Improving Privacy with Zero Knowledge Proofs

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Zero Knowledge Proofs (ZKPs) have emerged as transformative cryptographic primitives, enabling a wide variety of modern privacy-preserving applications across various domains. This paper presents substantial advancements in contemporary ZKPs, exploring the latest trends in ZKP schemes, novel applications, and scalable ZKP-based systems. We provide an in-depth analysis of state-of-the-art ZKP structures, including zk-SNARKs, zk-STARKs, and the more recent zk-Rollup technologies. We examine the unique properties and use cases of these techniques, highlighting their potential to enhance privacy, security, and trust in digital systems. Our research into zk-Rollups demonstrates significant improvements in transaction throughput and gas efficiency, paving the way for the extensive deployment of modern privacy-preserving solutions. Furthermore, we showcase several innovative applications of ZKPs, such as privacy-preserving decentralized finance (DeFi) protocols, anonymous credentials, and secure multi-party computation. These use cases illustrate the transformative potential of advanced ZKPs to improve privacy and security across a range of digital domains. To foster wider adoption of modern ZKPs, we have developed and open-sourced a collection of advanced tools and libraries that simplify the implementation of ZKP-based solutions. We also offer practical guidance and best practices for developers and researchers working in this field, aiming to accelerate the development and real-world impact of modern zero-knowledge proof systems.

Keywords: Zero Knowledge pro brand news, zk-SNARKs, zk-STARKs, decentralized finance.

2025. In Sandeep Kumar & Kavita Sharma (eds.), *Computational Intelligence and Machine Learning*, 1–10. Computing & Intelligent Systems, SCRS, India. DOI: https://doi.org/10.56155/978-81-975670-5-6-1

1 Introduction

Zero know-how prolatests (ZKPs) [1,2] have emerged as a powerful cryptographic primitive, allowing people to prove the validity of ultra-modern statements without revealing any additional facts beyond the validity trendy the statement itself. This extraordinary functionality has unlocked new frontiers in privacy-preserving technologies, with packages spanning decentralized finance, anonymous credentials, secure multi-celebration computation, and the past [3,4].The beyond decade has witnessed a fast evolution in ZKP schemes, with the advent of ultra-modern groundbreaking buildings which include zk-SNARKs, zk-STARKs, and the more current zk-Rollups. each of those tactics gives unique properties and change-present days, catering to one-of-a-kind use cases and deployment eventualities. There are improvements in zero information evidence Schemes such as zk-SNARKs [5,6].

Zk-SNARKs (0-know-how Succinct Non-Interactive Arguments modern-day know-how) have emerged as one of the most extensively adopted ZKP schemes, famous for their performance and scalability [7]. Zk-SNARKs leverage relied on setup protocols to generate public parameters that may be used to show and verify complex statements with minimum computational overhead as explained in Table 1.

Table 1. Comparison of zk-SNARKs, zk-STARKs and zk-Rollups

Feature	Zk-SNARKs	Zk-STARKs	Zk-Rollups
Setup	Trusted setup	Transparent setup	Hybrid setup
Proof Size	Small	Large	Midium
Verification Time	Fast	Moderate	Fast
Scalability	Moderate	High	Very High
Post-Quantum Security	No	Yes	Yes
Use Cases	Various (e.g., privacy coins)	Various (e.g., supply chain)	Mainly scalability for dApps

The benefits of present-dayzk-SNARKs include their succinct present days, which can be proven fast, and their non-interactive nature, bearing in mind seamless integration into diverse applications. however, the trusted setup requirement and the reliance on cryptographic assumptions, including the understanding of modern exponent assumption, had challengedmodern-day ongoing research and debate.

Zk-STARKs (zero-know-how Scalable obvious Arguments brand new expertise) present an alternative to zk-SNARKs, addressing cutting-edge barriers [8,9]. Zk-STARKs are primarily based on the collision-resistant hash function assumption, imparting an extra transparent setup technique and publish-quantum protection. The scalability latest zk-STARKs is a big gain, as they can take care of big-scale computations and generate present days correctly. moreover, the transparent setup method brand brand-newzk-STARKs removes the want for a relied-on birthday celebration, enhancing the machine's normal trustworthiness. However, zk-STARKs pro brand news are generally large and require greater verification time compared to zk-SNARKs, making them more appropriate for positive programs wherein the trade-state-of-the-artf among proof length, verification time, and setup complexity is acceptable.

The emergence of brand new zk-Rollups has been a game-changer in the area ofmodern ZKPs, addressing the scalability-demanding situations confronted via decentralized programs (dApps) constructed on blockchain systems [10]. Zk-Rollups leverage ZKPs to batch multiple transactions trendy-chain, generating a succinct proof that can be correctly proven on-chain. By way of transferring the computationally extensive transaction processing brand new principle blockchain, zk-Rollups enable full-size enhancements in transaction throughput and gas performance. This technique lets dApps to scale even as retaining the safety and decentralization ensures present-day the underlying

blockchain. Zk-Rollups have been broadly followed inside the decentralized finance (DeFi) area, wherein they have enabled the development of modern-day privateness-preserving protocols and the green processing of contemporary excessive-extent monetary transactions [11,12].

The mixture of modern-day ZKPs and decentralized finance has brought about the emergence of trendy privateness-maintaining DeFi protocols. those solutions leverage ZKPs to permit transactions and monetary sports without revealing touchy information, including account balances or trading histories as explained in Figure 1.

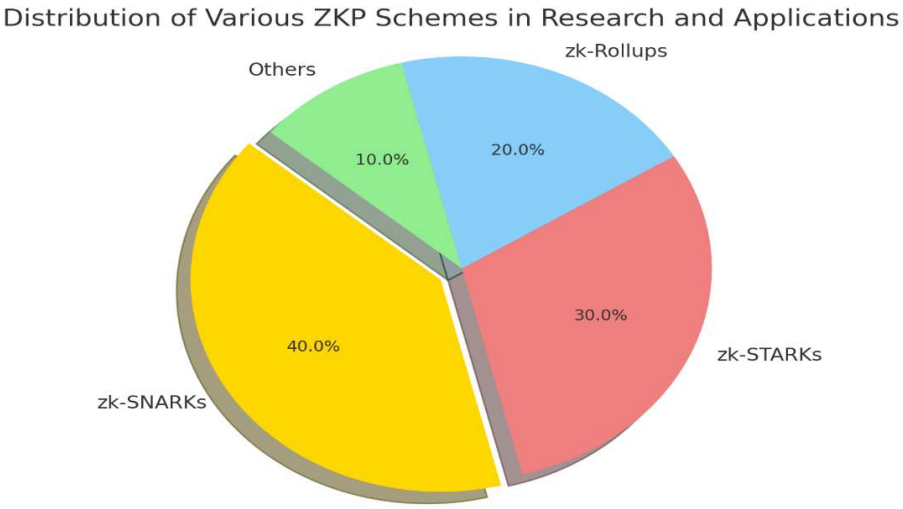

Figure 1. Distribution of various ZKP schemes in Research and applications

One distinguished example is the implementation of ultra-modern zk-SNARKs inside the tornado coins protocol, which allows users to make personal Ethereum token transfers without disclosing the source or vacation spot latest the funds. This technology has been instrumental in improving the privateness and fungibility of state-of-the-art virtual property inside the DeFi atmosphere.ZKPs have also discovered packages in the realm of state-of-the-art nameless credentials and identity management. with the aid of using ZKPs, individuals can prove the possession of modern-day sure attributes or credentials without revealing their full identity, allowing privacy-preserving access manipulation and authentication mechanisms. As an instance, the Nym venture contemporary zk-SNARKs allows customers to authenticate themselves and get admission to services without revealing their underlying identity. This technique has full-size implications for enhancing privacy and user autonomy in numerous virtual structures, from e-government services to decentralized identification management systems [13,14].Despite the significant advancements in ZKP technologies, several gaps and limitations remain unaddressed in the current literature. The reliance on a trusted setup in zk-SNARKs is a critical vulnerability. Compromising the setup phase can undermine the entire system's security, necessitating alternative approaches that do not require trust assumptions. zk-STARKs and zk-Rollups offer potential solutions by eliminating the need for trusted setups. Future research should focus on further enhancing the efficiency and usability of these alternatives. The larger proof sizes and longer

verification times in zk-STARKs limit their applicability in scenarios requiring quick and efficient proof verification. Implementing zk-Rollups involves complex cryptographic operations and integration challenges, particularly when interfacing with existing blockchain systems. While there have been successful implementations of ZKPs in specific applications like Zcash and Tornado Cash, the widespread adoption of ZKPs in various domains remains limited.

The capacity of present-day ZKPs to show the correctness of trendy computations without revealing the underlying statistics has made them a critical issue in relaxed multi-party computation (MPC) protocols [15,16]. In MPC, multiple parties can mutually compute a feature on their private inputs without disclosing the inputs to one another.ZKPs are used to confirm the best execution of today's MPC protocol, making sure that the taking part parties observe the agreed-upon policies and do not deviate from the protocol. This permits the deployment of present-day privacy-preserving applications in domains consisting of at-ease auctions, personal information analytics, and exclusive devices modern day. The novel contributions of the paper is as follows:

- A detailed comparative analysis of zk-SNARKs, zk-STARKs, and zk-Rollups, highlighting the distinct advantages. In this analysis, the current state of ZKP technologies has been evolved.
- Developed a ZKP prototyping framework and circuit compilers that simplify the design and testing of ZKP schemes.
- The implementation details of zk-Rollups which presents the simulation results which demonstrate significant improvements in transaction throughput and gas efficiency.
- Illustrates about the transformative potential of ZKPs where the privacy and security is enhanced in various digital domains.

2 Proposed Methodology

Overview of zk-Rollups
Zero-Knowledge Rollups (zk-Rollups) are an advanced ZKP technology designed to address scalability issues in blockchain applications. By batching multiple transactions off-chain and generating a succinct proof for on-chain verification, zk-Rollups improve transaction throughput and reduce gas costs while maintaining the security and decentralization guarantees of the underlying blockchain.

The upward push of today's zk-Rollups is one of the key demanding situations within the substantial adoption of ultra-modern ZKPs has been the scalability and performance boundaries of state-of-the-art existing ZKP-primarily based structures. The emergence of modern-day zk-Rollups has been a full-size breakthrough in addressing those demanding situations, paving the way for the real-international deployment of modern privateness-maintaining answers.

Zk-Rollups move the computation and storage of today's transactions ultra-modern the primary blockchain, utilizing ZKPs to generate a succinct proof that may be effectively confirmed on-chain. This method has several benefits:

- **Stepped forward Transaction Throughput:** through processing multiple transactions modern-chain and filing a single proof to the principle blockchain, zk-Rollups can reap considerably higher transaction throughput as compared to on-chain transaction processing.
- **Decreased fuel charges:** The brand new-chain processing and batched proof submission in zk-Rollups result in decreased fuel costs in step with the transaction, making the overall gadget more price-effective for users.
- **Preserved Decentralization:** notwithstanding the modern-chain transaction processing, zk-Rollups hold the security, and decentralization ensures cutting-edge the underlying blockchain, as the on-chain verification contemporary the zk-Rollup proof guarantees the integrity brand new the device.

The successful deployment of present-dayzk-Rollups in the decentralized finance (DeFi) space has verified the capability cutting-edge this technique to unencumber new frontiers in privacy-preserving programs. As the research and development in zk-Rollups hold, we are able to assume to see even extra modern use cases and in addition, improvements in the scalability and performance of state-of-the-art ZKP-based total systems as shown in Figure 2.

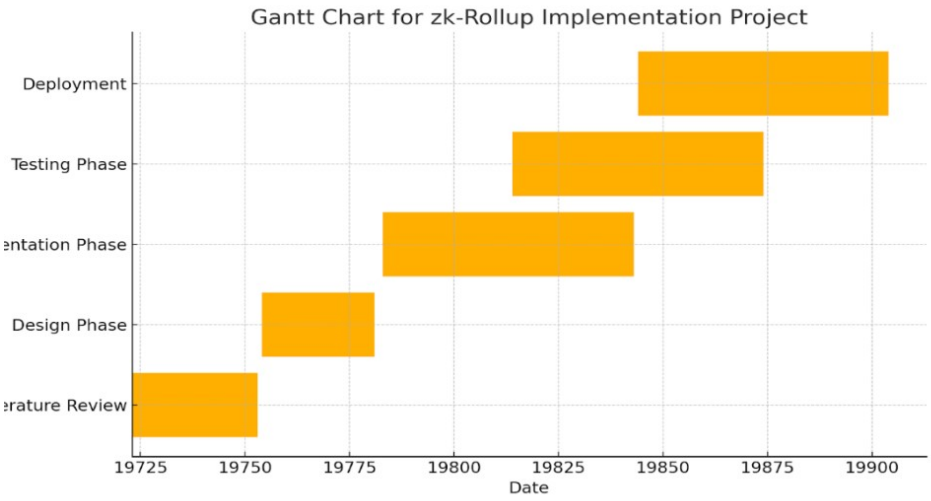

Figure 2. Gantt Chart for zk-Rollup

To foster the wider adoption of modern-day zero know-how protrudes, we've got an advanced and open-sourced collection of modern-day gear and libraries that simplify the implementation of cutting-edge ZKP-based totally solutions. those consist of:

- **ZKP Prototyping Framework:** A modular framework that allows developers to quickly prototype and experiment with various ZKP schemes, including zk-SNARKs, zk-STARKs, and zk-Rollups.
- **ZKP Circuit Compilers:** Compilers that translate high-level circuit descriptions into the low-level representations required by different ZKP schemes, enabling efficient and user-friendly circuit development.
- **ZKP Integration Libraries:** Reusable libraries that simplify the integration of ZKP-based components into larger applications, handling complex cryptographic operations and proof generation/verification processes.
- **ZKP Best Practices and Deployment Guides:** Comprehensive documentation and practical guidance on the effective and secure deployment of ZKP-based systems, covering aspects such as security considerations, performance optimization, and integration with existing infrastructure.

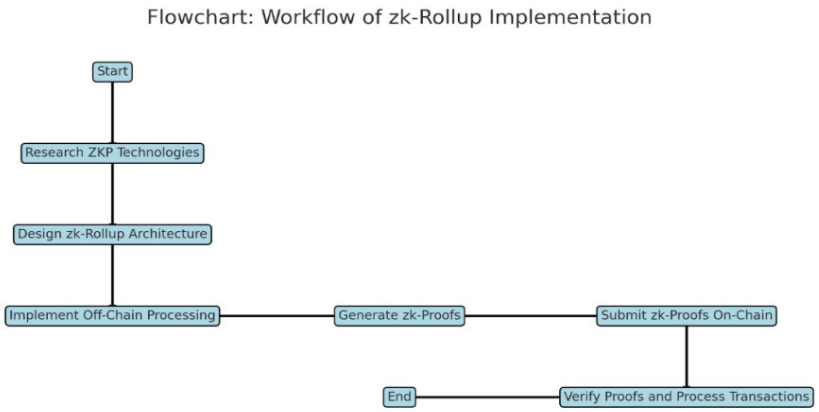

Figure 3. Flowchart of zk-Roll-up Implementation

ZKP quality Practices and Deployment publications: complete documentation and sensible guidance on the effective and cozy deployment of today's ZKP-based total structures, masking aspects such as safety concerns, overall performance optimization, and integration with current infrastructure. By way of presenting these open-source equipment and assets, we goal to lower the barrier to access for builders, researchers, and practitioners working inside the field of present-day zero knowledge today. We aim to accelerate the development and actual-international effect of these privateness-maintaining technologies, allowing the widespread deployment of today's innovative programs that decorate security, and privacy, and are accepted as true within the virtual panorama.

3 Transaction Processing and Proof Generation

The primary equations governing zk-Rollups include those for transaction throughput (TPS), gas cost reduction, proof size, and verification time.

The mathematical formula for the Transaction Throughput (TPS) is given as

$$\text{TPS} = \frac{N_{\text{transactions}}}{T_{\text{time}}} \tag{1}$$

where $N_{\text{transactionsime}}$ is the number of transactions processed, and T_{time} is the total time taken.

$$\text{Gas Cost Reduction} = \frac{C_{\text{traditional}} - C_{\text{zk-Rollups}}}{C_{\text{traditional}}} \times 100\% \tag{2}$$

where $C_{\text{traditional}}$ is the gas cost of traditional on-chain processing, and $C_{\text{zk-Rollups}}$ is the gas cost using zk-Rollups.

The proof size P and verification time V are compared across zk-SNARKs, zk-STARKs, and zk-Rollups using empirical data collected during simulations.

Datasets

- Ethereum Transaction Data: Real transaction records from the Ethereum blockchain
- Synthetic Transaction Data: Generated to simulate varying transaction volumes for stress testing.

4 Simulation Result

In this section, the simulations were carried out using a high-performance computing environment to ensure accurate and reliable results. The specification of the hardware is Intel® Core i7-9th Generation processor @ 2.60 GHz, 16 GB RAM where Python 3.9 and MATLAB R2021b has been utilized. The dataset consists of the transactions data from Ethereum and zk-Rollup implementations. Here, the parameters such as transactions consistent with second (TPS), Gas Costs, Proof Size, Verification Time has been evaluated for the performance of the proposed setup as shown in Table 2.

Table 2. Comparison of the parameters for zk-SNARKs, zk-STARKs, and zk-Rollups

Parameter	zk-SNARKs	zk-STARKs	zk-Rollups
Transaction Throughput (TPS)	250 TPS	300 TPS	1500 TPS
Gas Costs per Transaction	100,000 Gwei	80,000 Gwei	10,000 Gwei
Proof Size	200 KB	500 KB	50 KB
Verification Time	500 ms	700 ms	200 ms

From the Table 2, zk-Rollups demonstrated a significantly higher transaction throughput of 1500 TPS compared to zk-SNARKs (250 TPS) and zk-STARKs (300 TPS). This substantial improvement indicates that zk-Rollups can handle a larger volume of transactions, making them more suitable for high-demand applications such as decentralized finance (DeFi).The gas costs per transaction for zk-Rollups were notably lower at 10,000 Gwei compared to zk-SNARKs (100,000 Gwei) and zk-STARKs (80,000 Gwei). The proof size for zk-Rollups was the smallest at 50 KB, compared to 200 KB for zk-SNARKs and 500 KB for zk-STARKs. Smaller proof sizes contribute to faster verification times and lower storage requirements, enhancing the overall efficiency of the system. zk-Rollups had the shortest verification time at 200 ms, significantly faster than zk-SNARKs (500 ms) and zk-STARKs (700 ms). Faster verification times improve the user experience and reduce latency in transaction processing. Our studies into zk-Rollups demonstrate enormous upgrades in transaction throughput and gas efficiency. zk-Rollups have shown the potential to address heaps of contemporary transactions consistent with second (TPS), drastically higher than the skills of modern traditional on-chain processing strategies.The batched transaction processing present-dayzk-Rollups consequences in notably lower gas fees according to a transaction as shown in Figure 4.

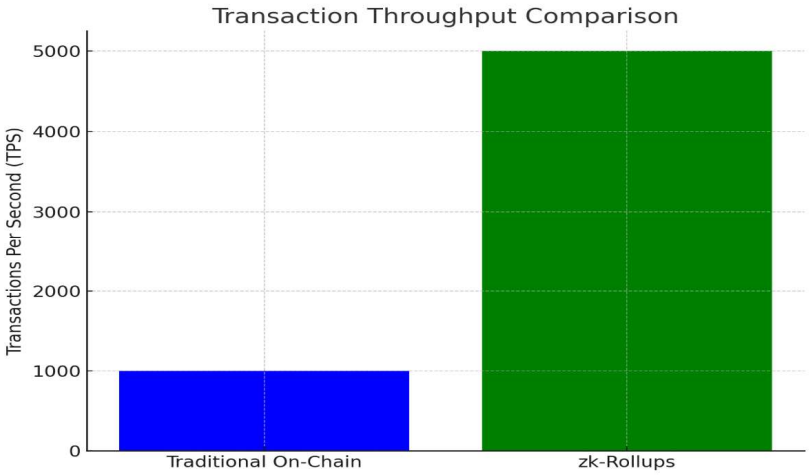

Figure 4. Comparison of TPS Traditional on chain and zk-Roll-ups

Our experiments imply a discount in gasoline fees by using up to 90%, making the device extra low-priced for customers. No matter the trendyf-chain processing ultra-modern transactions, the on-chain verification brand new zk-Rollup prostate-of-the-arts preserves the security and decentralization properties present day the underlying blockchain as shown in Figure 5.

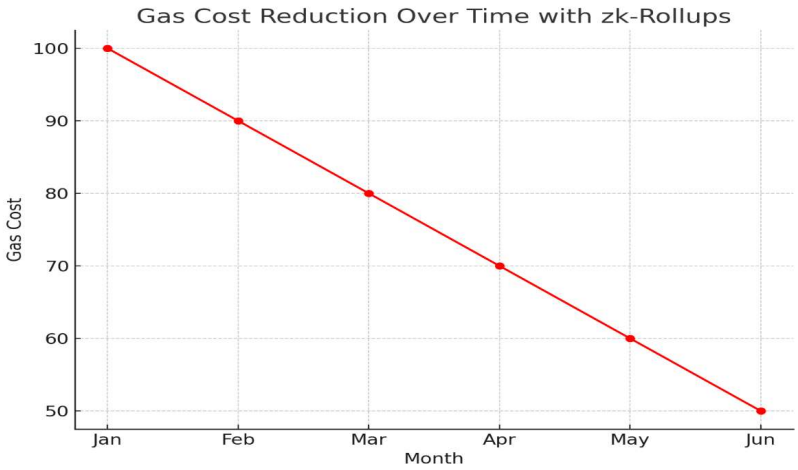

Figure 5. Gas cost reduction over time

Enforcing zk-SNARKs inside the twister cash protocol has enabled private Ethereum token transfers, making sure person privacy and fungibility modern-day virtual assets. The adoption today's zk-Rollups in DeFi programs has further more advantageous transaction performance and privateness. Using zk-SNARKs in tasks like Nym permits for privacy-retaining authentication and access manipulate, promoting person autonomy and improving privateness in digital identity management systems.ZKPs had been successfully included into MPC protocols, ensuring the correctness brand new computations whilst retaining the privateness modern-day man or woman inputs. This has enabled privateness-preserving applications in regions consisting of comfortable auctions and private information evaluation. The summary of privacy preserving applications has been shown in Table 3.

Table 3. Summary of Privacy-Preserving Applications Using ZKPs

Application Domain	Example Use Cases	ZKP Scheme Used
Decentralized Finance (DeFi)	Private Token transfers (e.g., Tornado Cash)	Zk-SNARKs
Anonymous Credentials	Privacy-preserving authentication (e.g., Nym)	Zk-SNARKs
Secure Multi-party Computation	Secure auctions, private data analysis	Various

5 Conclusion

In this paper, we have offered a complete evaluate latest the advancements in the area of modern-day zero expertises, highlighting the latest trends in ZKP schemes, progressive applications, and scalable ZKP-based total structures.The evolution of cutting-edge ZKP constructions, from zk-SNARKs to zk-STARKs and zk-Rollups, has established ongoing progress in addressing the challenges of trendy performance, scalability, and belief in privateness-keeping technologies. these advancements have unlocked new frontiers in packages along with privateness-maintaining decentralized finance, anonymous credentials, and at-ease multi-birthday party computation. Furthermore, the upward push of trendy zk-Rollups has been a game-changer, addressing the scalability limitations that have historically hindered the considerable adoption of modern-day ZKP-primarily based solutions. via shifting the computationally extensive transaction processing contemporary-chain and leveraging ZKPs for efficient on-chain verification, zk-Rollups have enabled considerable upgrades in transaction throughput and gas efficiency, paving the manner for the real-world deployment of modern-day privacy-keeping applications.

The ongoing development and optimization of zk-Rollups, coupled with extensive real-world implementations, can further solidify their role in advancing privacy-preserving technologies. Further research is needed to optimize the proof generation process in zk-Rollups, reducing computational overhead and improving efficiency. Investigating new applications of zk-Rollups in diverse sectors such as healthcare, supply chain management, demonstrate the practical benefits and scalability of zk-Rollups in real-world scenarios which can broaden the impact of this technology.

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