

# Shorter, Privacy-Preserving Proof of Reserves Protocols for Cryptocurrency Exchanges

*A Seminar Report  
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by*

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*Dedicated to ...*



# Acceptance Certificate

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The dissertation entitled “Shorter, Privacy-Preserving Proof of Reserves Protocols for Cryptocurrency Exchanges” submitted by Suyash Bagad (Roll No. 15D070007) may be accepted for being evaluated.

Date: 18 June 2020

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# Declaration

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# Abstract

The rise of cryptocurrencies began with the inception of Bitcoin in 2009. Since then, several cryptocurrencies with better privacy and security guarantees are being developed. Cryptocurrencies gained popularity among general masses with the establishment of cryptocurrency exchanges. Also known as digital currency exchanges or crypto exchanges, they are essentially businesses that allow customers to trade cryptocurrencies or digital currencies for other assets including conventional fiat money or different digital currencies. From a customer point of view, exchanges not only made owning cryptocurrencies possible to non-miners but also provided them with fast trading platforms for transactions within cryptocurrencies and fiat. Customers were also provided with custodial wallets freeing them from the hassle of storing and remembering private keys. In the early days of cryptocurrency, crypto exchanges were very few and less-known, but not too long ago their number increased dramatically and they became an integral part of the cryptoeconomic ecosystem. They were responsible for the boost in the transaction volumes of the vast majority of the cryptocurrency sales and liquidity.

The downside of such cryptocurrency exchanges is that they are required to store sensitive information of customers like the private keys and account balances. If in case an exchange is hacked, it might result in loss of customer-owned cryptocurrency assets. There have been many high-profile hacks over the years, many of which went unnoticed for some time [1]. Although having a fool-proof method to avoid such hacks might be a difficult task, proof of reserves is one way to uphold the trust of customers. A proof of reserves is the guarantee by the exchange that it owns reserves at least as much as its total liabilities towards customers. In this way, even after cases of hacking, the exchange could repay its liabilities to the customers.

The simplest way to publish a proof of reserves for an exchange is to reveal all the addresses or account details it owns so that the customers are convinced about the assets owned by the exchange. Another way could be to send all the reserves it owns from all its addresses to a single address it owns. If amounts involved in

a transaction are public as in the case of Bitcoin, such a self-transaction would be a proof of the exchange's reserves. For example, in 2011, Mt. Gox cryptocurrency exchange transferred 424,242 bitcoins from its wallets to a previously revealed Bitcoin address [2]. However, such proofs of reserves do not preserve the privacy of the exchanges. Information of an exchange's addresses or accounts and the total assets it owns are crucial for aspects of its business. Exchanges naturally would not be in a position to compromise such critical information as a part of proofs of reserves. The main challenge in design of proofs of reserves is to preserve privacy and confidentiality of exchanges but at the same time convince customers about an exchange's actual asset ownership. Regaining *trust* of the customers without compromising exchanges' *privacy* is the primary motivation behind the design of better proofs of reserves. Advanced cryptographic techniques make it possible to design proofs of reserves which reveal *nothing* beyond an assertion of the form:

Exchange ABC owns ? amount of Y cryptocurrency and here is a proof  
 $\Pi$  for customers to verify.

Note that here we do not intend to reveal even the total amount. The proof  $\Pi$  is a cryptographic tool known as a *Non-Interactive Zero-Knowledge* proof.

In this work, we study the existing proof of reserves protocols for privacy-centric cryptocurrencies Grin, Beam and Monero. The existing proof of reserves protocols possess some shortcomings which becomes a hurdle in their practical deployment. With an aim to alleviate limitations of previously designed proofs of reserves, we design novel proofs of reserves for crypto exchanges supporting the above cryptocurrencies. Our protocols are shorter and privacy enhancing in comparison to the existing state-of-the-art proofs of reserves. We also implement the protocols we design as well as the previous state-of-the-art protocols for comparison and show feasibility in practical deployment of our protocols. We believe that our work on proof of reserves could be well adopted by crypto exchanges and benefit several of their customers. Furthermore, our work also opens up avenues of exploration of establishing trust without compromising privacy or anonymity in a more general setting. We are hopeful that this work acts as a small but crucial contribution towards the goal of establishing a *trustless, decentralized economy*.

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# Chapter 1

## Introduction

The rise of cryptocurrencies have opened up unending possibilities of how minimal or no trust based systems could be established owing to decentralization. The concept of blockchain was introduced with the founding of Bitcoin by Satoshi Nakamoto [3]. Satoshi Nakamoto proposed and implemented idea of a consensus based, trustless, truly peer-to-peer system for financial transactions. Notwithstanding an instrumental step towards establishing a decentralized and a trustless system, Bitcoin has several practical limitations with regards to privacy, security and scalability [4]. This led to the development of more privacy and anonymity focussed cryptocurrencies like Monero [5] and Zcash [6]. Grin [7] and Beam [8] are two relatively new projects which are backed by the MimbleWimble protocol [9] and claim to promise scalability, anonymity and fungibility all at once. The rise in privacy-centric cryptocurrencies further led to growth in popularity of cryptocurrencies not only among investors but also common people.

### 1.1 Test



# Chapter 2

## Cryptographic Preliminaries

Before delving into the details of RevelioBP protocol, let us equip ourselves with some background knowledge about the math of cryptocurrencies.

### 2.1 Notation

Let  $\mathcal{G} = \{\mathbb{G}, q, g\}$  be the description of a cyclic group  $\mathbb{G}$  of prime order  $q$  with generator  $g$  of  $\mathbb{G}$ . Let  $h \in \mathbb{G}$  be another random generator of  $\mathbb{G}$  such that the discrete logarithm relation between  $g$  and  $h$  is not known. Let  $\mathbb{G}^n$  and  $\mathbb{Z}_q^n$  be the  $n$ -ary Cartesian powers of sets  $\mathbb{G}$  and  $\mathbb{Z}_q$  respectively. Group elements which are Pedersen commitments are denoted by uppercase letters and randomly chosen group elements are denoted by lowercase letters. Bold font denotes vectors. Inner product of two vectors  $\mathbf{a}, \mathbf{b} \in \mathbb{Z}_q^n$  is defined as  $\langle \mathbf{a}, \mathbf{b} \rangle := \sum_{i=1}^n a_i \cdot b_i$  where  $\mathbf{a} = (a_1, \dots, a_n)$ ,  $\mathbf{b} = (b_1, \dots, b_n)$ . Further, Hadamard and Kronecker products are defined respectively as,  $\mathbf{a} \circ \mathbf{b} := (a_1 \cdot b_1, \dots, a_n \cdot b_n) \in \mathbb{Z}_q^n$ ,  $\mathbf{a} \otimes \mathbf{c} := (a_1 \mathbf{c}, \dots, a_n \mathbf{c}) \in \mathbb{Z}_q^{nm}$  where  $\mathbf{c} \in \mathbb{Z}_q^m$ . For a base vector  $\mathbf{g} = (g_1, \dots, g_n) \in \mathbb{G}^n$ , vector exponentiation is defined as  $\mathbf{g}^{\mathbf{a}} = \prod_{i=1}^n g_i^{a_i} \in \mathbb{G}$ . For a scalar  $u \in \mathbb{Z}_q^*$ , we denote its consecutive powers in the form of a vector  $\mathbf{u}^n := (1, u, u^2, \dots, u^{n-1})$ . To represent the exponentiation of all components of a vector  $\mathbf{a}$  by the same scalar  $k \in \mathbb{Z}_q$ , we use  $\mathbf{a}^{ok}$  to mean  $(a_1^k, a_2^k, \dots, a_n^k)$ . If an element  $a$  is chosen uniformly from a set  $A$ , such a choice is denoted by  $a \xleftarrow{\$} A$ . We denote the relation *Relation* using the specified input and witness as  $\{(Public\ Input; Witness) : Relation\}$ . We refer to  $\mathcal{A}$  as a PPT adversary which is a probabilistic Turing Machine that runs in polynomial time in the security parameter  $\lambda$ . An *interactive proof* for the decision problem  $\pi$  is described as follows:

1. There are two participants, a **prover**  $\mathcal{P}$  and a **verifier**  $\mathcal{V}$ .
2. The proof consists of a specified number of rounds.

3. In the beginning, both participants get the same input.
4. In each round, the verifier challenges the prover, and the prover responds to the challenge.
5. Both the verifier and the prover can perform some private computation.
6. At the end, the verifier states whether he was convinced or not.

## 2.2 Assumptions

**Definition 2.2.1 (Discrete Log Relation)** *For all PPT adversaries  $\mathcal{A}$  and for all  $n \geq 2$ ,  $\exists$  a negligible function  $\mu(\lambda)$  s.t*

$$\Pr \left[ \begin{array}{l} \mathbb{G} = \text{Setup}(1^\lambda), g_1, \dots, g_n \leftarrow \mathbb{G} ; \\ a_1, \dots, a_n \in \mathbb{Z}_p \leftarrow \mathcal{A}(\mathbb{G}, g_1, \dots, g_n) \end{array} : \exists a_i \neq 0 \wedge \prod_{i=1}^n g_i^{a_i} = 1 \right] \leq \mu(\lambda)$$

We say  $\prod_{i=1}^n g_i^{a_i} = 1$  is a non trivial discrete log relation between  $g_1, \dots, g_n$ . If the Discrete Log Relation assumption stands, it implies that no PPT adversary can find a non-trivial relation between randomly chosen group elements.

We use additional cryptographic assumptions such as Decisional Diffie-Hellman and its variants as described in [10].

## 2.3 Cryptographic Commitments

**Definition 2.3.1 (Commitments)** *A non-interactive commitment consists of two PPT algorithms (Setup, Com). For a message  $x \in \mathbf{M}_{pp}$  (message space), the algorithm proceeds as follows:*

- public parameters  $pp \leftarrow \text{Setup}(1^\lambda)$  for security parameter  $\lambda$
- $\text{Com}_{pp} : \mathbf{M}_{pp} \times \mathbf{R}_{pp} \rightarrow \mathbf{C}_{pp}$ , where  $\mathbf{R}_{pp}$  is randomness space
- $r \leftarrow \mathbf{R}_{pp}$  and compute  $\text{com} = \text{Com}_{pp}(x; r)$

**Definition 2.3.2 (Homomorphic Commitments)** *A homomorphic commitment is a non-interactive commitment such that  $\mathbf{M}_{pp}$ ,  $\mathbf{R}_{pp}$ ,  $\mathbf{C}_{pp}$  are all abelian groups, and  $\forall x_1, x_2 \in \mathbf{M}_{pp}, r_1, r_2 \in \mathbf{R}_{pp}$ , we have*

$$\text{Com}(x_1; r_1) + \text{Com}(x_2; r_2) = \text{Com}(x_1 + x_2; r_1 + r_2)$$

**Definition 2.3.3 (Hiding Commitment)** A commitment scheme is said to be hiding if for all PPT adversaries  $\mathcal{A}$ ,  $\exists \mu(\lambda)$ , a negligible function such that,

$$\left| \Pr \left[ b' = b \mid \begin{array}{l} pp \leftarrow \text{Setup}(1^\lambda); \\ (x_0, x_1) \in \mathbf{M}_{pp}^2 \leftarrow \mathcal{A}(pp), \ b \leftarrow \{0, 1\}, \ r \leftarrow \mathbf{R}_{pp}, \\ \mathbf{com} = \text{Com}(x_b; r), \ b' \leftarrow \mathcal{A}(pp, \mathbf{com}) \end{array} \right] - \frac{1}{2} \right| \leq \mu(\lambda)$$

where the probability is over  $b', r, \text{Setup}$  and  $\mathcal{A}$ . For perfectly hiding schemes,  $\mu(\lambda) = 0$ .

**Definition 2.3.4 (Binding Commitment)** A commitment scheme is said to be binding if for all PPT adversaries  $\mathcal{A}$ ,  $\exists \mu(\lambda)$ , a negligible function such that,

$$\Pr \left[ \text{Com}(x_0; r_0) = \text{Com}(x_1; r_1) \wedge x_0 \neq x_1 \mid \begin{array}{l} pp \leftarrow \text{Setup}(1^\lambda), \\ x_0, x_1, r_0, r_1 \leftarrow \mathcal{A}(pp) \end{array} \right] \leq \mu(\lambda)$$

where the probability is over  $\text{Setup}$  and  $\mathcal{A}$ . Again, if  $\mu(\lambda) = 0$  then we say the scheme is perfectly binding.

**Definition 2.3.5 (Pedersen Commitment)**  $\mathbf{M}_{pp}, \mathbf{R}_{pp} = \mathbb{Z}_p$ ,  $\mathbf{C}_{pp} = \mathbb{G}$  of order  $p$ .

- Setup:  $g, h \leftarrow \mathbb{G}$
- $\text{Com}(x; r) = (g^x h^r)$

**Definition 2.3.6 (Pedersen Vector Commitment)**  $\mathbf{M}_{pp} = \mathbb{Z}_p^n$ ,  $\mathbf{R}_{pp} = \mathbb{Z}_p$ ,  $\mathbf{C}_{pp} = \mathbb{G}$  of order  $p$ .

- Setup:  $\mathbf{g} = (g_1, \dots, g_n), h \leftarrow \mathbb{G}$
- $\text{Com}(\mathbf{x} = (x_1, \dots, x_n); r) = (h^r \mathbf{g}^{\mathbf{x}})$

The Pedersen vector commitment is [perfectly hiding](#) and [computationally binding](#) under the discrete logarithm assumption.

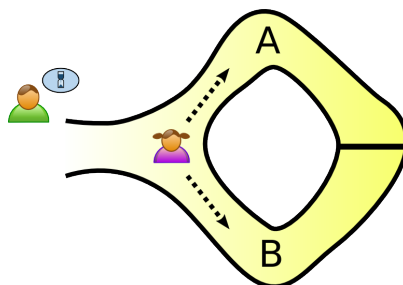
## 2.4 Zero-Knowledge Arguments of Knowledge

### 2.4.1 Zero-Knowledge Arguments

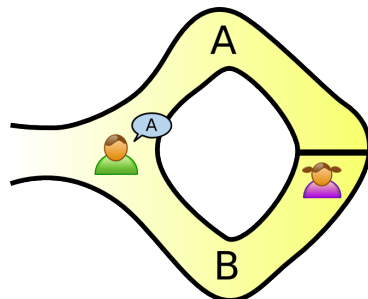
A protocol in which a prover convinces a verifier that a statement is true *without* revealing any information about why it holds is known as a Zero-knowledge argument. An argument is a proof only if the prover is computationally bounded

and some computational hardness holds. Hereafter, we use the terms *proof* and *argument* interchangeably.

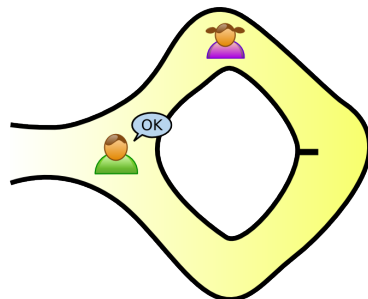
We illustrate the idea of zero-knowledge arguments of proof using the example of *Ali-Baba's secret cave* [11]. \*



(a) Peggy chooses a path uniformly from  $A, B$  without Victor knowing.



(b) Victor asks her to come out of the cave from path  $A$ .



(c) If Peggy had entered from path  $A$ , she returns trivially. Otherwise, she could open the door using the secret key and return from path  $A$ .

Figure 2.1: Example of a zero knowledge proof

In the above example, Peggy knows the secret word used to open a mysterious door in a cave. The cave is shaped like a horse-hoe. The entrance is on one side and the magic door blocking the opposite side. Victor wants to know whether Peggy knows the secret word; but Peggy, does not want to reveal her knowledge (the secret word) to Victor or to reveal the fact of her knowledge to anyone in the world.

Peggy and Victor run the protocol described in figure 2.1. Provided she really does know the magic word, and the path she enters and path Victor asks her to

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\*Figure courtesy: [https://en.wikipedia.org/wiki/Zero-knowledge\\_proof](https://en.wikipedia.org/wiki/Zero-knowledge_proof).

come from are same, then it's trivial for Peggy to succeed and Victor to believe that she actually knows the secret key. Further, if the chosen path by Peggy and asked by Victor doesn't match, even then she could open the door and return from a desired path. If they were to repeat this protocol many times, say 15 times in a row, her chance of successfully "guessing" all of Victor's requests would become exponentially small (about three in a lakh).

For zero-knowledge arguments presented in this report, we will consider arguments consisting of three interactive probabilistic polynomial time algorithms  $(\text{Setup}, \mathcal{P}, \mathcal{V})$ . These algorithms are described by:

- \* Setup:  $\sigma \leftarrow \text{Setup}(1^\lambda)$ ,  $\sigma$  is common reference string
- \*  $\mathcal{P}$ : prover,  $\mathcal{V}$ : verifier
- \* Transcript  $tr \leftarrow \langle \mathcal{P}, \mathcal{V} \rangle$
- \*  $\langle \mathcal{P}, \mathcal{V} \rangle = b$ ,  $b = 0$  if the verifier rejects or  $b = 1$  accepts

Further, we define the relation  $\mathcal{R}$  and the CRS-dependent language as:

$$\begin{aligned}\mathcal{R} &:= \{(\sigma, u, w) \in \{0, 1\}^* \times \{0, 1\}^* \times \{0, 1\}^* : w \text{ is a witness for } u \mid \sigma\} \\ \mathcal{L}_\sigma &:= \{x \mid \exists w \in \{0, 1\}^* \text{ such that } (\sigma, x, w) \in \mathcal{R}\}\end{aligned}$$

So,  $\mathcal{L}_\sigma$  is essentially the set of statements  $x$  that have a witness  $w$  in the relation  $\mathcal{R}$ .

## 2.4.2 Defining Zero-Knowledge Arguments of Knowledge

To mathematically define the notion of zero-knowledge and zero-knowledge arguments, we will provide the necessary definitions below.

**Definition 2.4.1 (Argument of Knowledge)** *The triple  $(\text{Setup}, \mathcal{P}, \mathcal{V})$  is called an argument of knowledge for relation  $\mathcal{R}$  if it is **perfectly complete** and has **computational witness-extended emulation**.*

**Definition 2.4.2 (Perfect completeness)**  *$(\text{Setup}, \mathcal{P}, \mathcal{V})$  has perfect completeness if for all non-uniform polynomial time adversaries  $\mathcal{A}$*

$$\Pr \left[ (\sigma, u, w) \notin \mathcal{R} \text{ or } \langle \mathcal{P}(\sigma, u, w), \mathcal{V}(\sigma, u) \rangle = 1 \mid \begin{array}{l} \sigma \leftarrow \text{Setup}(1^\lambda) \\ (u, w) \leftarrow \mathcal{A}(\sigma) \end{array} \right] = 1$$

*Perfect completeness* implies that if a statement is actually true, then an honest verifier is convinced with probability 1 about the truth of the statement by an honest prover.

**Definition 2.4.3 (Computational Witness-Extended Emulation)**

$(Setup, \mathcal{P}, \mathcal{V})$  has *witness-extended emulation* if for all deterministic polynomial time  $P^*$  there exists an expected polynomial time emulator  $\mathcal{E}$  such that for all pairs of interactive adversaries  $\mathcal{A}_1, \mathcal{A}_2$  there exists a negligible function  $\mu(\lambda)$  such that

$$\left| \Pr \left[ \mathcal{A}_1(tr) = 1 \mid \begin{array}{l} \sigma \leftarrow Setup(1^\lambda, ) \\ (u, s) \leftarrow \mathcal{A}_2(\sigma), \\ tr \leftarrow \langle (\mathcal{P}^*(\sigma, u, s), V(u, s)) \rangle \end{array} \right] - \Pr \left[ \begin{array}{l} \mathcal{A}_1(tr) = 1 \wedge \\ (tr \text{ accepted} \implies (\sigma, u, w) \in \mathcal{R}) \end{array} \mid \begin{array}{l} \sigma \leftarrow Setup(1^\lambda, ) \\ (u, s) \leftarrow \mathcal{A}_2(\sigma), \\ (tr, w) \leftarrow \mathcal{E}^\mathcal{O}(\sigma, u) \end{array} \right] \right| \leq \mu(\lambda)$$

where the oracle is given by  $\mathcal{O} = \langle (\mathcal{P}^*(\sigma, u, s), V(u, s)) \rangle$ , and permits rewinding to a specific point and resuming with fresh randomness for the verifier from this point onwards. We can also define computational witness-extended emulation by restricting to non-uniform polynomial time adversaries  $\mathcal{A}_1$  and  $\mathcal{A}_2$ .

*Computational witness-extended emulation* implies that when an adversary produces an argument to convince the verifier with some probability, then we have a corresponding emulator producing identically distributed argument with same probability, but also a witness.

**Definition 2.4.4 (Public coin)** An argument of knowledge  $(Setup, \mathcal{P}, \mathcal{V})$  is called *public coin* if all messages sent from the verifier to the prover are chosen uniformly at random and independent of the prover's messages, i.e., the challenges correspond to the verifier's randomness  $\rho$ .

**Definition 2.4.5 (Zero Knowledge Argument of Knowledge)** An argument of knowledge  $(Setup, \mathcal{P}, \mathcal{V})$  is *zero knowledge* if it reveals no information about  $w$  apart from what could be deduced from the fact that  $(\sigma, u, w) \in \mathcal{R}$ .

An argument of knowledge is zero knowledge if it does not leak information about  $w$  apart from what can be deduced from the fact that  $(\sigma, u, w) \in \mathcal{R}$ . More explicitly, we note that, a zero knowledge argument of knowledge ensures that no PPT adversary (or verifier) can ever recover  $w$  given it's relation with  $\sigma, u$ .



**Definition 2.4.6 (Perfect Special Honest-Verifier Zero-Knowledge)** A public coin argument of knowledge  $(Setup, \mathcal{P}, \mathcal{V})$  is a perfect special honest verifier zero knowledge (SHVZK) argument of knowledge for  $\mathcal{R}$  if there exists a probabilistic polynomial time simulator  $\mathcal{S}$  such that for all pairs of interactive adversaries  $\mathcal{A}_1, \mathcal{A}_2$

$$\begin{aligned} \Pr \left[ (\sigma, u, w) \in \mathcal{R} \wedge \mathcal{A}_1(tr) = 1 \left| \begin{array}{l} \sigma \leftarrow Setup(1^\lambda, ) \\ (u, w, \rho) \leftarrow \mathcal{A}_2(\sigma), \\ tr \leftarrow \langle (\mathcal{P}(\sigma, u, s), V(\sigma, u; \rho)) \rangle \end{array} \right. \right] \\ = \Pr \left[ (\sigma, u, w) \in \mathcal{R} \wedge \mathcal{A}_1(tr) = 1 \left| \begin{array}{l} \sigma \leftarrow Setup(1^\lambda, ) \\ (u, w, \rho) \leftarrow \mathcal{A}_2(\sigma), \\ tr \leftarrow \mathcal{S}(u, \rho) \end{array} \right. \right] \end{aligned}$$

PSHVZK AoK implies that even if an adversary chooses a distribution over statements and witnesses, it isn't able to distinguish between simulated transcript and honestly generated transcript for  $u \in \mathcal{L}_\sigma$ .



## Chapter 3

### Literature Survey



## Chapter 4

# Materials and Methods

### 4.1 Including Figures



# Chapter 5

## Results and Discussions

### 5.1 Including Tables

Tables are to be used in a special environment so that they have a Number, caption and appear in the list of tables. Table 5.1 is a sample table. In the case of tables, it is a convention to write the caption above the table. Note that in the case of figures the caption appears below the figure.

Table 5.1: Physical properties of the materials used.

Property	Value
Particle Density, $\rho_p$	2500 kg/m <sup>3</sup>
Viscosity, $\eta_s$	$1 \times 10^{-3}$ Pa-s





# Appendix A

## Supporting Material



# References

- [1] IDEX blog. A complete list of cryptocurrency exchange hacks [updated]. [Accessed 27-MAY-2020]. [Online]. Available: <https://blog.idex.io/all-posts/a-complete-list-of-cryptocurrency-exchange-hacks-updated>
- [2] Wikipedia contributors. Mt. Gox — Wikipedia, the free encyclopedia. [Accessed 10-JUNE-2020]. [Online]. Available: [https://en.bitcoin.it/wiki/Mt.\\_Gox](https://en.bitcoin.it/wiki/Mt._Gox)
- [3] S. Nakamoto. (2008) Bitcoin: A peer-to-peer electronic cash system. [Online]. Available: <http://bitcoin.org/bitcoin.pdf>
- [4] M. Conti, E. S. Kumar, C. Lal, and S. Ruj, “A survey on security and privacy issues of bitcoin,” *IEEE Communications Surveys & Tutorials*, vol. 20, pp. 3416–3452, 2018.
- [5] N. v. Saberhagen, “CryptoNote v 2.0,” White paper, 2013. [Online]. Available: <https://cryptonote.org/whitepaper.pdf>
- [6] E. B. Sasson, A. Chiesa, C. Garman, M. Green, I. Miers, E. Tromer, and M. Virza, “Zerocash: Decentralized anonymous payments from bitcoin,” in *2014 IEEE Symposium on Security and Privacy*, 2014, pp. 459–474.
- [7] “Grin project website.” [Online]. Available: <https://grin-tech.org/>
- [8] “Beam project website.” [Online]. Available: <https://www.beam.mw/>
- [9] A. Poelstra, “Mimblewimble,” 2016. [Online]. Available: <https://download.wpsoftware.net/bitcoin/wizardry/mimblewimble.pdf>
- [10] R. W. F. Lai, V. Ronge, T. Ruffing, D. Schröder, S. A. K. Thyagarajan, and J. Wang, “Omniring: Scaling private payments without trusted setup,” in *Proceedings of the 2019 ACM SIGSAC Conference on Computer and Communications Security*, November 2019, p. 31–48.

- [11] J.-J. Quisquater, M. Quisquater, M. Quisquater, M. Quisquater, L. Guillou, M. A. Guillou, G. Guillou, A. Guillou, G. Guillou, and S. Guillou, “How to explain zero-knowledge protocols to your children,” in *Advances in Cryptology — CRYPTO’ 89 Proceedings*, G. Brassard, Ed. New York, NY: Springer New York, 1990, pp. 628–631.

# List of Publications

- [1] S. Bagad and S. Vijayakumaran, “On the confidentiality of amounts in grin,” in *Crypto Valley Conference on Blockchain Technology (CVCBT)*, 2020.
- [2] S. Bagad and S. Vijayakumaran, “Performance trade-offs in design of mimblewimble proofs of reserves,” in *IEEE European Symposium on Security and Privacy Workshops (EuroS PW)*, 2020.



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