Slovak University of Technology in Bratislava
Faculty of informatics and information technologies

Reg. No.: FIIT-16768-116160

Lukáš Častven

Practical usage of Zero-knowledge in different use-cases in blockchains

Bachelor's thesis

Thesis supervisor: Ing. Kristián Košťál PhD.

December 2023

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Study programme: Informatics

Study field: Computer Science

Training workplace: Institute of Computer Engineering and Applied Informatics

Thesis supervisor: Ing. Kristián Košťál PhD.

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Slovenská technická univerzita v Bratislave
Ústav počítačového inžinierstva a aplikovanej informatiky

Fakulta informatiky a informačných technológií
2023/2024

ZADANIE BAKALÁRSKEJ PRÁCE

Autor práce:	Lukáš Častven
Študijný program:	informatika
Študijný odbor:	informatika
Evidenčné číslo:	FIIT-16768-116160
ID študenta:	116160
Vedúci práce:	Ing. Kristián Košťál, PhD.
Vedúci pracoviska:	Ing. Katarína Jelemenská, PhD.
Názov práce:	**Practical usage of Zero-knowledge in different use-cases in blockchains**
Jazyk, v ktorom sa práca vypracuje:	slovenský jazyk
Špecifikácia zadania:	Zero-knowledge proofs (ZKPs) are an exciting breakthrough in applied cryptography that will unlock new use cases across an array of industries, from Web3 to supply chains to the Internet of Things. By verifying the authenticity of information without revealing it, ZKPs can help enhance digital systems' privacy, security, and efficiency. Current use cases are decentralized identity, private transactions, secure and scalable Layer-2s, voting systems, IoT, supply chains, etc. Examine existing solutions and proposals in this domain by conducting state-of-the-art analysis. Propose a system that will utilize Zero-knowledge techniques in some of the existing blockchain networks to enhance its functionality by one of the picked goals. Implement such a solution, which can be done in a smart contract way or as a core network plugin. Potential blockchain networks to use are Polkadot, Kusama, Near, Tezos, Algorand, Moonbeam, Ethereum, etc. Evaluate the implemented solution and compare it with existing ones. Discuss the results and conclude with new findings.
Rozsah práce:	40
Termín odovzdania práce:	21. 05. 2024
Dátum schválenia zadania práce:	
Zadanie práce schválil:	

Anotácia

Slovenská technická univerzita v Bratislave
Fakulta informatiky a informačných technológií
Študijný program: Informačná bezpečnosť

Autor: Lukáš Častven
Bakalárska práca: Velmi dolezity projekt
Vedúci projektu: Ing. Kristián Košťál PhD.
December 2023

Bakalárska práca skúma aplikáciu dôkazov s nulovým vedomím (ZKPs) v blockchaine. Dôkazy s nulovým vedomím sú kryptografická metóda, ktorá umožňuje overenie dát bez odhalenia samotných dát, čo je ideálne pre bezpečné a súkromné aplikácie v blockchainoch. Táto práca je zameraná na návrh a implementáciu konceptu schémy tajne adresy s použitím ZKPs. Táto schéma umožňuje odosielateľom odvodiť tajnú adresu z verejných údajov príjemcu. Iba príjemca má kontrolu nad touto adresou, a zaroveň neodhaľuje žiadne informácie o tom, kto príjemca je.

Výskum zahŕňa analýzu kryptografických princípov za ZKPs, nasledovanú vysvetlením návrhu schémy tajne adresy a jej integráciou do blockchainu Ethereum.

Táto práca prispieva do oblasti ukázaním, ako možno využiť ZKPs v blockchaine na riešenie problémov súkromia, ponúkajúc riešenie vo forme konceptuálnej implementácie schémy tajne adresy s použitím ZKPs.

Annotation

Slovak University of Technology in Bratislava

Faculty of informatics and information technologies

Degree Course: Informatics

Author: Lukáš Častven

Bachelor’s thesis: Practical usage of Zero-knowledge in different use-cases in blockchains

Supervisor: Ing. Kristián Košťál PhD.

December 2023

This bachelor’s thesis investigates the application of Zero Knowledge Proofs (ZKPs) in blockchains. Zero Knowledge Proofs are a cryptographic method which enables the validation of data without revealing the data itself, making it ideal for secure and private applications in blockchain networks. The focus of this thesis is the design and implementation of a proof of concept Stealth Address scheme using ZKPs. This scheme allows any sender to derive a stealth address from recipients public data. Only the recipient has control over this address, yet it does not leak any information about who the recipient is.

The research includes an analysis of the cryptographic principles behind ZKPs, followed by a explanation of the Stealth Address scheme’s design and its integration into a an Ethereum blockchain.

This thesis contributes to the field by showcasing how ZKPs can be utilized in blockchain to address privacy concerns, offering a solution in the form of a proof of concept implementation of Stealth Address scheme using ZKPs.

Table of contents

List of Figures

List of abbreviations used

EVM	Ethereum Virtual Machine
ZK	Zero Knowledge
ZKP	Zero Knowledge Proof

Chapter 1

Introduction

Zero Knowledge Proofs (ZKPs) are a powerful cryptography primitive. They allow for the verification of a statement's truth without disclosing or in any way revealing the actual content of the statement. This characteristic is crucial for maintaining trust between parties while also preserving privacy.

The concept of ZKPs was first introduced in a 1989 research paper, "The Knowledge Complexity of Interactive Proof Systems."[1]. This work describes how in traditional proofs, such as demonstrating a graph is Hamiltonian, more information is typically revealed than just the truth of the theorem. This paper develops a computational complexity theory focusing on the knowledge part within a proof. It introduces zero knowledge proofs, a novel concept where proofs only confirm the correctness of a proposition without exposing any extra knowledge. The paper focuses on interactive proofs, where a dialogue between a prover and a verifier occurs. In these interactive proofs, the prover aims to convince the verifier about the truth of a private statement, with a very small probability of error. This interaction is pivotal in ZKPs, as it allows for the verification of a statement's truth without revealing the actual information or knowledge behind the statement, maintaining the principle of conveying no knowledge beyond the proposition's correctness.

This thesis extends the application of ZKPs to the concept of stealth addresses in blockchain, as outlined in Vitalik Buterin's article "An Incomplete Guide to Stealth Addresses."[2]. Stealth addresses are critical for privacy on blockchains, allowing assets to be transferred without revealing the recipient's identity and making it difficult to link transactions to specific individuals.

Stealth addresses allow a sender (Alice) to transfer assets to a receiver (Bob) without publicly revealing the Bob's identity. To achieve this, Bob must first provide a public meta stealth address generation data. This data has different structure based on the underlying stealth address generation schema. From this data Alice computes a new stealth address that only Bob can control, and sends the assets to that newly generated address. Bob can then access these assets from another address, only by providing a ZKP of given address ownership.

Chapter 2

Analysis

The analysis section of the thesis starts with demonstration of interactive proofs with goal to build up intuition behind interactive proofs [1, 3]. This section explains how Alice attempts to prove to Bob that she knows an algorithm, with which she computes some pair (N, y), such that this pair is part of the quadratic residue language QR. Specifically, Alice needs to convince Bob that there exists an x such that y equals x squared modulo N, effectively placing the pair (N, y) within the QR language, which includes all pairs where y is a quadratic residue of N.

The analysis section continues by highlighting a practical limitation of interactive proofs in real world cryptography. It notes that for Alice to prove something to multiple parties, she would need to engage in separate interactions with each one. This approach is not scalable and becomes impractical for widespread verification needs. However, the thesis introduces the Fiat-Shamir transform [4], a significant breakthrough that addresses this issue. This transform allows for converting the interactive proof into a non-interactive format by processing the interaction transcript, making the proof more practical and scalable for real-world cryptographic applications.

While in theory any NP statement [5] can be proven using interactive proofs, practical implementation requires specific definition and encoding of the statement. There are two main models of general computation, those are circuits and turing machines. To trace the computation of a turing machine, the representation needs to somehow handle memory and thus would accrue more complexity than if a circuit is used. To represent a statement as a circuit, an arithmetic circuit, a computation model composed of addition and multiplication operations, is used. This circuit encodes the statement into a form suitable for "zk-ifying", enabling the application of interactive proofs to a broader range of practical scenarios.

The analysis section then explores various ZKP systems, each with unique properties and proof constructions. The most renowned among these are SNARKs (Succinct Non-interactive ARguments of Knowledge), Bulletproofs, and STARKs (Scalable Transparent ARguments of Knowledge). These systems differ in aspects such as computational efficiency, size of proofs, and the need (or lack thereof) for a trusted setup. Each system offers advantages and challenges, making them suitable for different applications.

The final part of the analysis examines how ZKP systems such as SNARKs enable the creation of a stealth address scheme that upholds privacy and security. This section assesses how these systems fulfill the necessary properties for a stealth address scheme, focusing on their ability to ensure transaction confidentiality while maintaining the anonymity of the recipient's identity.

2.1 Proof of quadratic residuosity

This first part focuses on demonstrating an interactive proof where Alice aims to prove to Bob that she knows an algorithm, which computes some pair (N, y), such that this pair is part of the quadratic residue language QR [1]. QR is defined as:

$$QR = \{(N, y) : \exists x, y \equiv x^2 \pmod N\}$$

1. Alice generates pair (N, y)
2. Alice picks a random r such that $1 \leq r \leq N$ and $\gcd(r, N) = 1$ and calculates $s \equiv r^2 \pmod N$
3. Alice sends Bob s
4. Alice asks Bob which value he wants. Either $\sqrt{s}$ or $\sqrt{sy}$, but he can not have both!
5. Bob flips a coin and sends b such that if coin landed on heads $b = 1$ else $b = 0$
6. If $b = 1$ Alice sends to Bob $z \equiv \sqrt{sy} \equiv r\sqrt{y} \pmod N$ else she sends $z \equiv \sqrt{s} \equiv r \pmod N$
7. Bob accepts if $z^2 = sy^b$

If Alice was a cheating prover, and she didn't have the algorithm for generating pairs from QR, then the probability that Bob's coin toss favors Alice is one half. With one half probability Bob would ask cheating prover Alice to give him the equation she can not solve, because if the prover is cheating, she can not find the $\sqrt{s}$ and $\sqrt{sy}$. If she could, that would mean that she is

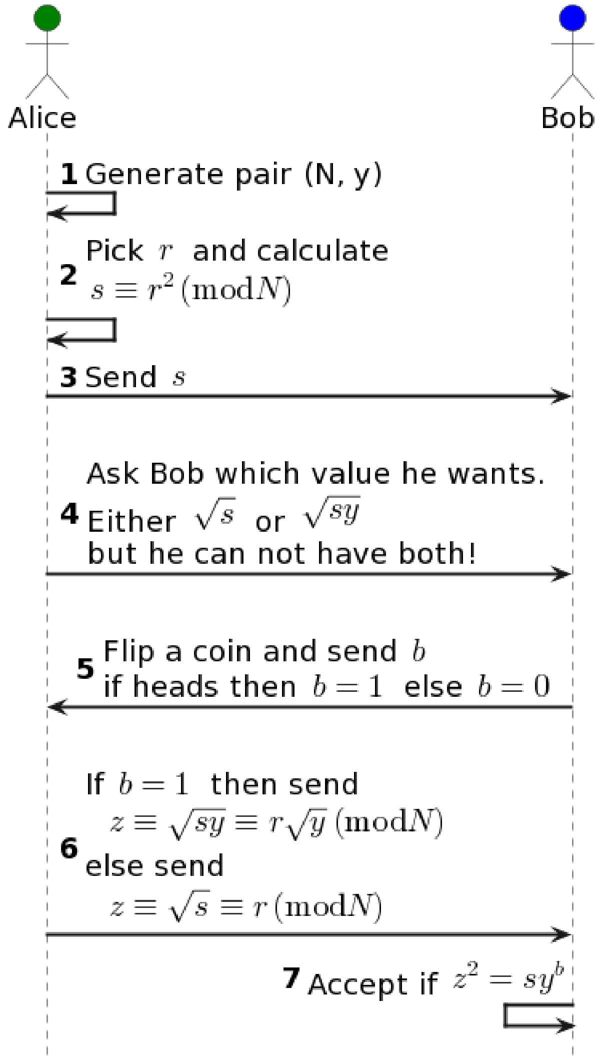

Figure 2.1: Interactive proof of language QR

not cheating.

If the Alice's claim is true, Bob will accept. If Alice is not honest, and cheats, all provers will not accept with probability $P(Accept) = 0.5$. But this probability may not be satisfying enough. To make the probability that Alice is cheating smaller, Bob and Alice can start the interaction once again. This would lead to $P(Accept) = (0.5)^2$. They can redo the process as many times as they wish, resulting in $P(Accept) = (0.5)^k$ where k is how many different interactions they performed.

Thanks to the randomness of the coin toss, there are 2^k possibilities how the interaction can go. Since Alice can't reliably predict what the random coin toss will yield, she must be ready to provide both equations. Thus Bob is convinced, that Alice isn't cheating, with probability $P(Accept) = (0.5)^k$, and can accept the proof.

2.2 Non-interactive proofs

Interactive proofs require Alice to engage in a unique interaction with each individual verifier, which is not scalable or feasible for widespread application. Many ZKP protocols only require from the verifier a random input (for instance, a coin toss). Protocols, in which the verifier's role is generating some randomness and making it public are called public coin protocols [6, 7]. The paper "How To Prove Yourself: Practical Solutions to Identification and Signature Problems"[4] by Fiat and Shamir demonstrates how these interactive public coin protocols can be efficiently transformed into non-interactive ones, offering a more scalable and practical solution for ZKPs.

To transform a interactive public coin protocol into a non-interactive, Alice uses a random oracle which can provide a random coin toss based on some input. In practice the source of randomness of the random oracle is a cryptographic hash function, such as SHA256. Instead of sending messages back and forth between Alice and Bob, Alice provides to Bob a transformed transcript of the interaction. Since Bob's role in this interaction would only be generating random coin toss, Alice can in advance query the random oracle for this random value, and supply the message as an input to the query. The transcript string would look like this $(msg1, query(msg1), msg2, ...)$, where $query$ is the output from random oracle. This string and the public input of the proof can then be published and anybody, not just Bob, can validate this proof on their own.

In scenario when Alice sends only two messages and requires one random coin toss from Bob, Bob at the end can compute the validity of the proof from

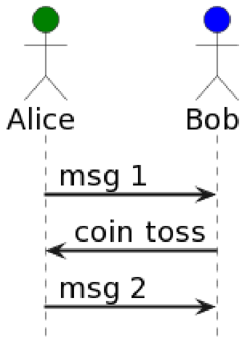

Figure 2.2: Interactive public coin proof

Alice with $validate(public\, input\ x,\ msg1,\ coin\, toss,\ msg2) = accept/reject$

Then after applying Fiat-Shamir transform, Alice only sends one message with the transcript string, and Bob can compute the validity of the proof like

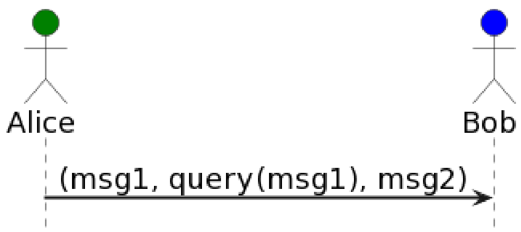

Figure 2.3: Non-interactive public coin proof

this $validate(public\, input\ x,\ msg1,\ query(msg1),\ msg2) = accept/reject$.

2.3 Arithmetic circuit

in a finite field $\mathbb{F}_p$

Chapter 3

Návrh riešenia

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Chapter 4

Implementácia

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Chapter 5

Testovanie

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Chapter 6

Záver

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6.1 Zhodnotenie projektu

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6.2 Možné vylepšenia

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Resumé

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References

Appendix A

Špecifikácia API rozhrania

This is the application programming interface

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A.1 Endpointy

- v1 - API version 1
- v2 - API version 2
- test - API placeholder

A.2 Cesty

- A.2.1 Auth
- A.2.2 Music
- A.2.3 Pictures
- A.2.4 Video
- A.2.5 Mail

A.2.1 Auth

A.2.2 Music

A.2.3 Pictures

A.2.4 Video

A.2.5 Mail

Appendix B

Project task schedule

B.1 Zimný semester

1^{st}-4^{th} week	Consultations & finding related research
5^{th}-6^{th} week	Working on the Introduction and Analysis chapters
7^{th} week	Consultations
8^{th}-10^{th} week	Working on the Analysis chapters
11^{th}-12^{th} week	Working on the Solution proposal chapter

B.2 Letný semester

1^{st}-2^{nd} week	Consultations & designing API specification
3^{rd}-6^{th} week	Consultations & implementation of back-end
7^{th}-9^{th} week	Implementation of server
10^{th} week	Consultations & implementation of front-end
11^{th}-12^{th} week	Finishing documentation & solution testing

Appendix C

Contents of the digital medium

Registration number of the thesis in the information system: FIIT-16768-116160

Contents of the digital medium (ZIP archive):

Name of the submitted archive: BP_LukasCastven.zip.