PROJECT REPORT ON ANONYMITY

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PRINCIPLES OF INFORMATION SECURITY

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By
TEAM: Risk Rangers

International Institue of Information Technology

Team Members:

Abhay Patil, 2020101022
Ishank Kapania, 2023701012
Praddyumn Shukla, 2022201001
Pranjal Thapliyal, 2020101108
Santhoshini Thota, 2021101097

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LIST OF ABBREVIATIONS

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Chapter 1

Quisquis: A New Design for Anonymous Cryptocurrencies

1.1 Network Model

1.2 Security Assumptions

1.2.1 Decisional Diffie-Hellman Problem

The authors have made the assumption that the Decisional Diffie-Hellman (DDH) problem is computationally hard. The DDH problem is the task of determining whether g^{ab} is equal to g^c given the elements g, g^a, and g^b in a cyclic group G.

1.2.2 Zero Knowledge Arguments of Knowledge

The authors have assumed that zero-knowledge arguments of knowledge work as intended. This means that they have made the following assumptions:

- **Perfect Completeness** - An honest prover can always convince an honest verifier if a statement is true.
- **Special Honest-Verifier Zero Knowledge (SHVZK)** - A simulator exists that can generate a conversation that looks like an interaction between the prover and verifier, without knowing the proverś secret.
- **Argument of Knowledge** - If a prover can convince a verifier that a statement is true, then the prover must know a witness to the statement.

1.2.3 Commitment Schemes

The authors have assumed that commitment schemes are secure, which means that they have made the following assumptions:

- **Computational Hiding** - It is computationally hard for an adversary to determine which value has been committed to. In other words, they have a negligible advantage in distinguishing between $\text{Commit}_{pk}(m_0; U_R)$ and $\text{Commit}_{pk}(m_1; U_R)$ where U_R is the uniform distribution over the randomness space.

- **Unconditional Binding** - It is impossible (even with infinite computational power) to change the committed value after the commitment has been made.

- **Key Anonymity** - The adversary cannot distinguish commitments made under different keys, even if they know the commitment key.

1.2.4 Updatable Public Keys

- **Indistinguishably** - An adversary cannot distinguish between a freshly generated public key and an updated version of a public key they already know.

- **Unforgeability** - An adversary canâ€™t produce a public key that is an update of an honestly generated public key unless they already know the secret key for the original public key.

1.3 Adversary Model

1. The adversary begins by specifying the initial balances $\tilde{bl}$ of all participants in the protocol.

2. The adversary can direct honest parties to make specific transactions via *transact* queries.

3. The adversary can inject fully malicious transactions in the system via *verify* queries.

4. The adversary can learn the secret key for any account in the system via *disclose* queries.

- **Oracle Queries:**

  - (disclose, i): If $(i, acct_i, sk_i, bl_i)$ was stored, call J the set of all j such that there is a record $(j, acct_j, sk_j, bl_j)$ with $sk_i = sk_j$. Remove i and J from honest, add them to corrupt, and return $(sk_i, bl_i, J, bl_j j \in J)$ to the adversary.

  - (transact, i,P, A, $\tilde{v}$): If $(i, acct_i, sk_i, bl_i)$ was not stored return $\perp$. Otherwise run $tx \leftarrow \text{Trans}(sk_i, P, A, \tilde{v})$, and $state' \leftarrow \text{Verify}(state, tx)$. If $state' \neq \perp$ update $state = state'$, run the bookkeeping for tx, and return tx.

– (verify,tx): run $state' \leftarrow \text{Verify}(state, tx)$. If $state' \neq \perp$ update $state = state'$, run the bookkeeping for tx, and return $state'$.

– (challenge, b,(i0, i1, j0, j1, A, v0, v1)): If i0 or i1 is in corrupt, or j0 or j1 is in corrupt (except if j0 = j1 and v0 = v1), or $bli0 < v0$ or $bl_{i1} < v1$, then halt and return 0. Otherwise, compute $tx_x \leftarrow \text{Trans}(sk_{ix}, acct_{ix}, acct_{jx}, A_x, (-v_x, v_x))$. If $\text{Verify}(state, tx_x) = \perp$, then again we say the adversary lost the game. Otherwise, run the bookkeeping for tx_b.

In terms of security:

- **Anonymity:** Anonymity holds if no PPT A has non-negligible advantage in the anonymity game.
- **Theft prevention:** Theft prevention holds if no PPT A can win the theft prevention game with non-negligible probability.

The adversary model is designed to capture a wide range of attacks while preventing trivial attacks that could arise from the ability to learn secret keys or perform unauthorized transactions.

1.4 Motivation

1.5 Key Results

1.6 Key Techniques used

1.7 History of the Problem

1.8 Future Directions

1.9 What I Understood

This paper was picked by Abhay Patil, a BTech Computer Science student bearing the Roll no. 2022201001. The paper can be accessed here.

1.10 Motivation

The paper is mainly concerned with addressing the limitations of current cryptocurrencies, specifically concerns relating to privacy and efficiency. Most cryptocurrencies, bitcoin included, provide pseudo-anonymity by allowing users to create and operate multiple addresses. However, this degree

of anonymity is not complete since these addresses can be linked together, and can even be linked to their real world identities.

Tumblers exist to allow senders to mix their coins with those of other senders, and therefore provide an additional layer of anonymity. However, users are required to trust a central mixer, defeating the purpose of cryptocurrency. Additionally, an unavoidable latency factor exists, since the users have to wait for other senders to make transactions in order to be able to mix with them.

There exist cryptocurrencies focused on anonymity such as Montero and Zcash. However, the UTXO set (the set of unspent transaction outputs) is always growing, which then means that all nodes will inevitably store the entire blockchain, unlike Bitcoin which can store a much more concise representation.

Therefore, the authors propose Quisquis, a new design for anonymous cryptocurrencies offering improved privacy, reduced latency, and a more efficient UTXO management system.

Chapter 2

Literature Survey

2.1 Introduction

Lorem Ipsum is simply dummy text of the printing and typesetting industry. Lorem Ipsum has been the industry's standard dummy text ever since the 1500s, when an unknown printer took a galley of type and scrambled it to make a type specimen book. It has survived not only five centuries, but also the leap into electronic typesetting, remaining essentially unchanged. It was popularised in the 1960s with the release of Letraset sheets containing Lorem Ipsum passages, and more recently with desktop publishing software like Aldus PageMaker including versions of Lorem Ipsum. [**?**].

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3.3 Adversary Model

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3.9 What I Understood

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3.10 Keywords

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Chapter 4

Untagging Tor: A Formal Treatment of Onion Encryption

Abstract

Tor is essential for online anonymity, offering a secure way for two parties to communicate without revealing their identities, even if parts of the network are compromised. It uses onion routing to protect users' identities but is susceptible to tagging attacks, where an adversary can deanonymize users by controlling the network's entry and exit points. The paper discusses a new defense mechanism against such attacks, proposing an enhanced onion encryption scheme based on tweakable ciphers, aiming to strengthen Tor against these vulnerabilities.

4.1 Introduction

The concept of anonymity in digital communication extends beyond mere confidentiality and integrity, addressing the need to protect users' identities against automatic disclosure through public networks. This principle was first encapsulated in David Chaum's mix-nets, which laid the groundwork for onion routing, the foundation of protocols like Tor. Unlike other privacy-enhancing technologies, onion routing provides a unique approach to anonymity, allowing users to communicate over a network without exposing their identities to potential surveillance or attacks.

Tor represents the pinnacle of this development, offering a low-latency, circuit-based system that is widely adopted for anonymous internet access. Its architecture is designed to conceal the identities of its users by routing their communications through a series of relay nodes, each adding a layer of encryption, much like the layers of an onion. This method ensures that no single point in the network can link the origin and destination of a message, significantly reducing the risk of identity disclosure.

However, the reliance on cryptographic techniques does not render Tor invulnerable. It faces threats from tagging attacks, a form of active attack that can compromise user anonymity by marking and tracking data packets as they traverse the network. Recognizing the severity of this threat, the Tor community has proposed enhancements to its encryption scheme, aiming to thwart tagging attacks without compromising the network's performance or user experience.

The introduction sets the stage for a detailed exploration of Tor's operational principles, its vulnerability to specific attack vectors, and the ongoing efforts to fortify its defenses. By examining Proposal 261's approach to onion encryption, the paper endeavors to provide a comprehensive understanding of the challenges and solutions in maintaining anonymity within the Tor network, highlighting the balance between security and usability in the design of privacy-enhancing technologies.

4.2 Network Model Overview

The paper abstracts Tor's network into a theoretical model to analyze its security and anonymity aspects comprehensively. This model simplifies the network into a directed graph, with nodes representing onion proxies and routers. The communication channels between these nodes are depicted as edges in the graph, facilitating a secure (though not anonymous) communication protocol directly between any two nodes. This setup assumes a complete directed graph structure, enabling unrestricted secure communication across the network.

4.2.1 Circuits and Path Representation

- ***Circuits***: A circuit in this model is initiated by an onion proxy and consists of a path through the network of onion routers, designed for unidirectional communication. The path is defined to be acyclic, and its length, denoted by l, varies depending on the specific circuit setup. This variability is key to understanding the flexibility and robustness of Tor's design in maintaining anonymity across diverse network conditions.

- ***Path Representation***: Each circuit is uniquely identified by a vector of nodes, starting with the initiating onion proxy, through the routers it traverses, and ends with a special symbol to

indicate the end of the circuit. This representation ensures each circuit's unique identification and facilitates the encryption and decryption processes as the data traverses the network.

4.2.2 State Management

Both onion proxies and routers maintain states associated with the circuits they participate in. However, the use of these states differs significantly between proxies and routers:

- ***Onion Proxies***: Use their state primarily for encryption, with a clear association between each state and its corresponding circuit. This association is crucial for the encryption process, ensuring data confidentiality as it begins its journey through the Tor network.

- ***Onion Routers***: Upon receiving a cell (a packet of data), must first identify the intended circuit before proceeding with decryption. This process involves a two-stage decryption mechanism, where the first stage identifies the relevant circuit, and the second stage performs the actual decryption and processing of the cell. This differentiation in state usage underscores the complexity of maintaining anonymity and security within the network, ensuring that routers can efficiently and securely forward data without compromising the network's integrity.

4.2.3 Detailed Aspects

- ***Communication Security***: The model emphasizes the importance of secure communication between nodes, even if anonymity is not guaranteed at this layer. This secure communication foundation is critical for the overall security posture of the Tor network, ensuring that adversaries cannot easily intercept or manipulate data as it moves between nodes.

- ***Circuit Identification and Processing***: The unique identification of circuits through vectors and the two-stage decryption process for routers highlight the sophisticated mechanisms in place to manage data flows within the network. These processes ensure that data can be securely and efficiently routed, maintaining the confidentiality and integrity of the information being transmitted.

- ***State Isolation***: By maintaining separate state vectors for each circuit and limiting state updates to the current circuit being processed, the model ensures that interactions with one

circuit do not adversely affect another. This isolation is vital for the network's robustness, preventing potential cross-circuit leakage that could compromise security or anonymity.

4.3 Introduction

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The introduction sets the stage for a detailed exploration of Tor's operational principles, its vulnerability to specific attack vectors, and the ongoing efforts to fortify its defenses. By examining Proposal 261's approach to onion encryption, the paper endeavors to provide a comprehensive understanding of the challenges and solutions in maintaining anonymity within the Tor network, highlighting the balance between security and usability in the design of privacy-enhancing technologies.

Chapter 5

Privacy-Preserving Transactions With Verifiable Local Differential Privacy

This paper was choosen by Thota Santhoshini, an BTech Computer Science student bearing the Roll no. 2021101097. The paper can be accessed here.

5.1 Network Model

The network model described in the paper focuses on the interaction between two key entities: the users and the data analyst within a privacy-preserving transaction system on blockchain networks. Users engage in token exchanges through transfer transactions recorded on the blockchain, with specific individual attributes disclosed confidentially to the data analyst. These attributes can encompass various areas, such as indicating the user's location, tax-exempt status, or any other pertinent information that can be denoted as a binary variable. The data analyst collects aggregated information from the private attributes and activities of the users for statistical analysis while ensuring user confidentiality.

The scheme operates in a permissioned setting, where user attributes are issued by a registration authority to prevent users from arbitrarily mutating their attributes. This ensures that users cannot manipulate their attributes as they see fit. The network model also considers the potential deviation from the protocol by both the user and the data analyst, introducing an element of uncertainty. This model aims to devise a protocol that protects the interests of either party as long as that party is honest, ensuring user privacy and data integrity.

5.2 Security Assumptions

The security assumptions outlined in the paper are crucial for ensuring the integrity and privacy of the privacy-preserving transaction system. The document emphasizes the potential dishonest behavior of both users and the data analyst, highlighting the need to protect the interests of honest parties. The scheme operates in a permissioned setting, where user attributes are issued by a registration authority to prevent users from arbitrarily mutating their attributes. This ensures that users cannot manipulate their attributes as they see fit. The paper also acknowledges the potential deviation from the protocol by both the user and the data analyst, introducing an element of uncertainty. This uncertainty arises from the fact that a party adhering to the protocol cannot definitively determine if the other party is also following the protocol or diverging from it.

The security assumptions also consider the threat model, which involves the interaction between the user and the data analyst, both of whom may exhibit dishonest behavior and possess conflicting objectives. The first threat arises from the data analyst's desire to compute aggregated information derived from the user's transactions while potentially disregarding the user's privacy. This could lead to attempts to link between the transaction and the user who submitted it. The second threat arises from users who prioritize their privacy at the expense of providing misleading or corrupted data, which can undermine the integrity of the analysis conducted by the analyst.

5.3 Adversary Model

The adversary model described in the paper encompasses the potential deviation from the protocol by both the user and the data analyst, introducing an element of uncertainty. This model is designed to consider the interaction between the user and the data analyst, both of whom may exhibit dishonest behavior and possess conflicting objectives.

The first threat arises from the data analyst's desire to compute aggregated information derived from the user's transactions while potentially disregarding the user's privacy. The analyst may deviate from the protocol in an attempt to link between the transaction and the user who submitted it. This threat highlights the potential for the data analyst to compromise user privacy for the sake of computing aggregated information.

The second threat arises from users who prioritize their privacy at the expense of providing misleading or corrupted data, which can undermine the integrity of the analysis conducted by the analyst. Users can intentionally introduce randomness or noise manipulatively, rendering the data unreliable for generating unbiased and trustworthy aggregate statistical estimations. Additionally, data poisoning attacks targeted at differential privacy mechanisms involve adversarial manipulation of the input to influence the final aggregate result.

5.4 Motivation

The motivation described in the paper revolves around the significant importance and ongoing challenges of privacy in blockchain systems. Traditional financial institutions seeking to adopt blockchain technologies have been hindered by the issue of privacy, which has led to the emergence of privacy-preserving blockchain systems. The paper highlights the need to address user concerns and develop schemes that enable users to exchange tokens within the system while preserving their individual attributes confidentially. These attributes can cover a wide range of information, such as the user's location, tax status, or other pertinent details denoted as binary variables.

5.5 Key Results

The key results described in the paper "Privacy-Preserving Transactions With Verifiable Local Differential Privacy" are centered around the development of a modular scheme that incorporates verifiable local differential privacy (LDP) techniques into a privacy-preserving transaction system on blockchain networks. The scheme aims to address the challenge of preserving individual privacy while enabling aggregate analysis, which is crucial for economic and sociological research conducted by central banks, statistics bureaus, and research companies.

The paper presents a comprehensive framework that involves several key components and participants. These include users who can exchange tokens within the system using transfer transactions, and a data analyst who has the authority to collect aggregated information from the private attributes and activities of the users in the system. The scheme ensures that users can disclose specific individual attributes confidentially to the data analyst, while the analyst is only interested in analyzing data using statistical models regarding the system as a whole and is not interested in learning about specific individuals in the system.

The scheme's key results include the development of a non-interactive approach based on zero-knowledge Succinct Non-interactive ARgument of Knowledge (zk-SNARKs) to adapt the implementation of select LDP mechanisms to a verifiable computation technique. This approach ensures the correctness of a differentially private query output. Additionally, the scheme involves a protocol to obtain and bind randomness, a verifiable LDP mechanism, and an expanded privacy-preserving asset transfer using zk-SNARK proofs to verify the integrity of the data disclosed by the user.

5.6 Key Techniques used

The key techniques used in the paper "Privacy-Preserving Transactions With Verifiable Local Differential Privacy" include cryptographic randomized response techniques, verifiable local differential privacy (LDP) mechanisms, zero-knowledge proofs, and modular scheme design. These techniques are employed to address the challenge of preserving individual privacy while enabling aggregate analysis in privacy-preserving transaction systems on blockchain networks.

1. Cryptographic Randomized Response Techniques: The paper discusses the use of cryptographic randomized response techniques, as presented by Kato et al., to validate existing LDP mechanisms. This approach ensures the complete execution of privacy protection on the client side without sacrificing user privacy. The cryptographic randomized response techniques involve the use of randomness and cryptographic protocols to enable users to disclose specific individual attributes confidentially to the data analyst, while ensuring the integrity of the process.

2. Verifiable Local Differential Privacy Mechanisms: The paper introduces verifiable LDP mechanisms, which allow data analysts to verify how users introduce noise to the data. This ensures that the noise generation and application process is reliable and preserves the integrity of the data under examination. The verifiable LDP mechanisms are crucial for ensuring the correctness of a differentially private query output and for preventing manipulation attacks that threaten the integrity of the data.

3. Zero-Knowledge Proofs: The paper employs zero-knowledge Succinct Non-interactive ARgument of Knowledge (zk-SNARKs) to adapt the implementation of select LDP mechanisms to a verifiable computation technique. This approach ensures the correctness of a differentially private query output and provides a way to prove the integrity of the response. Additionally, the paper addresses the limitations of previous zero-knowledge approaches and ensures that the randomness used in the scheme is unbiased and sampled correctly.

4. Modular Scheme Design: The paper presents a modular scheme that incorporates the aforementioned techniques into a privacy-preserving transaction system. This modular design allows for the integration of verifiable local differential privacy techniques into the transaction system, ensuring the integrity and privacy of user transactions in a secure and reliable manner.

5.7 History of the Problem

The history of the problem as described in the paper involves the evolution of blockchain systems and the emergence of privacy-preserving blockchain systems to address the challenges of privacy and data integrity. Traditional methods for preserving privacy often relied on the assumption that the process of noise generation and application is intrinsically reliable. However, recent scholarly work has underscored the naivety of this assumption, exposing vulnerabilities to a range of manipulation attacks that threaten the integrity of the data under examination.

To address these challenges, the paper discusses the development of differential privacy techniques, which have been proposed to preserve individuals' privacy while still making aggregate analysis possible. Differential privacy techniques, such as local differential privacy (LDP) mechanisms, have been proposed to allow users to introduce noise to their data, enabling the gathering and analysis of aggregated data without risking the exposure of sensitive information tied to individual transactions. However, challenges arise in ensuring the correctness of introduced noise when implementing local differential privacy, as some users may distort this feature by injecting biased noise into it, which may adversely affect the integrity of the information collected.

In response to these challenges, the paper introduces the Verifiable Differentially Private (VDP) transaction scheme, designed to ensure user privacy and data integrity during the data collection process for aggregated models. The scheme incorporates verifiable local differential privacy techniques into a privacy-preserving transaction system, addressing the need to balance privacy and data integrity in blockchain networks.

5.8 Future Directions

The future directions outlined in the paper "Privacy-Preserving Transactions With Verifiable Local Differential Privacy" focus on potential areas for further research and development in the field of privacy-preserving transaction systems and verifiable differential privacy. The paper suggests several potential avenues for future work, building upon the scheme presented and the challenges identified in the current research.

1. Enhanced Verifiable Differential Privacy Techniques: Future research could explore the development of enhanced verifiable differential privacy techniques that address the limitations and trade-offs identified in the current scheme. This may involve refining the verifiable local differential privacy mechanisms to improve the correctness, unlinkability, and untraceability properties required in privacy-preserving transaction systems.

2. Scalability and Efficiency: The paper highlights the importance of scalability and efficiency in privacy-preserving transaction systems. Future research could focus on optimizing the performance of the scheme, particularly in terms of computational efficiency and communication overhead. This may involve exploring non-interactive approaches and reducing resource-intensive aspects of the scheme.

3. Security and Threat Mitigation: Further research could delve into enhancing the security and threat mitigation capabilities of the scheme. This may involve investigating additional security measures to protect against potential attacks, such as data poisoning attacks and malicious behavior from users and data analysts. Additionally, exploring methods to mitigate the impact of dishonest behavior and ensure the integrity of the analysis conducted by the data analyst could be a potential area for future work.

4. Real-World Applications: The paper suggests that future research could focus on the practical implementation and application of the VDP transaction scheme in real-world scenarios, particularly in the context of Central Bank Digital Currencies (CBDCs) and regulated financial institutions. This may involve conducting pilot studies and evaluating the scheme's performance and usability in real-world settings.

5. Blockchain and Federated Learning Integration: Given the increasing interest in blockchain-based federated learning and secure Internet of Things (IoT) systems, future research could explore the integration of privacy-preserving transaction systems with blockchain-based federated learning for securing IoT. This integration could lead to the development of comprehensive solutions that address privacy and security challenges in IoT environments.

5.9 What I Understood

The paper "Privacy-Preserving Transactions With Verifiable Local Differential Privacy" introduces a scheme designed to address the challenges of privacy and data integrity in blockchain-based transaction systems. The scheme involves the use of verifiable local differential privacy (LDP) techniques, zero-knowledge proofs, and cryptographic randomized response techniques to ensure the confidentiality of user attributes and the integrity of data analysis. The scheme operates in a permissioned setting, where users exchange tokens within the system using transfer transactions, and a data analyst collects aggregated information from the private attributes and activities of the users in the system.

The paper outlines the key participants in the scheme, including users who possess specific individual attributes and engage in token exchange transactions, and data analysts who collect aggregated information from the private attributes and activities of the users. The focus is on protecting the interests of honest parties, as both users and analysts may deviate from the protocol, introducing an element of uncertainty.

The scheme addresses the threat model, considering potential dishonest behavior from both users and data analysts, and emphasizes the importance of preserving integrity and user privacy. It incorporates local differential privacy techniques, ensuring that an honest user cannot trust the analyst to properly blind their data without leaking it.

The paper also discusses the security analysis, proving that the scheme preserves integrity despite malicious parties and preserves user privacy. It introduces the Verifiable Differentially Private (VDP) transaction scheme, designed to ensure user privacy and data integrity during the data collection process for aggregated models.

5.10 Keywords

- Verifiable Local Differential Privacy (LDP)
- Zero-Knowledge Proofs
- Privacy-Preserving Transaction Systems
- Cryptographic Randomized Response Techniques
- Secure Multi-Party Computation (sMPC)
- Blockchain