SBvote: Scalable Self-Tallying Blockchain-Based Voting

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ABSTRACT
Decentralized electronic voting solutions represent a promising advancement in electronic voting. One of the e-voting paradigms, the self-tallying scheme, offers strong protection of the voters’ privacy while making the whole voting process verifiable. Decentralized smart contract platforms become interesting practical instantiation of the immutable bulletin board that this scheme requires to preserve its properties. Existing smart contract-based approaches employing the self-tallying scheme (such as OVN or BBB-Voting) are only suitable for a boardroom voting due to their scalability limitation. The goal of our work is to build on existing solutions to achieve scalability without losing privacy guarantees and verifiability. We present SBvote, a blockchain-based self-tallying voting protocol that is scalable in the number of voters, and therefore suitable for large-scale elections. The evaluation of our proof-of-concept implementation shows that the protocol’s scalability is limited only by the underlying blockchain platform. We evaluated the scalability of SBvote on two public smart contract platforms - Gnosis and Harmony. Despite the limitations imposed by the throughput of the blockchain platforms, SBvote can accommodate elections with millions of voters.

CCS CONCEPTS
• Applied computing → Voting / election technologies; • Security and privacy → Distributed systems security;

KEYWORDS
E-voting, blockchain, scalability, privacy, smart contracts.

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1 INTRODUCTION
Voting is an essential means of achieving a collective decision. Traditionally, in large-scale voting such as national elections, the participants cast anonymous paper ballots that are later tallied by a trusted authority. With the advances in information technology, electronic voting systems have been introduced. While several small-scale or boardroom e-voting protocols with decentralized architecture have been proposed [19, 27], large-scale electronic voting systems mostly follow a centralized model [1, 8]. However, a centralized entity that is in control of the voting process represents a single point of failure as well as a possible element for misbehavior.

The verifiability of many e-voting protocols depends on the assumed existence of a public bulletin board (PBB) that allows appending modifications and immutability of the historical data [14]. Voting systems such as Helios [1] implement the public bulletin board as a single web server. However, this introduces a possibility of several issues, including unavailability of the server (e.g., due to a denial-of-service attack) or a censorship by the authority controlling the server.

Other systems [19, 27, 31] instantiate the public bulletin board by a blockchain with a smart contract platform. On top of the immutability and append-only features, such blockchains also provide correct execution of a code that enables decentralized e-voting schemes to utilize public verifiability of the data submitted to the bulletin board (e.g., votes and a tally). Protocols such as Open Vote Network (OVN) [19] and BBB-Voting [27] use smart contracts to orchestrate the procedures of the boardroom voting protocol. The distributed nature of these protocols also eliminates the need to rely on the authority to tally the votes. In these approaches, referred to as self-tallying voting, any participant can sum and verify the tally.

We base our work on BBB-Voting since it enables more than two voting choices and a recovery of faulty participants in contrast to OVN. Our goal is to build a voting protocol that resolves the scalability limitation of the self-tallying approaches while maintaining the maximum voter privacy. Therefore, we introduce SBvote, a decentralized blockchain-based e-voting protocol providing scalability in the number of participants by grouping them into voting booths instantiated as dedicated smart contracts that are controlled and verified by the aggregation smart contract. Our approach is suitable for privacy-preserving self-tallying large-scale e-voting.

Contributions. We make the following contributions:

i) We introduce SBvote, a blockchain-based self-tallying e-voting protocol that enables scalability in the number of voters and is based on BBB-Voting protocol. SBvote introduces multiple voting smart contracts booths that are managed and aggregated by the main smart contract.

ii) Our extended solution maintains all properties of decentralized e-voting, including public verifiability, perfect ballot secrecy, and fault tolerance. Moreover, it improves the privacy of voters within booths.

iii) We made a proof-of-concept implementation and evaluated it on two smart contract platforms, Harmony and Gnosis. We
achieved the best scalability results using the Harmony blockchain, allowing us to run elections with 1.5M voters and two candidates within a two-days interval.

**Organization.** The rest of this paper is organized as follows. Essential preliminaries are presented in Section 2. We introduce SBVote in Section 3 and evaluate its scalability in Section 4. We provide the security analysis of SBVote and discuss its properties in Section 5. We review the related work in Section 6 and finally conclude our paper in Section 7.

## 2 PRELIMINARIES

We briefly review the properties of voting protocols and provide a short description of blockchains and smart contracts. Finally, we describe the BBB-Voting protocol on which we base our work.

### 2.1 Voting

We provide a list of the most important “desired” properties of voting protocols in the following.

**Privacy.** The votes remain anonymous. Only the voter herself knows which candidate she voted for. Privacy protection is a crucial attribute of voting systems used in practice and is very important in publicly verifiable voting schemes.

**Perfect Ballot Secrecy.** It was defined by Kiayias and Yung [16], and it extends the privacy property. In a scheme with perfect ballot secrecy, a partial result can only be revealed if all remaining voters collude to uncover it.

**Self-Tallying.** This property ensures that any interested party can compute the tally once all the votes are cast.

**Fault Tolerance.** The protocol allows for excluding faulty participants in a publicly verifiable manner without restarting the whole voting protocol.

**Verifiability.** Verifiability includes individual verifiability (allowing the voter to verify her vote has been counted) and universal verifiability (allowing any interested party to verify all cast votes have been correctly tallied). Furthermore, the verifiability of a voting system can be described [3] as follows:

- **cast-as-intended:** a voter can verify the encrypted vote contains her choice of candidate,
- **recorded-as-cast:** a voter can verify the system recorded her vote correctly,
- **tallied-as-recorded:** any interested party is able to verify whether the final tally corresponds to the recorded votes.

A voting system that satisfies all these properties is considered end-to-end verifiable.

**Dispute-Freeeness.** The protocol’s design prevents any disputes among involved parties by allowing anyone to verify whether a participant followed the protocol.

**Completeness.** All valid votes are included in the final tally.

### 2.2 Blockchains and Smart Contracts

Blockchain is a continuously growing distributed ledger consisting of blocks maintained by a network of consensus nodes that run a consensus protocol. Once the consensus nodes agree on a new block, it is added to the blockchain. The blocks are cryptographically linked to ensure the immutability of the entire ledger and typically contain records of cryptocurrency transfers executed within the network. Orders to execute transfers are communicated to the network in messages called transactions. A block may also contain application code written in a supported language of a blockchain equipped with a smart contract platform. This code is invoked by a transaction containing execution orders (i.e., function calls of a smart contract). The blockchain network then acts as a decentralized computation platform – the blockchain nodes execute the smart contract code.

Smart contract platforms (such as Ethereum [30]) measure the execution complexity of smart contracts in units of gas. The sender of a transaction containing a smart contract invocation has to pay for the consumed gas to cover the expenditures of the consensus nodes executing the computation. The gas price is volatile and based on the demand on the network.

### 2.3 BBB-Voting

BBB-Voting [27] is a system for boardroom voting supporting $k \geq 2$ voting choices. The basic protocol used in BBB-Voting consists of five phases (i.e., registration, setup, pre-voting, voting, tally) and an optional fault-recovery phase.

In the registration phase, a voting authority registers eligible voters and their wallet addresses to the voting smart contract. In the setup phase, the cryptographic parameters of the voting are agreed upon by all participants. Each voter then creates her ephemeral private/public key pair and submits her ephemeral public key to the smart contract. The multi-party computation (MPC) key for each voter is computed by the smart contract in the pre-voting phase. In the voting phase, each voter computes her blinding key (consisting of ephemeral private key and MPC key), uses the blinding key to encrypt a vote to a selected candidate and then submits the blinded vote to the smart contract. A 1-out-of-$k$ non-interactive zero-knowledge (NIZK) proof of set membership is submitted to the smart contract along with the blinded vote. Next, the smart contract verifies the correctness of such a vote. During the tally phase of the protocol, the tally of votes is computed off-chain by an arbitrary party and submitted to the smart contract. The smart contract verifies that the tally was computed correctly.

The protocol also includes an optional fault-recovery extension that can be placed after the voting phase. This phase is useful if some participants have stalled and have not cast their blinded votes.

The BBB-Voting scheme provides perfect ballot secrecy, fairness, public verifiability, self-tallying feature, dispute-freeeness, resistance to serious failures, and maximizes the voters’ privacy (see Section 2.1). Also, it introduces several optimizations of the implementation to decrease the costs of the protocol and accommodate a larger number of participants than the previous approaches (i.e., OVN [19]). BBB-Voting is designed as a single smart contract deployed on the Ethereum blockchain. Nevertheless, BBB-Voting is intended only for boardroom voting with a low number of involved participants. Hence it does not provide scalability as might be required in national elections. Another limitation of BBB-Voting is the low number of stalling participants the system can recover from in a single fault recovery round due to the block gas limit.
3 SCALABLE VOTING PROTOCOL

In this section, we propose SBvote, a scalable e-voting protocol that is based on BBB-Voting (see Section 2.3).

3.1 System Model

We focus on a decentralized e-voting that provides all desired properties of e-voting schemes mentioned in Section 2.1 as well as scalability in the number of the participants. We assume a centralized authority that is responsible for the enrollment of the participants and shifting the stages of the protocol. However, the authority can neither change nor censor the votes of the participants, and it cannot compromise the privacy of the votes.

We assume that a public bulletin board required for e-voting is instantiated by a blockchain platform that moreover supports the execution of smart contracts. We assume that all participants of voting have their thin clients that can verify the inclusion of their transactions in the blockchain as well as the correct execution of the smart contract code.

Adversary Model. We consider an adversary that passively listens to a communication on the blockchain network. The adversary cannot modify or replace any honest transactions since she does not hold the private keys of the participants. Next, we assume that the adversary cannot block an honest transaction due to the censorship-resistance property of the blockchain. The adversary can link a voter’s IP address to her blockchain address. However, she does not possess the computational resources to break the cryptographic primitives used in the blockchain platform and the voting protocol. The adversary cannot access or compromise the voter’s device or the user interface of the voting application. We assume that in each voting group of $n$ participants, at most $t$ of them can be controlled by the adversary and disobey the voting protocol, where $t \leq n - 2$ and $n \geq 3$. This eliminates the possibility of full collusion against a single voter [13].

3.2 Proposed Approach

Involved Parties. Our proposed approach has the following actors and components: (1) a participant $P$ (a voter) who chooses a candidate (i.e., a voting choice) and casts a vote, (2) a voting authority $VA$ responsible for the registration of participants and initiating actions performed by smart contracts, (3) a booth contract $BC$, which is replicated into multiple instances, where each instance serves a limited number of participants. New instances might be added on-demand to provide scalability, (4) The main contract $MC$, which assigns participants to voting booths, deploys booth contracts, and aggregates the final tally from booth contracts.

Protocol. We depict our protocol in Figure 1. SBvote follows similar phases as BBB-Voting but with several alterations that enable better scalability. The registration phase requires $VA$ to authenticate users and generate a list of eligible voters. In BBB-Voting, the setup phase of the protocol allows users to submit their ephemeral public keys. However, in contrast to BBB-Voting, SBvote requires additional steps to set up the booth contracts. First, eligible voters are assigned to voting groups and then $BC$ is deployed for each voting group. Once the setup is finished, voters proceed to submit their ephemeral public keys during a sign-up phase. These keys are further used to compute multi-party computation (MPC) keys within each voting group during a pre-voting phase. In the voting phase, voters cast their blinded votes along with corresponding NIZK proofs. The NIZK proof allows $BC$ to verify that a blinded vote correctly encrypts one of the valid candidates. If some of the voters who submitted their ephemeral public keys have failed to cast their vote, the remaining active voters repair their votes in the subsequent fault recovery phase. This is achieved by removing the key material of stalling voters from the encryption of the correctly cast votes. The key material has to be provided by each active voter along with NIZK proof of correctness. After the repair of votes, the tallies for individual voting groups are computed during the tally phase of a booth. Then, partial tally results are aggregated to obtain the final tally by $MC$.

In the following, we describe the phases of our protocol in more detail. Phases 2–6 are executed independently (and thus in parallel) within each of the voting groups/booth contracts.

Registration. In this phase, the participants interact with $VA$ to register as eligible voters. A suitable identity management (IDM) system is required, allowing $VA$ to verify participants’ identities and eligibility to vote. Each participant creates her blockchain wallet address and registers it with $VA$ that stores a mapping between a participant’s identity and her wallet address.

Phase 1 (Setup). First, $VA$ deploys $MC$ to the blockchain. Then, $VA$ enrolls the wallet addresses of all registered participants to $MC$ within a transaction. Once all the registered participants have been enrolled, $VA$ triggers $MC$ to pseudo-randomly distribute enrolled participants into groups whose size is pre-determined and ensures a certain degree of privacy. Note that distributed randomness protocols such as RoundHound [25] might be used for this purpose, however, in this work we assume a trusted randomness source that is agreed upon by all voters (e.g., a hash of a Bitcoin block).

In every group, the participants agree on the parameters of the voting. Let $n$ be the number of participants in the group and $k$ the number of candidates. We specify the parameters of voting as follows:

1) a common generator $g \in \mathbb{F}_p$, where $p = 2 \cdot q + 1$, $q$ is a prime and $n < p - 1$.

2) $k$ independent generators $\{f_1, \ldots, f_k\} \in \mathbb{F}_p^*$ such that $f_i = g^{2^{(i-1)m}}$, where $m$ is the smallest integer such that $2^m > n$.

Then, $VA$ deploys a booth contract $BC$ for each group of participants with these previously agreed upon voting parameters. $MC$ stores a mapping between a participant’s wallet address and the group she was assigned to.

Phase 2 (Sign-Up). Eligible voters enrolled in the setup phase review the candidates and the voting parameters. Each voter who intends to participate obtains the address of $BC$ she was assigned to by $MC$. From this point onward, each participant interacts only with her $BC$ representing the group she is part of. Every participant $P_i$ creates her ephemeral key pair consisting of a private key $x_i \in \mathbb{F}_p$ and public key $g^{x_i}$. The $P_i$ then sends her public key to $BC$. By

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1The details of IDM are out-of-scope for this work.

2Note that in practice this step utilizes transaction batching to cope with the limits of the blockchain platform (see Section 3.3).
submitting an ephemeral public key, the participant commits to cast a vote later. Furthermore, participants are required to send a deposit within this transaction. If the voter does not cast her vote or later does not participate in the potential fault recovery phase, she will be penalized by losing the deposit. Voters who participate correctly retrieve their deposit at the end of the voting.

**Phase 3 (Pre-Voting).** In this step, each BC computes synchronized multi-party computation (MPC) keys from the participants’ ephemeral public keys submitted in the previous step. To achieve scalability, the MPC keys are computed independently in each BC over the set of ephemeral public keys within the group. The MPC key for participant \( P_i \) is computed as follows:

\[
g^y_i = \prod_{j=1}^{i-1} g^{x_j} / \prod_{j=i+1}^{n} g^{x_j},
\]

(1)

Figure 1: Overview of SBvote protocol.

Figure 2: Non-interactive zero-knowledge proof for 1-out-of-\( k \) set membership.

where \( y_i = \sum_{j<i} x_j - \sum_{j>i} x_j \) and \( \sum_i x_i y_i = 0 \) (see Hao et al. [13] for the proof). The computation of MPC keys is triggered by VA in each BC. After the computation, each participant obtains her MPC key from BC and proceeds to compute her ephemeral blinding key as \( g^{x_i y_i} \) using her private key \( x_i \).

**Phase 4 (Voting).** Before participating in this phase of the protocol, each voter must create her blinded vote and a NIZK proof of its correctness. The blinded vote of the participant \( P_i \) is \( B_i = g^{x_i y_i} f_j \), where \( f_j \in \{ f_1, \ldots, f_k \} \) represents her choice of a candidate. The participant casts the blinded vote by sending it to BC in a transaction \( \text{cast}(B_i, \pi_M) \), where \( \pi_M \) is a 1-out-of-\( k \) NIZK proof of set membership. This proof allows BC to verify that the vote contains one of the candidate generators from \( f_1, \ldots, f_k \) without revealing the voter’s choice. BC performs a check of the proof’s correctness and accepts well-formed votes. Construction and verification of the NIZK proof are depicted in Figure 2.
Let $w_i \in \mathbb{G} \subseteq \mathbb{F}_p$.

$C \leftarrow g^{x_i \cdot x_j}$

$m_1 \leftarrow g^{w_i}$

$m_2 \leftarrow B^{w_i}$

$c \leftarrow H(A, B, m_1, m_2)$

$r_i \leftarrow w_i + c x_i$

\[ C, r_i, m_1, m_2 \]

Phase 5 (Fault-Recovery). The use of synchronized MPC keys ensures that a vote cast by each voter contains the key material shared with all voters within the group. If some of the voters within a group stall during the voting phase, the tally cannot be computed from the remaining data. Therefore, we include a fault-recovery phase, where remaining voters provide \( \mathcal{B} \mathcal{C} \) with the key material they share with each stalling voter, enabling \( \mathcal{B} \mathcal{C} \) to repair their votes. In detail, for a stalling voter \( P_i \) and an active voter \( P_j \) (\( i \neq j \)), the shared key material \( g^{x_i \cdot x_j} \) consists of the stalling voter’s ephemeral public key \( g^{x_i} \) (previously published in \( \mathcal{B} \mathcal{C} \)) and the active voter’s ephemeral private key \( x_j \). The active voters send the shared key material to \( \mathcal{B} \mathcal{C} \) along with a NIZK proof depicted in Figure 3. The NIZK proof allows \( \mathcal{B} \mathcal{C} \) to verify that the shared key material provided by the voter corresponds to the ephemeral public keys \( g^{x_i} \) and \( g^{x_j} \).

Suppose some of the previously active voters become inactive during the fault-recovery phase (i.e., do not provide the shared key material needed to repair their votes). In that case, the fault-recovery phase can be repeated to exclude these voters. Note that this phase takes place in groups where all the voters who committed to vote during the sign-up phase have cast their votes.

Phase 6 (Booth Tallies). At first, the tally has to be computed for each group separately. Computation of the result is not performed by \( \mathcal{B} \mathcal{C} \) itself. Instead, \( \forall A \) (or any participant) obtains the blinded votes from \( \mathcal{B} \mathcal{C} \), computes the tally, and then sends the result back to \( \mathcal{B} \mathcal{C} \), which verifies whether a provided tally fits

\[
\prod_{i=1}^{n} B_i = \prod_{i=1}^{n} g^{x_i y_i f_j} = g^{\sum_{i=1}^{n} x_i y_i f_j} = f_1^{c_{t_1}} f_2^{c_{t_2}} \ldots f_k^{c_{t_k}},
\]

where \( c_{t_j} \in c_{t_1}, \ldots, c_{t_k} \) denotes the vote count for each candidate.

Phase 7 (Final Tally). Once \( \mathcal{B} \mathcal{C} \) obtains a correctly computed tally, it sends it to \( \mathcal{M} \mathcal{C} \). \( \mathcal{M} \mathcal{C} \) collects and summarizes the partial tallies from individual booths and announces the final tally once all booths have provided their results. The participants can also review the partial results from already processed booths without waiting for the final tally since the booth tallies are processed independently.

### 3.3 Design Choices and Optimizations

We introduce several specific features of SBvote, which allow us to achieve the scalability and privacy properties.

**Storage of Voters’ Addresses.** If we were to store the voters’ wallet addresses in the booth contracts, it would cause high storage overhead and thus high costs. However, we proposed to store these addresses only in \( \mathcal{M} \mathcal{C} \), while booth contracts can only query \( \mathcal{M} \mathcal{C} \) whenever they require these addresses (i.e., when they verify whether a voter belongs to the booth’s group). As a result, this eliminates the costs of transactions when deploying booth contracts, and moreover saving the blockchain storage space.

**Elimination of Bottlenecks.** The main focus of our proposed approach is to eliminate the bottlenecks that limit the number of voters and thus the size of the voting groups. In particular, passing the necessary data within a single transaction could potentially exceed the block gas limit.

The scalability of the Setup phase of SBvote is straightforward to resolve since it does not involve any transient integrity violation checks (excluding duplicity checks). In all these cases, \( \forall A \) splits the data into multiple independent transactions. Similarly, each active voter can send the key material required to repair her vote in several batches in the Fault-Recovery phase, allowing the system to recover from an arbitrary number of stalling participants.

In contrast to the Setup and Fault-Recovery phases, batching in the Pre-Voting phase is not trivial since it requires transient preservation of integrity between consecutive batches of the particular voting group. Therefore, we designed a custom batching mechanism, which eliminates this bottleneck while also optimizing the cost of the MPC computation.

**MPC Batching and Optimization.** If computed independently for each participant, the computation of MPC keys leads to a high number of overlapping multiplications. Therefore, we optimize this step by dividing the computation into two parts, respecting both

### Algorithm 1 Pre-computation of right side values from Equation 1.

**Inputs:**
- \( n \# \) of voters
- \( mpc\_batch \# \) batch size for MPC computation
- \( voterPKs \# \) array of voters’ ephemeral public keys

**Outputs:**
- \( right\_markers \# \) pre-computed right side values

```plaintext
1: right_tmp ← 0
2: if \( n \mod mpc\_batch \neq 0 \) then
3: \( right\_markers\_push(right\_tmp) \)
4: end if
5: for \( i \leftarrow 0 \) to \( n \) do
6: \( \text{if } n \mod mpc\_batch = (i - 1) \mod mpc\_batch \) then
7: \( right\_markers\_push(right\_tmp) \)
8: end if
9: \( right\_tmp \leftarrow right\_tmp + voterPKs[n - i] \)
10: end for
```
**Algorithm 2** Computation of a batch of MPC keys.

**Inputs:**
- `voterPKs`: array of voters' ephemeral public keys
- `mpc_batch`: batch size for MPC computation
- `start, end`: start and end index of the current batch
- `right_marker`: pre-computed right side value for the first index in a batch
- `act_left`: left side value from the previous batch

**Outputs:**
- `act_left`: left side value at the last index of the current batch
- `mpc_keys`: array of MPC keys for the current batch

Compute right side values for the batch:
1. `right_tab[mpc_batch − 1] ← right_marker`
2. for `i ← 0 to mpc_batch`
   3. `j ← mpc_batch − i`
   4. `right_tab[i − 1] ← right_tab[j] * voterPKs[i − 1]`
5. end for

Compute the current batch of MPC keys:
6. for `i ← start to end`
7. `act_left ← act_left * voterPKs[i − 1]`
8. end for
9. `mpc_keys[i] ← act_left ÷ right_tab[i] mod mpc_batch`

sides of the expression in Equation 1 and reusing accumulated values for each side.

First, we pre-compute the right part (i.e., divisor) of Equation 1, which consists of a product of ephemeral public keys of voters with a higher index than the current voter’s one (i.e., `i` in Equation 1). The product is accumulated and saved in the contract’s storage at regular intervals during a single iteration over all ephemeral public keys. The size of these intervals corresponds to the batch size chosen for the computation of the remaining (left side) of the equation. We refer to these saved values as right markers (see Algorithm 1). We only choose to save the right markers in the storage of `BC` instead of saving all accumulated values due to the high cost of storing data in the smart contract storage. Though the intermediate values between right markers have to be computed again later, they are only kept in memory (not persistent between consecutive function calls). Therefore, they do not significantly impact the cost of the computation.

The second part of the computation is processed in batches. First, the right-side values for all voters within the current batch are obtained using the pre-computed right marker corresponding to this batch (see lines 1–5 of Algorithm 2). Then, the left part of Equation 1 is computed for each voter within the batch, followed by evaluating the entire equation to obtain the MPC key (lines 6–9 of Algorithm 2). This left-side value is not discarded; therefore, computing the left side for the next voter’s MPC key only requires single multiplication. The last dividend value in the current batch is saved in the contract’s storage to allow its reuse for the next batch.

### 4 EVALUATION

To evaluate the scalability of SBvote, we created the proof of concept implementation that builds on BBB-Voting [27]. We used the Truffle framework and Solidity programming language to implement the smart contract part and Javascript for the client API of all other components. We also utilized the Witnet library [29] for on-chain elliptic curve operations on the standardized Secp256k1 curve [23]. Although Solidity was primarily intended for Ethereum and its Ethereum Virtual Machine (EVM), we have not selected Ethereum for our evaluation due to its high operational costs and low transactional throughput, which is contrary to our goal of improving scalability. However, there are many other smart contract platforms supporting Solidity and EVM, out of which we selected Gnosis and Harmony due to their low costs and high throughput.

Throughout our evaluation, we considered the following parameters of the chosen platforms: 30M block gas limit with 5 second block creation time on Gnosis and 80M block gas limit with 2 second block creation time on Harmony.

**MPC Batch Size.** The MPC keys in the Pre-Voting phase are computed in batches (see Section 3.3). In detail, there is a pre-computed value available for the first voter in each batch. Using a small batch size imposes many transactions and high execution costs due to utilizing fewer pre-computed values. In contrast, using a large batch size requires more expensive pre-computation and storage allocation, which results in a trade-off. This trade-off is illustrated in Figure 4, depicting how the batch size affects the cost of the computation per voter. We can see that the best value for our setup is 150 voters per batch.

**The Number of Candidates.** The number of candidates our voting system can accommodate remains limited. This is mainly caused by the block gas limit of a particular platform. In detail, we can only run voting with a candidate set small enough so that the vote-casting transaction does not exceed the underlying platform’s block gas limit. Such transaction must be accompanied by a NIZK proof of set membership (i.e., proof that the voter’s encrypted choice belongs to the set of candidates), and the size of the candidate set determines its execution complexity. Figure 5 illustrates this

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1. https://developers.gnosischain.com, Accessed: 2022-09-26.
2. https://www.harmony.one, Accessed: 2022-09-26.
dependency. Our experiments show that the proposed system can accommodate up to 38 and 14 candidates on Harmony and Gnosis, respectively.

The Total Number of Participants. The time period over which the voters can cast their ballots typically lasts only several days in realistic elections. The platform’s throughput over a restricted time period and the high cost of the vote-casting transactions result in a trade-off between the number of voters and the number of candidates. We evaluated the limitations of the proposed voting protocol on both Harmony and Gnosis, as shown in Figure 6 and Figure 7. Note that in these examples, we considered only the most expensive phase of the protocol (i.e., voting phase) to be time-restricted.

We determined that with two candidates, the proposed system can accommodate ~1.5M voters over a 2-day voting period and up to 3.8M voters over a 5-day voting period on the Harmony blockchain. On the other side of the trade-off, with the maximum number of 38 candidates on Harmony, maximally 216K voters can participate within a 5-day voting period.

5 SECURITY ANALYSIS AND DISCUSSION

We discuss the properties and scenarios affecting the security and privacy of SBvote.

Privacy. Within each voting group, SBvote maintains perfect ballot secrecy. The adversary, as defined in Section 3.1, cannot reveal a participant’s vote through a collusion of all remaining participants since adversary can control at most \( n - 2 \) participants. The privacy of votes can be violated only if all participants in a voting group vote for the same candidate. However, this is a natural property of voting protocols, which output the tally rather than only the winning candidate. SBvote mitigates this problem by implementing transaction batching, which allows the authority to maintain a sufficiently large size of the voting groups to lower the probability of a unanimous vote within the groups. This probability is further decreased in SBvote by the smart-contract-based pseudo-random assignment of participants to the groups. We refer the reader to the work of Ullrich [26] that addresses the issue of unanimous voting and the probability of its occurrence.

Deanonymization & Linking Addresses. In common blockchains, the network-level adversary might be able to link the participant’s address with her IP address. Such an adversary can also intercept the participant’s blinded vote; however, she cannot extract the vote choice due to the privacy-preserving feature of our voting protocol. Therefore, even if the adversary were to link the IP address to the participant’s identity, the only information she could obtain is whether the participant has voted. Nevertheless, to prevent the linking of addresses, participants can use VPNs or anonymization services such as Tor.

Re-Voting. It is important to ensure that no re-voting is possible, which is to avoid any inference about the final vote of a participant in the case she would reuse her ephemeral key to change her vote during the voting stage. Such a re-voting logic can be easily enforced by the smart contract, while the user interface of the participant should also not allow re-voting. Also, note that ephemeral keys are one-time keys and thus are intended to use only within one instance of e-voting protocol to ensure the security and privacy of the protocol. If a participant were to vote in a different instance of e-voting, she would generate new ephemeral keys.

Forks in Blockchain. Blockchains do not guarantee immediate immutability due to possible forks. This differentiates blockchains from public bulletin boards, as defined in [16]. However, since our protocol does not contain any two-phase commitment scheme with revealed secrets, its security is not impacted by accidental or malicious forks. Temporary forks also do not impact the voting stage since the same votes can be resubmitted by client interfaces.

Self-Tallying Property. The self-tallying property holds within each voting group since the correctness of obtained tallies can be verified by anybody. Consequently, this property holds for the whole voting protocol since the main contract aggregates the booth tallies of the groups in a verifiable fashion.

Verifiability. SBvote achieves both individual and universal verifiability. By querying the booth contract, each voter can verify her vote has been recorded. Each voter (and any interested party) can verify the booth tally since it satisfies the self-tallying property, i.e., the Equation 2 would not hold should any vote be left out. Any
parties can verify the final tally aggregated in the main contact by querying all the booth contracts to obtain individual booth tallies.

**Platform-Dependent Limitations.** Although our system itself does not limit the number of participants, the required transactions are computationally intensive, which results in high gas consumption. Therefore, large-scale voting using our system might be too demanding on the underlying smart contract platform. As a potential solution, public permissioned blockchains dedicated to e-voting might be utilized.

**Adversary Controlling Multiple Participants in the Fault Recovery.** One issue that needs to be addressed in the fault recovery is the adversary controlling multiple participants and letting them stall one by one in each fault recovery round. Even though the fault recovery mechanism will eventually finish with no new stalling participants, such behavior might increase the costs paid by remaining participants who are required to submit counter-party shares in each round of the protocol. For this reason, similar to the voting stage, we require the fault recovery stage to penalize stalling participants by losing the deposit they put into the smart contract at the beginning of our protocol. On the other hand, the adversary can cause a delay in the voting protocol within a particular booth. However, it does not impact other booths. To further disincentivize the adversary from such behavior, the fault-recovery might require additional deposits that could be increased in each round, while all deposits could be redeemed at the tally stage.

**Tally computation.** Tallying the results in individual booths requires an exhaustive search for a solution of Equation 2 with $(n+k^{-1})$ possible combinations [13], where $n$ is the number of votes and $t$ is the number of candidates. Therefore, the authority should select the size of the voting groups accordingly to the budget and available computational resources (see [27] for the evaluation).

6 RELATED WORK

We provide a brief survey of e-voting solutions in the following.

Several protocols have been proposed, focusing on ensuring the vote’s privacy rather than breaking the map between the voter and her ballot. Cohen and Fisher [7] proposed a verifiable voting scheme where the participants cannot unveil the votes. However, the election authority in this scheme has the ability to read any vote. Cohen [6] provided an extension to this scheme, where the function of authority is distributed among a number of tellers: at least one honest teller is sufficient to ensure the privacy of the votes.

A few other works build on the approach from [7], such as [4, 9, 10, 22]. The multi-authority protocol proposed by Cramer et al. [10] employs the ElGamal cryptosystem to guarantee vote privacy. This protocol can tolerate malicious behavior of a constant fraction of authorities. Baudron et al. [2] focused on multi-candidate elections with hierarchical levels of authorities.

Kiayias and Yung [16] introduced a new voting paradigm with several properties they defined – perfect ballot secrecy, self-tallying, and dispute-freeness. The protocol presented by Groth [12] improved the computational complexity of [16] but required more rounds of computation as a trade-off. Hao et al. [13] further improved this approach and created a 2-round self-tallying voting scheme. Khader et al. [15] proposed a variant of [13] that also ensures fairness and robustness.

Protocols based on [7] and [16] as well as other approaches [1, 5, 8, 18, 21] require a public bulletin board (PBB), defined as a broadcast channel with memory. According to its definition, PBB is not affected by denial-of-service attacks and allows each participant to write solely in her designated section in an append-only manner. To achieve these properties in practice, Cramer et al. [10] suggest implementing PBB as a set of replicated servers running a Byzantine agreement protocol. The introduction of blockchain technology brought a suitable solution for a practical instantiation of PBB since it offers the required properties of immutability and availability.

McCorry et al. [19] were the first to implement the self-tallying scheme using smart contracts on Ethereum in the system called Open Vote Network (OVN). However, OVN is only suitable for a small-scale (boardroom) voting. Venugopalan et al. [27] presented BBB-Voting, also a boardroom voting protocol, but with several improvements in contrast to OVN. BBB-voting [27] supports multiple candidate choices, fault recovery, and provides cost-optimized...
implementation on Ethereum. Seifelnasr et al. [24] improved the scalability of [19] by reducing the storage requirements and delegating the tally computation to an off-chain entity.

Besides self-tallying approaches, other blockchain-based voting systems have been proposed, such as Zhang et al. [33], Dagher et al. [11] (BroncoVote), Keller et al. [17] (Provotum), Venugopalan et al. [28] (Always on Voting), and Zhang et al. [32] (Chaintegrity). Blockchain-based voting was also criticized by Park et al. [20] for bringing additional security issues rather than improvements.

7 CONCLUSION

In this paper, we present a scalable self-tallying blockchain-based voting protocol. We implemented the protocol and evaluated its performance on two EVM-compatible platforms – Gnosis and Harmony. We showed that our protocol is scalable to accommodate large-scale voting, with the only limitation being the throughput of the underlying blockchain platform. Our experiments show that our system can run voting with millions of participants on a sufficiently fast blockchain (e.g., Harmony).

In future work, we will focus on replacing the NIZK proofs of the voting phase with zk-SNARKs to improve on-chain overhead of vote casting. Furthermore, we intend to investigate the techniques that increase the throughput of smart contract platforms (e.g., sharding) and analyze the impact of these approaches on the security properties and scalability of SBvote.

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