysis of cross-correlation functions was established as a consistent method for selecting the bit duration, ensuring that consecutive symbols are transmitted using sufficiently decorrelated chaotic waveforms. This relationship was experimentally validated for two structurally different chaotic oscillators.
- A comprehensive study of chaotic synchronization under additive noise conditions showed that the synchronization quality strongly depends on the selected circuit node used for coupling the drive and response oscillators. Based on these findings, a systematic methodology for selecting synchronization signals was developed, enabling the identification of synchronization configurations that ensure higher stability in noisy environments.
- It was shown that different state variables of the same chaotic oscillator may show unequal correlation level under identical synchronization conditions. This effect leads to an imbalance in correlation-based detection when CSK is applied. To address this issue, a compensation threshold for correlation-based detection was proposed, restoring balanced symbol decision-making and improving detection reliability.
- The impact of synchronization signal selection on the overall performance of chaos-based communication systems was evaluated. The results demonstrated that inappropriate synchronization choices can degrade BER performance.
- Advanced modulation techniques were successfully integrated with chaos-based communication systems. QAM and FM were combined with CSK to enable transmission in RF bands while preserving chaotic synchronization feasibility. The resulting systems were evaluated in AWGN channels and two-ray propagation channels.
- Comparative performance analysis revealed that chaos-based communication systems ex-

hibit increased resilience to frequency-selective fading compared to conventional modulation schemes operating under identical bandwidth constraints, particularly in severe two-ray propagation conditions.

All investigated systems were implemented using a combined simulation and experimental framework, where chaotic oscillators were modeled at the circuit level and signal processing, detection, and performance evaluation were performed in MATLAB. Experimental prototypes based on discrete analog circuits and commercial modulation modules confirmed the validity of the proposed approaches.

Beyond theoretical validation, the obtained results provide experimentally validated insight into the feasibility and operational characteristics of chaos-based communication. In particular, the demonstrated relationship between the chaotic oscillator fundamental frequency and achievable data rate establishes a clear connection between oscillator parameters and transmission speed, which is relevant for low-rate wireless communication scenarios such as sensor-to-base-station links. The achieved data rates were shown to fall within the same order of magnitude as those employed by existing IoT communication technologies, indicating that chaos-based systems can be parameterized to operate within practically relevant transmission regimes. Furthermore, the conducted analysis of synchronization signal selection yields qualitative and quantitative observations that can inform circuit- and system-level design choices aimed at improving resilience in noisy and multipath environments.

In conclusion, the results of this Doctoral Thesis confirm that chaos-based communication systems can be systematically designed and optimized through the appropriate selection of oscillator parameters, synchronization signals, detection strategies, and modulation techniques. The obtained results demonstrate the feasibility and adaptability of chaos-based communication for operation in noisy and multipath environments. Therefore, the objective of the Thesis has been successfully achieved, the stated research tasks have been completed, and the formulated theses have been defended.

Future research may further extend the presented results by investigating the behavior of chaos-based communication systems under more complex and time-varying channel conditions, including mobility-induced fading and nonstationary interference. The development of adaptive synchronization and detection strategies that dynamically adjust system parameters in response to changing noise and propagation conditions represents another important direction. In addition, integrated, low-power implementations of chaotic oscillators and synchronization circuits should be explored to evaluate the practical feasibility of deployment in compact wireless devices. Finally, the combination of chaos-based signaling with more spectrally efficient modulation and multi-user access techniques may enable broader applicability of the proposed concepts in next-generation secure and low-rate wireless communication systems.

BIBLIOGRAPHY

[1] P. Jonsson et al. *Ericsson Mobility Report November 2025*. en. Tech. rep. Nov. 2025. URL: https://www.ericsson.com/4aca6f/assets/local/reports-papers/mobility-report/documents/2025/ericsson-mobility-report-november-2025.pdf (visited on 11/28/2025).

[2] P. Sun et al. "A Survey of IoT Privacy Security: Architecture, Technology, Challenges, and Trends." en. In: *IEEE Internet of Things Journal* 11.21 (Nov. 2024), pp. 34567–34591. ISSN: 2327-4662, 2372-2541.

[3] N. M. Karie et al. "A Review of Security Standards and Frameworks for IoT-Based Smart Environments." en. In: *IEEE Access* 9 (2021), pp. 121975–121995. ISSN: 2169-3536.

[4] K. K. S. Gautam et al. "Investigation of the Internet of Things (IoT) Security and Privacy Issues." en. In: *2023 5th International Conference on Inventive Research in Computing Applications (ICIRCA)*. Coimbatore, India: IEEE, Aug. 2023, pp. 1489–1494. ISBN: 9798350321425.

[5] M. S. Sharbaf. "IoT Driving New Business Model, and IoT Security, Privacy, and Awareness Challenges." en. In: *2022 IEEE 8th World Forum on Internet of Things (WF-IoT)*. Yokohama, Japan: IEEE, Oct. 2022, pp. 1–4. ISBN: 978-1-66549-153-2.

[6] T. Sauter and A. Treytl. "IoT-Enabled Sensors in Automation Systems and Their Security Challenges." en. In: *IEEE Sensors Letters* 7.12 (Dec. 2023), pp. 1–4. ISSN: 2475-1472.

[7] B. Omoniwa et al. "Fog/Edge Computing-Based IoT (FECIoT): Architecture, Applications, and Research Issues." In: *IEEE Internet of Things Journal* 6.3 (June 2019), pp. 4118–4149. ISSN: 2327-4662.

[8] J. M. Hamamreh, H. M. Furqan, and H. Arslan. "Classifications and Applications of Physical Layer Security Techniques for Confidentiality: A Comprehensive Survey." en. In: *IEEE Communications Surveys & Tutorials* 21.2 (2019), pp. 1773–1828. ISSN: 1553-877X, 2373-745X.

[9] P. Rojas, S. Alahmadi, and M. Bayoumi. "Physical Layer Security for IoT Communications - A Survey." en. In: *2021 IEEE 7th World Forum on Internet of Things (WF-IoT)*. New Orleans, LA, USA: IEEE, June 2021, pp. 95–100. ISBN: 978-1-66544-431-6.

[10] E. Illi et al. "Physical Layer Security for Authentication, Confidentiality, and Malicious Node Detection: A Paradigm Shift in Securing IoT Networks." en. In: *IEEE Communications Surveys & Tutorials* 26.1 (2024), pp. 347–388. ISSN: 1553-877X, 2373-745X.

[11] Z. A. Traynor et al. “Physical-layer security solutions for IoT devices using Radio Frequency Fingerprints.” en. In: *2024 International Conference on Computing, Internet of Things and Microwave Systems (ICCIMS)*. Gatineau, QC, Canada: IEEE, July 2024, pp. 1–4. ISBN: 9798350351736.

[12] V. Mohan and A. Mathur. “Secrecy Analysis of DCSK-Based PLC Systems With Multiple Eavesdroppers.” en. In: *IEEE Systems Journal* 17.3 (Sept. 2023), pp. 3646–3657. ISSN: 1932-8184, 1937-9234, 2373-7816.

[13] F. Capligins et al. “FPGA Implementation and Study of Synchronization of Modified Chua’s Circuit-Based Chaotic Oscillator for High-Speed Secure Communications.” In: 2021. ISBN: 978-1-66542-538-4.

[14] F. Yu et al. “CCII and FPGA Realization: A Multistable Modified Fourth-Order Autonomous Chua’s Chaotic System with Coexisting Multiple Attractors.” In: *Complexity* 2020 (2020), pp. 1–17. ISSN: 10990526.

[15] J. Sun et al. “A Memristive Fully Connect Neural Network and Application of Medical Image Encryption Based on Central Diffusion Algorithm.” en. In: *IEEE Transactions on Industrial Informatics* 20.3 (Mar. 2024), pp. 3778–3788. ISSN: 1551-3203, 1941-0050.

[16] A. E. George et al. “Real-World Secure Communication based on Synchronised Lorenz Chaotic Circuits.” en. In: *2024 13th International Conference on Modern Circuits and Systems Technologies (MOCAST)*. Sofia, Bulgaria: IEEE, June 2024, pp. 1–6. ISBN: 979-8-3503-8542-7.

[17] A. J. Michaels and C. Lau. “Generalized Multi-carrier Chaotic Shift Keying.” en. In: *2014 IEEE Military Communications Conference*. Baltimore, MD, USA: IEEE, Oct. 2014, pp. 657–662. ISBN: 978-1-4799-6770-4.

[18] C. Bai et al. “Double-Stream Differential Chaos Shift Keying Communications Exploiting Chaotic Shape Forming Filter and Sequence Mapping.” In: *IEEE Transactions on Wireless Communications* 21.7 (July 2022), pp. 4954–4972. ISSN: 1536-1276, 1558-2248.

[19] V. Mohan and A. Mathur. “Performance Evaluation of DCSK-Based PLC Systems Under Pulse Jamming Attacks.” en. In: *2024 IEEE 99th Vehicular Technology Conference (VTC2024-Spring)*. Singapore, Singapore: IEEE, June 2024, pp. 1–6. ISBN: 9798350387414.

[20] T. Bonny and W. Al Nassan. “Optimizing Security and Cost Efficiency in N-Level Cascaded Chaotic-Based Secure Communication System.” en. In: *Applied System Innovation* 7.6 (Oct. 2024), p. 107. ISSN: 2571-5577.

[21] Z. Hua and Y. Zhou. “Exponential Chaotic Model for Generating Robust Chaos.” en. In: *IEEE Transactions on Systems, Man, and Cybernetics: Systems* 51.6 (June 2021), pp. 3713–3724. ISSN: 2168-2216, 2168-2232.

[22] T. I. Karimov et al. “The Study on Multiparametric Sensitivity of Chaotic Oscillators.” en. In: *2020 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering (EIConRus)*. St. Petersburg and Moscow, Russia: IEEE, Jan. 2020, pp. 134–137. ISBN: 978-1-72815-761-0.

[23] M. Sadia et al. “Robust Chaos With Novel 4-Transistor Maps.” en. In: *IEEE Transactions on Circuits and Systems II: Express Briefs* 70.3 (Mar. 2023), pp. 914–918. ISSN: 1549-7747, 1558-3791.

[24] S. Ergun and S. Tanriseven. “Random Number Generator Based on Skew-tent Map and Chaotic Sampling.” en. In: *2020 IEEE Asia Pacific Conference on Circuits and Systems (APCCAS)*. Ha Long, Vietnam: IEEE, Dec. 2020, pp. 224–227. ISBN: 978-1-7281-9396-0.

[25] S. Araki, J.-H. Wu, and J.-J. Yan. “A Novel Design of Random Number Generators Using Chaos-Based Extremum Coding.” In: *IEEE Access* 12 (2024), pp. 24039–24047. ISSN: 2169-3536.

[26] C.-C. Liu et al. “Design of a Multiple Pseudorandom Number Generator Combined Chaotic System With RNS and Its Application to Secure Image Processing.” en. In: *IEEE Access* 12 (2024), pp. 155246–155258. ISSN: 2169-3536.

[27] J. Arif et al. “A Novel Chaotic Permutation-Substitution Image Encryption Scheme Based on Logistic Map and Random Substitution.” en. In: *IEEE Access* 10 (2022), pp. 12966–12982. ISSN: 2169-3536.

[28] M.-A. Estudillo-Valdez, V.-A. Adeyemi, and J.-C. Nuñez-Perez. “FPGA realization of an image encryption system using the DCSK-CDMA technique.” en. In: *Integration* 96 (May 2024), p. 102157. ISSN: 01679260.

[29] H. Lu et al. “Chip-Scale Random Number Generator Based On Self-Chaotic Dynamics Of Broad-Area VCSELs.” en. In: *2024 IEEE 29th International Semiconductor Laser Conference (ISLC)*. Orlando, FL, USA: IEEE, Sept. 2024, pp. 1–2. ISBN: 9798350372991.

[30] X. Hu et al. “Color Image Encryption Algorithm Based on Dynamic Chaos and Matrix Convolution.” en. In: *IEEE Access* 8 (2020), pp. 12452–12466. ISSN: 2169-3536.

[31] R. Kiliç and F. Yildirim. “A survey of Wien bridge-based chaotic oscillators: Design and experimental issues.” en. In: *Chaos, Solitons & Fractals* 38.5 (Dec. 2008), pp. 1394–1410. ISSN: 09600779.

[32] A. Elwakil and M. Kennedy. “A family of Colpitts-like chaotic oscillators.” en. In: *Journal of the Franklin Institute* 336.4 (May 1999), pp. 687–700. ISSN: 00160032.

[33] E. V. Efremova. “Generation of Dynamic Chaos in a Range of 10–30 GHz.” en. In: *Journal of Communications Technology and Electronics* 63.4 (Apr. 2018), pp. 367–373. ISSN: 1064-2269, 1555-6557.

[34] K. Maezawa et al. "Direct Observation of High-Frequency Chaos Signals from the Resonant Tunneling Chaos Generator." en. In: *Japanese Journal of Applied Physics* 43.8R (Aug. 2004), p. 5235. ISSN: 0021-4922, 1347-4065.

[35] K. Maezawa. "A new generation of negative-resistance devices—New developments in ultrahigh-frequency applications based on resonant tunneling elements." en. In: *Electronics and Communications in Japan (Part II: Electronics)* 89.4 (Apr. 2006), pp. 29–38. ISSN: 8756-663X, 1520-6432.

[36] L. M. Pecora and T. L. Carroll. "Synchronization of chaotic systems." In: *Understanding Complex Systems* 48 (2009), pp. 101–133. ISSN: 18600832.

[37] A. A. Kekha Javan et al. "Design of adaptive-robust controller for multi-state synchronization of chaotic systems with unknown and time-varying delays and its application in secure communication." In: *Sensors (Switzerland)* 21.1 (2021), pp. 1–21. ISSN: 14248220.

[38] A. Karimov et al. "Adaptive Generalized Synchronization between Circuit and Computer Implementations of the Rössler System." en. In: *Applied Sciences* 11.1 (Dec. 2020), p. 81. ISSN: 2076-3417.

[39] H. Xie et al. "A Secure Communication Framework Based on Chaotic Synchronization via Approximate Nonlinear Model Predictive Control." en. In: *IEEE Control Systems Letters* 8 (2024), pp. 1559–1564. ISSN: 2475-1456.

[40] E. Ozpolat, V. Celik, and A. Gulten. "A Novel Four-Dimensional Hyperchaotic System: Design, Dynamic Analysis, Synchronization, and Image Encryption." en. In: *IEEE Access* 12 (2024), pp. 126063–126073. ISSN: 2169-3536.

[41] X. Cui et al. "A Chaotic Synchronization Method Based on Time-Synchronized Control." en. In: *2024 43rd Chinese Control Conference (CCC)*. Kunming, China: IEEE, July 2024, pp. 335–340. ISBN: 978-988-758-158-1.

[42] D. Cirjulina et al. "Experimental Study of the Impact of Component Nominal Deviations on the Stability of Vilnius Chaotic Oscillator." In: *2020 IEEE Microwave Theory and Techniques in Wireless Communications (MTTW)*. Riga, Latvia: IEEE, Oct. 2020, pp. 231–236. ISBN: 978-1-72819-398-4.

[43] R. Babajans et al. "Impact of the Chaotic Synchronization's Stability on the Performance of QCPSK Communication System." In: *Electronics* 10.6 (2021), p. 640. ISSN: 2079-9292.

[44] V. Rybin et al. "Estimating Optimal Synchronization Parameters for Coherent Chaotic Communication Systems in Noisy Conditions." In: *Chaos Theory and Applications* 5 (July 2023).

[45] D. Cirjulina et al. “Experimental Study on Frequency Modulated Chaos Shift Keying Communication System.” In: *2022 Workshop on Microwave Theory and Techniques in Wireless Communications (MTTW)*. Riga, Latvia: IEEE, Oct. 2022, pp. 1–4. ISBN: 978-1-6654-6439-0.

[46] R. Babajans et al. “Performance Analysis of Vilnius Chaos Oscillator-Based Digital Data Transmission Systems for IoT.” en. In: *Electronics* 12.3 (Jan. 2023), p. 709. ISSN: 2079-9292.

[47] D. Cirjulina et al. “Fundamental Frequency Impact on Colpitts Chaos Oscillator Dynamics.” In: *2023 Workshop on Microwave Theory and Technology in Wireless Communications (MTTW)*. Riga, Latvia: IEEE, Oct. 2023, pp. 19–23. ISBN: 9798350393491.

[48] D. Cirjulina et al. “Experimental Study on Colpitts Chaotic Oscillator-Based Communication System Application for the Internet of Things.” en. In: *Applied Sciences* 14.3 (Jan. 2024), p. 1180. ISSN: 2076-3417.

[49] D. Cirjulina, R. Babajans, and D. Kolosovs. “Experimental Study on Quadrature Chaos Shift Keying Communication System.” In: *2024 IEEE Workshop on Microwave Theory and Technology in Wireless Communications (MTTW)*. Riga, Latvia: IEEE, Oct. 2024, pp. 29–32. ISBN: 979-8-3315-3317-5.

[50] D. Cirjulina et al. “Fundamental Frequency Impact on Vilnius Chaos Oscillator Dynamics.” en. In: *16th Chaotic Modeling and Simulation International Conference*. Ed. by C. H. Skiadas and Y. Dimotikalis. Cham: Springer Nature Switzerland, 2024, pp. 87–101. ISBN: 978-3-031-60906-0 978-3-031-60907-7.

[51] D. Cirjulina, R. Babajans, and D. Kolosovs. “Design Particularities of Quadrature Chaos Shift Keying Communication System with Enhanced Noise Immunity for IoT Applications.” en. In: *Entropy* 27.3 (Mar. 2025), p. 296. ISSN: 1099-4300.

[52] A. Ascoli et al. “Edge of Chaos Induces a Hopf Bifurcation in a Bio-Inspired Thermally-Activated Memristor Oscillator.” In: *2025 IEEE International Symposium on Circuits and Systems (ISCAS)*. London, United Kingdom: IEEE, May 2025, pp. 1–5. ISBN: 979-8-3503-5683-0.

[53] L. O. Chua et al. “A Universal Circuit for Studying and Generating Chaos—Part II: Strange Attractors.” In: *IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications* 40.10 (1993), pp. 745–761. ISSN: 10577122.

[54] M. Kennedy. “Chaos in the Colpitts oscillator.” en. In: *IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications* 41.11 (Nov. 1994), pp. 771–774. ISSN: 10577122.

[55] G. A. Gottwald and I. Melbourne. “On the Implementation of the 0-1 Test for Chaos.” In: (2009).

[56] A. Tamaševičius et al. “A simple chaotic oscillator for educational purposes.” In: *European Journal of Physics* 26.1 (Nov. 2004), p. 61.

[57] A. Ipatovs et al. “Complete Bifurcation Analysis of the Vilnius Chaotic Oscillator.” en. In: *Electronics* 12.13 (June 2023), p. 2861. ISSN: 2079-9292.

[58] D. Pikulins et al. “Study of Nonlinear Dynamics of Vilnius Oscillator.” en. In: *Nonlinear Dynamics and Applications*. Ed. by S. Banerjee and A. Saha. Cham: Springer International Publishing, 2022, pp. 1219–1228. ISBN: 978-3-030-99791-5 978-3-030-99792-2.

[59] *LoRaWAN™ 1.1 Specification*. Nov. 2017. URL: https://resources.lora-alliance.org/technical-specifications/lorawan-specification-v1-1 (visited on 03/26/2024).

[60] *IEEE Standard for Low-Rate Wireless Networks*. ISBN: 9798855713152. URL: https://ieeexplore.ieee.org/document/10794632/ (visited on 01/15/2025).

[61] *ETSI EN 300 220-2*. Mar. 2025. URL: https://www.etsi.org/deliver/etsi_en/300200_300299/30022002/03.03.01_60/en_30022002v030301p.pdf (visited on 09/19/2025).

[62] L. M. Pecora and T. L. Carroll. “Synchronization in chaotic systems.” en. In: *Physical Review Letters* 64.8 (Feb. 1990), pp. 821–824. ISSN: 0031-9007.

[63] R. Babajans, D. Cirjulina, and D. Kolosovs. “Field-Programmable Gate Array-Based Chaos Oscillator Implementation for Analog–Discrete and Discrete–Analog Chaotic Synchronization Applications.” en. In: *Entropy* 27.4 (Apr. 2025), p. 334. ISSN: 1099-4300.

[64] B. Bilgehan and O. Sabuncu. “Synchronization and Analysis of Chaotic Circuit with Application to Communication in the internet of things (IoT) Services.” In: *2022 International Conference on Artificial Intelligence in Everything (AIE)*. Lefkosa, Cyprus: IEEE, Aug. 2022, pp. 674–678. ISBN: 978-1-6654-7400-9.

[65] L. M. Pecora et al. “Fundamentals of synchronization in chaotic systems, concepts, and applications.” eng. In: *Chaos (Woodbury, N.Y.)* 7.4 (Dec. 1997), pp. 520–543. ISSN: 1089-7682.

[66] Z. Yu et al. “Compounding and Synchronization of Fractional Order Chaotic Systems With Prescribed Performance for Secure Communication.” In: *IEEE Transactions on Circuits and Systems I: Regular Papers* 71.3 (Mar. 2024), pp. 1335–1345. ISSN: 1549-8328, 1558-0806.

[67] Z. Liu et al. “Stabilization and complete synchronization of a new time-reversed system.” In: *2023 IEEE International Conference on Memristive Computing and Applications (ICMCA)*. Jinan, China: IEEE, Dec. 2023, pp. 1–5. ISBN: 9798350316230.

Darja Čirjuļina was born in 1999 in Riga, Latvia. She received an Academic Bachelor's degree in Electrical Engineering (2020) and a Professional Master's degree in Electronics and the qualification of Lead Electronics Engineer (2022) from Riga Technical University (RTU). Since 1 March 2019, she has been working at RTU, initially as a Research Assistant and since September 2022, as a Researcher at the Institute of Photonics, Electronics and Telecommunications, where she participates in research projects and teaches students.

During her doctoral studies, she has participated in several international mobilities and professional visits, including KTH Royal Institute of Technology (Sweden), Infineon Technologies Austria, Cracow University of Technology (Poland), Keysight Technologies GmbH (Germany), Politecnico di Torino (Italy), and Aristotle University of Thessaloniki (Greece). Her scientific and academic achievements during doctoral studies have been recognised with several awards, including the IEEE Student and Young Professional travel grant (2025) and the Best Student Presentation Award at the Days of Applied Nonlinearity and Complexity (DANOC'24) conference.

Her research interests focus on chaos-based data transmission systems for IoT applications. During her doctoral studies, she has also expanded her research activities in photonics, particularly high-speed IM/DD transmission systems, enabling her to participate in major international conferences such as OFC, ECOC, and IPC.