We introduce Blockene, a blockchain that reduces resource usage at member nodes by orders of magnitude, requiring only a smartphone to participate in block validation and consensus. Despite being lightweight, Blockene provides a high throughput of transactions and scales to a large number of participants. Blockene consumes negligible battery and data in smartphones, enabling millions of users to participate in the blockchain without incentives, to secure transactions with their collective honesty. Blockene achieves these properties with a novel split-trust design based on delegating storage and gossip to untrusted nodes.

We show, with a prototype implementation, that Blockene provides throughput of 1045 transactions/sec, and runs with very low resource usage on smartphones, pointing to a new paradigm for building secure, decentralized applications.

1 Introduction

Blockchains provide a powerful systems abstraction: they allow mutually untrusted entities (members) to collectively manage a ledger of transactions in a decentralized manner.

All blockchains today require member nodes to run powerful servers with significant network, storage, and compute resources. Blockchains based on proof-of-work [5, 30] push resource usage to an extreme, requiring significant compute for puzzle-solving, but even consortium blockchains [13] and blockchains based on proof-of-stake [21] incur significant network and storage costs to keep the blockchain up to date at a high transaction throughput. Blockchains today are therefore limited to use-cases where members have a strong incentive to participate, and can hence afford the high resource cost. For example, in consortium blockchains [13], business efficiency improves, while in cryptocurrencies [21, 30], members earn currency.

Interestingly, the high resource requirement of blockchains also weakens reliability for several real-world applications. Blockchains require that majority (typically two-thirds) of members are honest, a property that is easier to guarantee when a large number of members participate. However, wide-scale adoption of a blockchain is hard given the high resource requirement, especially in scenarios where members do not have a direct incentive to participate. Not surprisingly, public blockchains with high membership today target cryptocurrencies [5, 30].

In this paper, we present Blockene¹, an ultra-lightweight, large scale blockchain that provides high throughput for real-world transactions. By being lightweight and scalable, it enables wide-scale adoption by millions of users. By enabling large scale of participation, Blockene makes it plausible to assume honest-majority. By being high-throughput, Blockene supports real-world transaction rates.

The key breakthrough in Blockene is that instead of requiring members to run powerful servers, Blockene is the first blockchain that enables members to participate as first-class citizens in consensus even while running on devices as lightweight as smartphones, lowering cost by orders of magnitude.

Network: Blockchains rely on peer-to-peer gossip between members; at a high transaction rate, gossip would require tens of GBs of data transfer per day; Blockene requires only about 60MB of data transfer per day on a smartphone.

Storage: Member nodes in blockchains keep a copy of the entire blockchain (terabytes at high-throughput); in Blockene, members incur only a few hundred MBs of storage.

Compute: Even the gossip cost of typical blockchains would drain battery on mobile nodes; Blockene ensures that battery drain is less than 3% per day.

Thus, a user incurs no perceptible cost while running Blockene. As the low resource usage in Blockene makes it feasible even in a smartphone, Blockene can also run on desktops, with much lighter resource usage than state-of-the-art.

Blockene achieves three conflicting properties: large scale of participation, high throughput, and lightweight resource usage, catering to even scenarios where there is no direct incentive (e.g., altruistic participation), and handling transactions across variety of use-cases including those on public funds. A comparison of Blockene with other blockchain architectures is depicted in Table 1.

Example application: Audited Philanthropy. Charitable donations to non-profits are in excess of USD 500 billion annually worldwide [7, 8, 10]. However, from a donor’s perspective, the lack of transparency on the end-use of funds makes donations vulnerable to sub-optimal use or mismanagement by non-profits, especially in regions where regulatory enforcement is ineffective or crippled by corruption. A sys-

¹Named after Graphene, one of the lightest and strongest materials.
tem that provides a public, end-to-end trail of funds from the donor to the end beneficiary, will exert market pressure on non-profits, besides motivating donors. A blockchain can provide such tracking, but given the scale of funds involved, a small consortium of members cannot be trusted with operation of the blockchain. Ideally, such a blockchain should be jointly controlled by millions of citizens altruistically. Similar requirements arise in government/public spending.

Key techniques in Blockene: Blockene adopts a novel system design based on a split-trust architecture with a new security model. There are two types of nodes in Blockene: Citizens and Politicians. Citizens run on smartphones and are the real members of the blockchain, i.e., they have voting power in consensus protocol; hence we assume that two-thirds of the Citizens are honest (a reasonable assumption with millions of Citizens). On the other hand, Politicians run on servers and are untrusted, i.e., do not participate in consensus. Politicians are fewer in number (few hundreds), and we require only 20% of them to be honest. Although Politicians do the heavy work such as storing the blockchain, our protocols ensure that Citizens can detect and handle malicious behavior even if 80% of the Politicians collude with the one-third of malicious Citizens. Citizens deal with high dishonesty of Politicians by using a new primitive called replicated verifiable reads: the Citizen reads the same data from multiple Politicians and can get the correct value even if one (out of, say, 25) is honest.

Citizens perform transaction validation, and decide on the block and resulting global state to commit, by running Byzantine consensus. To make consensus feasible with millions of Citizens, Blockene borrows an idea from Algorand [21] (modified to make it battery-friendly), where a different random committee of (≈2000) Citizens is cryptographically chosen to run consensus for each block. Unlike Algorand, Blockene exposes the set of committee members a few minutes before their participation: this enables Blockene to reduce data and battery cost at Citizens. While this may appear to increase the window for a targeted attack on the committee, we discuss in § 4.2 why this is not a serious concern.

To keep storage/communication costs at the Citizens low, only Politicians store the blockchain and the global state (i.e., key-value pairs), freeing Citizens from gossiping all blocks (≈50GB/day). Citizens only read a small subset of data from Politicians (e.g., key-values for transactions for the current block), and write out the new block. Further, because Politicians are untrusted, Citizens cannot rely on the correct latest values returned by them for, say, a given key. Blockene uses a novel technique of sampling-based Merkle tree read/write that reduces communication cost while ensuring tolerance to 80% malicious Politicians.

When in the committee, Citizens reduce their communication cost by not gossiping directly, but through Politicians; data written by a Citizen gets gossiped among Politicians, and interested Citizens read from Politicians.

As participation in Blockene is lightweight, the system needs to protect against Sybil attacks [17]; preventing an adversary from spinning up lots of virtual nodes to get disproportionate voting share. To thwart such attacks, Blockene requires the participant identity to be certified by the trusted hardware (TEE) available in most smartphones [6, 11], and enforces that each TEE can have at most one active identity on the blockchain, thus raising the economic cost of participation to the cost of a unique smartphone.

To limit damage that 80% malicious Politicians can cause to performance, Blockene employs several techniques to restrict their ability to lie. First, we use a technique called pre-declared commitments to make some malicious behaviors detectable. Second, to perform gossip among Politicians reliably and efficiently despite 80% dishonesty, we introduce a novel technique called prioritized gossip. These techniques reduce cost at Citizens, enabling Blockene to achieve high throughput despite running on smartphones.

We have built a prototype of Blockene; the Citizen node is implemented as an Android application, and Politician node is implemented as a cloud server. We evaluate Blockene along various dimensions, and show that it achieves good transaction throughput of 1045 transactions/sec (6.8 MB/min) while ensuring a commit latency of 270s in the 99th percentile. We also demonstrate very little data use (61 MB/day) and battery use (3%/day) at Citizens.

The key contributions of this paper are as follows:

- We present the first blockchain system where nodes can participate as first-class members in consensus while running on devices as lightweight as smartphones, supporting high scale of members and high throughput.
- We present a novel split-trust design with a new security model comprised of resource constrained Citizens (honest majority) and resource heavy Politicians (dishonest majority), and Citizens performing validation and consensus by offloading heavy work to untrusted Politicians in a verifiable way.
- We make several novel optimizations (e.g., pre-declared commitments, sampling-based Merkle tree read/write, prioritized gossip) that achieve good performance despite 80% malicious Politicians.
- With a thorough theoretical analysis, we prove that Blockene satisfies safety, liveness, and fairness.
- We perform a thorough empirical evaluation of this architecture, demonstrating its feasibility as a shared scalable blockchain service.

The rest of the paper is structured as follows: In § 2, we provide a background on blockchains, and discuss existing blockchain architectures in § 3. § 4 provides an overview of Blockene, and its threat model, and § 5 presents its design. We discuss optimizations for resource-heavy steps in § 6, present an overview of safety and liveness proofs in § 7, and describe the implementation in § 8. We evaluate Blockene in § 9, and conclude (§ 10).
2 Background

In this section, we discuss the key principles and abstractions in a blockchain, and its applications.

2.1 Basic properties

A blockchain is a distributed ledger of transactions. Without a trusted authority (e.g., a bank) managing the ledger, a group of mutually untrusted parties collectively validate transactions, and maintain a consistent ledger, provided at least a threshold of participants (e.g., two-thirds) are honest. A blockchain must provide safety, liveness, and fairness. Safety ensures that honest participants have a consistent view of the ledger. Liveness ensures that malicious participants cannot indefinitely stall the blockchain by preventing new block additions. Fairness ensures that all valid transactions submitted to the blockchain get eventually committed.

2.2 Building blocks

A blockchain is a replicated, peer-to-peer distributed system built on the following basic primitives: Merkle tree for Global State: A key part of a blockchain is the global state database that tracks keys and their current values. This global state is managed in a tamper-proof manner, typically using a Merkle tree where the leaf nodes contain the key-value pairs, while each intermediate node contains a hash of the concatenated contents of child nodes. The root is a single hash value that represents the entire state. An update of a key requires recomputation of hashes only along the path from that leaf to the root. Given the root, the value of any key can be proved by a path of valid hashes to the root.

Signed transactions: The basic unit of work in a blockchain is a transaction. A transaction reads and updates a few keys in the global state (e.g., transfer $1000 from Alice to Bob). To be valid, (a) the transaction must be signed (b) the user signing requires the member nodes to be always up-to-date with the "current" state of the blockchain. Given the high transaction rate (1000s of transactions per second) that such blockchains enable, replication of the entire state across member nodes is expensive: at 1000 transactions/sec, the blockchain would commit roughly 9GB per day, which needs to be gossiped across member nodes, resulting in a network cost of roughly 45 GB/day (assuming a gossip fanout of 5 neighbors) that every member node has to incur. Further, such a blockchain would consume terabytes of storage on member nodes, as every member node stores a local copy of the blockchain.

Even blockchains that target smartphones [34] adopt the same philosophy of member nodes staying up to date, and thus incur the network and storage overheads.

3 Comparison with Existing Blockchains

In this section, we present a brief survey of related work on existing blockchain architectures. Blockene provides three properties: lightweight resource usage, large scale of participation, and high transaction throughput. We use the same three dimensions to compare Blockene with related work.

3.1 Resource usage by member nodes

Existing blockchains span a wide spectrum in resource usage by participating member nodes, depending on the mechanism used for consensus. We first discuss compute cost incurred by members, and then the network and storage cost.

Compute Cost. In terms of compute cost, the most expensive are blockchains based on Nakamoto consensus [30], also referred to as proof-of-work; examples are Bitcoin [30] and Ethereum [5]. In Nakamoto consensus, the first member node to solve a compute-intensive cryptographic puzzle is chosen as the winner in committing a new block. Such blockchains therefore require heavy compute resources at member nodes.

In order to address the high compute (and energy) costs of proof-of-work blockchains, two popular alternative architectures have emerged. The first is consortium blockchains (e.g., HyperLedger [13]), which, by limiting the blockchain membership to a small number of nodes, can run traditional Byzantine consensus algorithms, instead of the compute-intensive proof-of-work based consensus. The second architecture is proof-of-stake blockchains, which tie the voting power of a member node with the amount of money the member node has on the blockchain. Examples of these blockchains are Algoland [21], Ouroboros [14, 22], PeerCoin [23], etc. Inherently, proof-of-stake blockchains target cryptocurrency applications where such a “stake” is meaningful.

Network and Storage cost. While the above two architectures, i.e., consortium blockchains and proof-of-stake blockchains, address the raw compute cost of member nodes, they are still too expensive for smartphones. In particular, they are heavy on network and storage resources, as they require the member nodes to be always up-to-date with the "current" state of the blockchain. Given the high transaction rate (1000s of transactions per second) that such blockchains enable, replication of the entire state across member nodes is expensive: at 1000 transactions/sec, the blockchain would commit roughly 9GB per day, which needs to be gossiped across member nodes, resulting in a network cost of roughly 45 GB/day (assuming a gossip fanout of 5 neighbors) that every member node has to incur. Further, such a blockchain would consume terabytes of storage on member nodes, as every member node stores a local copy of the blockchain.
Some blockchains address storage cost by sharding. OmnilLedger [25] is a recent blockchain that allows participants to only store a shard of the blockchain. It uses a variant of Byzcoin [24] for fast consensus. RapidChain [36] also uses sharding to reduce storage cost. Both these works scale only to a few thousand participants and also require participants to store a large fraction ($\frac{1}{3}$ or $\frac{1}{5}$) of the entire blockchain. **Lightweight but Incapable Nodes.** A class of “lightweight” blockchains adopt an approach of “unequal members”: only the first-tier, resource-heavy members participate in consensus and have voting power, while the second-tier members simply serve as read-only query frontends, and do not participate in consensus. In such a model, the “majority-honest” property must be met purely by the heavy nodes, as light nodes do not contribute to security. Not surprisingly, given the limited responsibility, the “light” nodes don’t consume much resources. An example of this architecture is the separation between light and heavy nodes in Ethereum [32]. **Blockene.** In contrast, Blockene, achieves lightweight source usage for first-class members that participate in consensus and block validation. Further, unlike Ethereum which depends on honest majority among heavy nodes (only heavy nodes can vote), Blockene tolerates up to 80% of the “heavy” nodes (i.e., Politicians) being corrupt. Members in Blockene require only a smartphone and negligible2 data transfer (< 60 MB/day, i.e., three orders of magnitude lower) and negligible compute (battery use of <3% per day). It achieves this by enabling member nodes to operate with minimal state needed for committing a particular block, and performing work only a few times a day, i.e., not striving to stay up-to-date always.

### 3.2 Scale of participation

As the security of a blockchain fundamentally relies on a majority of the participating members being honest, blockchains need to protect against collusion of a large number of participants. Consortium blockchains [13] carefully structure the blockchain for a particular business process, such that members have a shared incentive in the success of the blockchain. It is sometimes infeasible/hard to structure a consortium with the above guarantee; in the philanthropy example, if a small number of members are in control of the blockchain, they may collude to say, facilitate siphoning of donations meant for the poor. Moreover, a consortium blockchain is intricately tied to a specific business process among a set of entities, resulting in high setup and operational overhead, besides limiting inter-operability.

Another approach to guard against collusion among majority, is to enable large scale participation; by onboarding a large number of participants (say millions), majority-collusion can be made hard and unlikely. Most “public” blockchains such as Bitcoin [30], Ethereum [5], and Algorand [21] enable large-scale participation. Blockene also supports a large number of participants, but unlike most public blockchains today that target cryptocurrencies, Blockene is not tied to cryptocurrency (e.g., no proof-of-stake), but enables generic business transactions. Unlike consortium blockchains, Blockene can additionally enable real-world scenarios where there is potential for collusion among a small number of members.

### 3.3 Transaction throughput

Public blockchains based on proof-of-work are low in throughput (~4-10 transactions/sec). Proof-of-stake based Algorand [21] is the first public blockchain with ~1000 transactions/sec. Consortium blockchains, due to low scale of participants and traditional consensus (e.g., PBFT), provide 1000s of transactions/sec. Similar to Algorand, Blockene also provides a high transaction throughput. By not being tied to cryptocurrency applications, Blockene can serve traditional business applications similar to consortium blockchains.

| Blockchain     | Scale of members | Trans. rate | Cost | Incentive needed? |
|----------------|------------------|-------------|------|-------------------|
| Public (e.g., Bitcoin) | Millions | 4-10 /sec. | Huge (PoW) | Yes |
| Consortium (e.g., [13]) | Tens | 1000s /sec. | High | Yes |
| Algorand [21] | Millions | 1000-2000/sec. | High | Yes |
| Blockene | Millions | 1045 /sec. | Tiny | No |

Table 1: Comparison of blockchain architectures.

### 3.4 Incentives to Participants

Because of high resource cost (compute, network, or storage), existing blockchains need an incentive for participants (e.g., mining coins in cryptocurrencies, or business efficiency in consortiums). Blockchains that depend on such incentives cannot work for applications such as philanthropy (§ 1). To scale without incentives and to enable altruistic participation, the cost of participation has to be negligible.

Table 1 compares blockchain architectures along these dimensions. Blockene is the first blockchain to achieve all of the above: scale, throughput, and low cost. With low cost, Blockene supports real-world use-cases even where participants do not have a direct incentive, but are altruistic to run a background app with negligible battery and data usage.

### 3.5 Other related work

The committee-based consensus in Blockene is heavily inspired by Algorand [21]; Like Blockene, Algorand also

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2 Cellular data costs in several countries are much cheaper than in the US [18]; in US/Europe, users are on WiFi/broadband most of the day.

3 Assuming 100-byte transactions and 2.2 MB in 20s, 10MB blocks @750MB/hr.
4.1 Two-tier Architecture

Blockene employs a novel two-tier architecture with asymmetric trust. This architecture is depicted in Figure 1.

There are two kinds of nodes in Blockene: Citizens and Politicians. Citizens are resource-constrained (i.e., run on smartphones), are large in number (millions), and are the only entities having voting power in the system (i.e., participate in consensus). Politicians are powerful and run servers (similar to existing blockchains like Algorand), and are lot fewer in number (low hundreds), but they do not have voting power. Politicians only execute decisions taken by Citizens, and cannot take any decisions on their own.

The low resource usage enables a large number of Citizens to participate without incentives, while Politicians being few in number, will be run by large entities that have interest in the particular use-case (e.g., in the audited philanthropy case, large donors and foundations).

As Citizens participate in consensus, at least two-thirds of Citizens are required to be honest, while others can be malicious and collude. This is reasonable as Blockene allows millions of Citizens, making large-scale corruption hard. However, Politicians enjoy much lower trust. Blockene only requires 20% of politicians to be honest; the remaining 80% of the politicians can be malicious and collude among themselves, and with one-third malicious Citizens.

4.1.1 Offloading work to Politicians

Intuitively, given the two-tier architecture, Citizens can offload expensive responsibilities such as storage and communication to Politicians. However, as 80% of Politicians are corrupt, a write made by a Citizen could just be dropped by a Politician or, a read could return incorrect value. To get useful work done out of Politicians Blockene uses a novel mechanism of replicated reads and writes. Reads and writes by Citizens to Politicians happen with a random safe sample of Politicians. The size of this sample is fixed such that with high probability, at least one Politician in the sample is honest (e.g., for a sample size of 25, this probability is \(1 - (0.8)^{25} = 99.6\%\)). Blockene is resilient to a small number of Citizens (0.4%) picking all dishonest Politicians.

4.1.2 Division of responsibilities

We now describe how the Citizens and Politicians collaborate to perform the various standard blockchain tasks:

Storage: In a traditional blockchain, every participant keeps a replica of the entire blockchain, but Citizens in Blockene cannot afford to store TBs of data. In Blockene, only Politicians store the ledger and the global state (i.e., database of key-values § 2). Citizens read subsets of this data from Politicians as needed. The only state Citizens store (and periodically update) is a list of valid Citizen identities (§ 5.3).

Transaction Validation: As Citizens are the actual participants in consensus, they validate transactions, ensuring that transactions are signed, and have semantic integrity (e.g., no double-spending). To perform validation, Citizens read transactions from Politicians, and lookup latest values of the keys referenced in them, from the global state with Politicians. Citizens then propose a block with valid transactions.

Gossip: To ensure that all honest participants agree on the state of the blockchain, participants need to gossip among themselves. However, as discussed in § 3, direct gossip among Citizens is expensive. Blockene solves this problem by having Citizens gossip through Politicians. When a Citizen needs to broadcast information to other Citizens, it sends a message to a safe sample of Politicians. Politicians then gossip data
among themselves; they can afford to do so because they have good network connectivity. Other Citizens then perform a replicated read from the Politicians when they need to, e.g., when they are in the committee⁴. For gossip through Politicians, we need the guarantee that a message that reaches one honest Politician always reaches all other honest Politicians via gossip, a challenging property when 80% of the Politicians are malicious; our custom gossip protocol is described in § 6.1. Thus, we achieve the same semantics as direct gossip among Citizens, but with minimal network load on Citizens. Consensus: Citizens participate in consensus by performing gossip through Politicians. Given the large scale of Citizens, all Citizens cannot participate in consensus. Instead, we cryptographically select a random committee of citizens (roughly 2000 members) for each block (§ 5.2).

4.2 Threat Model

While our threat model is similar to Algorand [21], there is a tradeoff between Algorand and Blockene on the resilience to targeted attacks. On one hand, Algorand is based on proof-of-stake, which allows an adversary infinite time to target nodes with higher stake (who will appear in the committee more frequently); Blockene avoids this attack, as all Citizens have equal votes. On the other hand, Algorand protects the secrecy of the committee members until they perform their role, but Blockene exposes their identities a few minutes (1-2 blocks) before they participate. To conserve battery, Citizens normally poll Politicians for current state of the blockchain roughly every 10 blocks (5.2), but when they are going to be in the committee, will poll again shortly (e.g., 1 block) before their expected turn, thus exposing their identity to malicious Politicians. This potentially provides a window for a targeted attack (e.g., by bribing the committee: § 4.2.1).

4.2.1 Attack vector of Citizens

Bribing attack on Citizens: As Blockene implicitly exposes the public keys of the committee a few (e.g., 2) minutes in advance, an adversary could in theory perform a targeted attack by bribing a sufficient number of committee members. However, we believe this is not a concern for the following reasons. First, with just the IP address, it is non-trivial for an adversary to “send a message” offering bribe to a Citizen, because of carrier-grade NAT [4] and the architecture for push notifications in smartphones; the existing channel from a malicious Politician to the Citizen cannot be misused for this, as an untampered Blockene app on the Citizen will ignore any spurious traffic on that channel. Second, as the committee is randomly chosen every block, pull-based bribing where the Citizens (who know of their selection up to 10 blocks in advance - § 5.2) proactively reach out to the adversary cannot happen, as that would imply violation of the honesty assumption on Citizens, i.e., greater than 70% being honest.

Sybil Attack by Citizens: Given the lightweight cost of participation, Blockene needs to ensure that an adversary cannot get disproportionate share of voting by spinning up several virtual nodes (i.e., Sybil attacks [17]). A common way of addressing Sybil attacks is Proof-of-stake which is resource-intensive and does not fit the goals of Blockene; another alternative is Proof-of-stake [21] where a participant’s voting power is proportional to the amount of “stake” (money) on the blockchain, but it is specific to cryptocurrencies.

In Blockene, we protect against Sybil attack by exploiting the trusted hardware (TEE) available in smartphones [6, 11], and ensuring that a smartphone can have at most one identity on the blockchain. Thus, Blockene imposes an economic cost to participation, i.e., the cost of a smartphone; this is sunk cost already incurred in owning the smartphone, but protects against Sybil as each identity is a unique smartphone.

In particular, each TEE has a unique public key that is certified by the platform (Android/iOS) vendor. The TEE can certify an EdDSA public-private keypair generated by an app; this generated public key serves as the identity on Blockene. The global state of Blockene tracks the set of valid public keys, along with the public key/certificate of the TEE that authorized it. When a transaction for adding a new member is proposed, Blockene looks up the TEE public key to see if that TEE (i.e., the same smartphone) already has an identity in Blockene; if yes, it rejects the transaction⁵. Thus, every Citizen on Blockene is tied to a unique smartphone, making it economically infeasible/unattractive for a single entity to get large participation on Blockene.

Note that Blockene only assumes that every certificate signed by Google/Apple for a TEE public-key corresponds to a unique smartphone. It does not depend on the security of an individual TEE (unlike running the blockchain consensus inside TEE, e.g. SGX [33], that opens up side-channel attacks compromising integrity and security). As a result, the TEE identity can be replaced/combined with other unique identities. In India, one-way-hash of Aadhaar-ID [1, 12] (digitally verifiable, biometric-deduped, 1.2 billion-reach) can be used. Other de-duped IDs (e.g.SSN) augmented with digital verifiability can also be used.

4.2.2 Attack vector of Politicians

Dealing with 80% dishonesty among the politicians is one of the main technical challenges in the design of Blockene. Malicious behavior by Politicians falls under two kinds: detectable and covert. Detectable maliciousness where there is a succinct proof of lying, can be used to improve performance by blacklisting. For example, if a Politician is supposed to only send one group of transactions in a round, but there are

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⁴Direct gossip among Citizens would require all Citizens (i.e., including those outside the committee) to participate in gossip of all data.

⁵We can also support replacing the old identity with the new one for the same TEE with appropriate bookkeeping.
two versions signed by the same Politician, it is detectable with proof. Covert maliciousness is harder to handle, and is the focus of our techniques. We list broad (non-exhaustive) classes of covert attacks a Politician can employ.

**Staleness Attack:** When a Citizen node asks the Politician for some state (e.g., the latest committed block), the Politician could return a stale block. Such a response would appear to be valid because the old block would also have been signed by a quorum of Citizens (§ 5.3).

**Split-View Attack:** A Politician can respond selectively to some Citizens and not to others, causing a split in the worldview seen by honest Citizens. Worse, a Politician can respond with two different values to different subsets of Citizens. In a coordinated split-view attack, the malicious Politicians could only gossip among themselves, so that no honest Politician has a certain data. Malicious Politicians can then selectively relay this data only to some Citizens (e.g., § 5.5.2).

**Drop Attack:** A malicious Politician may drop data written by a Citizen without committing it or gossiping it to other Politicians. Similarly on a read, the Politician may choose to not respond, even though the Politician has the data (§ 4.1.1).

**Denial-of-Service Attack:** As Politicians are powerful servers typically hosted in the cloud, we assume that honest Politicians employ standard DoS protection that public clouds offer [2, 3]. For Citizens, most ISPs employ carrier-grade NAT to handle the explosion of IP addresses on mobile phones [4], which also provides DoS protection. Malicious Politicians can make our gossip protocol more expensive by asking for more data than they need (§ 6.1).

**Sibyl Attack:** An adversary could try pushing the dishonesty fraction of Politicians beyond 80% by spinning up several nodes. However, given the small number (say 200), we envision that Politician nodes would have an out-of-band registration mechanism (e.g., mapping them to real entities, say one per Fortune-500 company) - robust because only 20% of them need to be honest (unlike Citizens).

Blockene protects against both detectable and covert maliciousness of the Politicians including the attacks listed above.

5 Design

In this section, we present in more detail how Citizens and Politicians coordinate on the key steps in Blockene.

5.1 System Configuration

We first outline the system configuration for Blockene. Citizens in Blockene run on a smartphone, so we assume that their network bandwidth is low, i.e., 1 MB/s. We choose a block size of 9MB (to amortize fixed cost per block), containing about 90k transactions (~100 bytes each including a 64-byte signature). We assume a network bandwidth of 40 MB/s between Politicians (representative of bandwidth in the cloud, e.g., between an Azure and a Google Cloud VM across east-US and west-US). We choose the number of Politicians as 200. The work done per block only depends on committee size, so the system scales to millions of Citizens.

Transaction originators submit signed transactions to a safe sample or to all Politicians, continuously in the background. Transactions can modify keys that the originator has access to. Transactions from the same originator can depend on each other; we preserve their order by tracking a per-originator nonce in the global state. In this paper, (without loss of generality) each transaction accesses three keys (debits one key and credits another, third key is nonce). Politicians gossip transactions among each other.

5.2 Selecting Committee of Citizens

The committee of citizens for validating and signing each block is chosen on the basis of a VRF (Verifiable Random Function) [27], inspired by Algorand [21] but with one key modification. Algorand requires each participant to check in each round whether it is chosen in the committee. A Citizen on a mobile phone cannot afford to do such frequent checks because waking up the phone every round and communicating would cause significant battery drain. Therefore, instead of computing the VRF on the hash of the previous block \(N-1\), Blockene uses the hash of block \(N-10\), thus allowing a Citizen to wake up once every 10 blocks. Note that this modification still preserves the security guarantee required from VRFs in our threat model. Specifically, for a citizen, the VRF for block \(N\) is calculated as Hash(Sign\(sk\), (Hash(Block\(_{N-10}\))\(||\)N)) where sk is private key known to the citizen. \(^6\) A Citizen is in the committee if the VRF has 0’s in the last k bits (hence a Citizen is part of a committee with probability \(2^{-k}\); k can be set appropriately). Only the concerned Citizen can generate the VRF as it requires its private key, but anyone can verify its validity based on the public key given the signature.

**Committee size:** The size of the committee needs to balance performance and security. A small committee is good for performance, but for security of consensus protocol, we require that in any committee, at least 2/3 Citizens are honest. As our committee selection is probabilistic, by the Chernoff bound [29], this security requirement cannot be met for very small committee size even if we have 2/3 honest Citizens overall. Committee size increases with the fraction of dishonest Citizens. We calibrate this tradeoff to obtain an expected committee size of 2000 with a citizen dishonesty threshold of 25%. While these computations are described in detail in Appendix B, we provide an overview below.

**Proof overview:** We prove several properties about the committee for a block. We call a Citizen that participates in a committee as **good** if the Citizen is honest and speaks to at least 1 honest Politician through \(m\) fan-out read/write. Otherwise, we say that the Citizen is **bad**. For a configuration with 25% corrupt Citizens, 80% corrupt Politicians, and \(m = 25\),

\(^6\)We use EdDSA signatures. ECDSA uses random number which the adversary can exploit to brute-force itself into the committee.
we show that our committee satisfies the following properties: size of all committees lies in the range [1700..2300] (Lemma 1), every committee has at least 1137 good citizens (Lemma 2), every committee has at least a 2/3 fraction of good citizens (Lemma 3), and no committee has more than 772 bad citizens (Lemma 4).

5.3 Fork-proof Structural Validation

Blockene is designed to prevent forks from occurring. To enable this, each Citizen periodically verifies the structural integrity of the blockchain to enforce that the chain of hashes and VRFs are consistent and to prevent forks.

Track local state: Each Citizen locally remembers the block number \( N \) until which the Citizen validated the structural integrity of the blockchain, and the hashes of blocks \( N \) to \( N - 9 \). In addition, a Citizen stores an up to date list of public keys of other valid Citizens. The total storage size is <100MB for 1 million Citizens.

Chained ID sub-blocks: To enable Citizens to efficiently update local state, the public keys of new users added as part of each block \( B \), are tracked in an ID sub-block (SB) within \( B \). SBs are chained together by embedding Hash\((SB_{i-1})\) within \( SB_i \). To aid cheap verification, committee members sign Hash\( (\text{Hash}(B_i), \text{Hash}(SB_i), \text{GlobalStateRoot}(B_i)) \).

Incremental Validation: Roughly every 10 blocks (12-15 mins), each Citizen performs a getLedger call to validate the incremental structural integrity (i.e., from last validation point to the latest state), and to check if it will be in the committee soon (committee for a block \( N \) is a function of the hash of block \( N - 10 \)). To find the latest block, a Citizen queries a safe sample of Politicians for the latest block number. It picks the highest number reported by any Politician, and asks for proof, i.e., signatures of committee of that block and the corresponding VRFs. Thus, if at least one Politician in the safe sample is honest, the Citizen will know the latest block hash. If the latest block is greater than \( N + 10 \), it first verifies block \( N + 10 \). Further, it refreshes its set of valid public keys by downloading the chained sub-blocks \( SB_{N+1} \ldots SB_{N+10} \) that contain new Citizens added in each block, verifying the integrity of \( SB_i \) based on the chained hashes.

Cool-off period for new nodes: To prevent a (low-probability) attack where an adversary can manufacture public-private keypairs\(^7\) to increase chances of getting higher malicious fraction for a particular block \( N \), we allow a Citizen to be in the committee only \( k = 40 \) blocks after the block in which the Citizen was added. To verify this as part of VRF checks, a Citizen’s local state tracks the block number of “recently” added Citizens. This is similar to the “look back parameter” in Algorand [21].

Proof overview: Our getLedger protocol (Appendix C) is used for verifying ledger height \( i + 10 \), given the Citizen \( v \) has last verified height \( i \), without an explicit brute-force verification of signatures of all 10 blocks. The algorithm generalizes to verifying any height \( i + j \) for \( 1 \leq j \leq 10 \). We show (Lemma 5) that if a good Citizen with a verified state for height \( i \) invokes the getLedger protocol at round \((i + 11) \) and accepts, then the Citizen’s updated structural state is consistent with the blockchain up to height \((i + 10) \). Using this, we can show that honest Citizens can obtain the consistent structural state of the blockchain, along with all registered public keys, for every round of the protocol (Corollary 2).

5.4 Transaction Validation

Citizens perform the task of verifying signatures of transactions, checking the transaction nonce to detect replay attacks, and verifying semantic correctness of the transaction (e.g., double spending). However, only Politicians store the Merkle tree (§ 2.2) of the global state; keeping a large and up to date global state in Citizens is unaffordable. To validate a transaction, a Citizen must lookup the correct value of keys referenced therein. On commit, the Citizen must update the Merkle tree with new values from the transaction, and sign the new Merkle root. The challenge lies in doing so correctly given untrusted Politicians.

The Merkle root (along with block number) is signed by the committee of the previous block, so the Politician cannot lie about the Merkle root. Once the Citizen learns the latest block number (§ 5.3), it learns the correct Merkle root as well. To verify a value returned for a key, Citizen asks the Politician to send the challenge path for this key, i.e., all the sibling nodes (hashes) along the path from the leaf to the root. This enables the Citizen to reconstruct the Merkle path and match the root hash with the signed Merkle root. By security of hashes, the Politician cannot present spurious challenge paths that verify. In a tree with 1 billion key-value pairs, the challenge path would contain 30 hashes.

Update of keys in the Merkle tree follows a similar protocol. The Citizen could build a partial Merkle tree with the new values at the leaves, and compute the new Merkle root. Both the read and update paths mentioned above are expensive, and we optimize them in § 6.

5.5 Block Proposal

Like in any blockchain, committee members can propose a new block for committing to the blockchain.

5.5.1 Pick winning proposer

For efficiency, we allow only a subset of committee members called proposers to actually propose a block, based on the VRF of the Citizen. For this selection, we use an additional VRF that is based on the hash of the previous block \( N - 1 \) (instead of \( N - 10 \)); only committee members who have the last \( k' \) bits of the additional VRF set to zero can propose a block,
and the winner is the one with the least VRF. Using the previous block hash in this VRF ensures that the adversary does not know about the proposers until the last minute (similar to Algorand) thus preventing a targeted attack on the proposers. Any committee member can consistently determine the winning VRF among the proposers. All proposers upload their block to Politicians and other committee members download the block of the winning proposer.

5.5.2 Pre-declared commitments

The upload of the proposed block by a proposer needs to be done to a safe sample of 25 Politicians. In Blockene, as the blocks are ~9MB in size, assuming 1MB/s bandwidth at mobile nodes, this would take 225 sec. To optimize this step, we make the transaction selection process deterministic, so that any Citizen can reconstruct what the original proposer would have done, without the proposer explicitly uploading the full block. Determinism is challenging, however, because the 80% malicious Politicians can send different transactions to different Citizens. Our technique of pre-declared commitments to transactions addresses this.

1. Freeze Transactions. At the start of block \( N \), each Politician freezes the exact set of transactions it will send to Citizens reading from it. It does so by creating a tx\_pool, which includes a set of (about 2000) transactions, and then generates a commitment which is a signed hash of the tx\_pool along with the block number. Malicious Politicians are forced to issue only one commitment for a given block \( N \), because two signed commitments from a Politician is a proof of malicious behavior, and can be used for efficient blacklisting; Citizens then drop all commitments from that Politician in the same round. Intuitively, with frozen commitments, a Citizen proposing a block, need not upload the full block, but only a digest with the commitments that went into the block, and other Citizens can reconstruct that block by downloading the tx\_pools for those commitments from Politicians.

2. Ensure that enough honest citizens have commitments. A malicious Politician can respond with its tx\_pool only to a subset of Citizens, and refuse to respond to others; thus, a tx\_pool committed in the proposed block may not be readable by all honest Citizens, thus thwarting consensus. To address this, we perform three steps. First, we limit the exact set of Politicians from whom to pull transactions for a given block to a randomly chosen set of 45 politicians based on the hash of the block number and hash of previous block. Instead of reading tx\_pools from a random safe sample, a Citizen reads from these 45 designated Politicians for a block. Second, the Citizen uploads a witness list to a safe sample of Politicians; the witness list contains the list of tx\_pools the Citizen was able to successfully download. The witness list of all Citizens gets gossiped between Politicians. Third, the proposer reads the witness list of all other Citizens, and picks only commitments whose tx\_pools were successfully downloaded by at least a threshold number of Citizens. This threshold is fixed to be \( \bar{n}_b + \Delta \), where \( \bar{n}_b \) is the maximum number of malicious nodes in any committee (computed to be 772, from §B, Lemma 4), and \( \Delta \) is chosen to be 350. Intuitively, all commitments (and tx\_pools) that pass this condition are available with at least \( \Delta \) honest Citizens. As 20% of Politicians are honest, in expectation, at least 9 out of the 45 commitments will pass this test.

3. Ensure that all honest citizens get commitments. The commitments available with at least \( \Delta \) honest Citizens now need to be propagated to all honest Citizens. Each Citizen in Step 4, re-uploads 5 random tx\_pools it has, to 1 random Politician. This ensures that (with high probability) each tx\_pool (including those from malicious Politicians) that belongs to at least \( \Delta \) honest Citizens reaches at least one honest Politician (who then gossips it to other honest politicians). Thus, other honest Citizens can successfully download that tx\_pool (by querying a safe sample of politicians), preventing a split-view attack by malicious Politicians.

4. Handle malicious proposer. When the winner of block proposal is a malicious Citizen, it need not respect the witness list criteria, and can pick a commitment whose tx\_pool is known to very few Citizens. This attack is possible only when consensus outputs the block proposed by this malicious proposer, so we can argue that at least 1/3 honest Citizens had all tx\_pools at the beginning of the consensus. To ensure that all honest Citizens are able to download all required tx\_pools, a second re-upload of randomly chosen tx\_pools happens (step 9), now including the downloaded tx\_pools from previous step. Formal proofs capturing the guarantees provided by these re-uploads needed to prove security of our system are presented in Lemmas 10 and 11 of §E.2.

5.6 Block Commit Protocol

The main operation in a blockchain is adding a new block to the blockchain. We list below the key steps in the process of committing block \( N \). The protocol for block \( N \) starts once the previous block \( N - 1 \) gathers a threshold number of signatures (set to 850 in our case, § E.1) from the committee members for block \( N - 1 \).

1. A new committee of Citizens is chosen for block \( N \) (using Hash of block \( N - 1 \)), denoted by \( C^N \). The Citizens in \( C^N \) keep polling for the latest committed block number, and start the protocol once that number is \( N - 1 \).

2. Each Citizen \( C^N_i \) in \( C^N \) downloads tx\_pools & commitments from \( \rho = 45 \) designated Politicians for the block.

3. Each \( C^N_i \) uploads a signed witness list with the commitments downloaded, to a safe sample of Politicians.

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8To reduce overlap of transactions across tx\_pools from multiple Politicians (which would reduce the unique transactions in the final block), transactions are deterministically partitioned across Politicians using a hash on transaction identifier and round number. Given a tx\_pool and commitment, it is easy to detect blacklist a Politician that doesn’t follow this.
4. Each Citizen $C_i^{N}$ picks 5 random tx_pools it has, and re-uploads them to 1 random Politician.
5. Each proposer in $C^{N}$ downloads all witness lists of $C^{N}$ from a safe sample of Politicians, and picks commitments with at least a threshold (1122) of votes (§5.5.2). Then, it makes a block proposal with those commitments, along with its VRF to prove proposer eligibility.
6. Politicians gossip on block proposals/VRFs and on the tx_pools that were re-uploaded by Citizens.
7. Each Citizen $C_i^{N}$ tries to download missing tx_pools in step 2 from safe sample of Politicians, relying on the re-upload (Step 4) by other Citizens.
8. Each $C_i^{N}$ reads the VRFs of all proposers in $C^{N}$ from a safe sample of Politicians, and picks the lowest correct VRF as the local winner. If $C_i^{N}$ already has all tx_pools in the winning proposal, it enters consensus with that set of commitments, otherwise, NULL.
9. Each Citizen $C_i^{N}$ performs a second re-upload of 10 random tx_pools it has to 1 random Politician.
10. Citizens in $C^{N}$ run a consensus protocol (§5.6.1) with gossip through Politicians, where each $C_i^{N}$’s vote is decided in Step 8. At the end, all honest Citizens either agree on same set of commitments or an empty block. $C_i^{N}$ downloads the tx_pools missing w.r.t. the output of consensus from safe sample of Politicians.
11. Each Citizen $C_i^{N}$ performs transaction validation by downloading challenge paths for all keys from Politicians (§5.4) and drops transactions that fail validation.
12. Based on valid transactions (Step 11), each $C_i^{N}$ creates a block, computes the new Merkle root of the global state using updated values of keys and signs the block hash and new Merkle root, along with block number $N$. It uploads the block hash, new Merkle root, and this signature to a safe sample of Politicians.
13. When more than a threshold number of signatures have accumulated for block $N$, block $N+1$ starts.

Our complete protocol description can be found in Algorithm 4, §E.1. We give an overview of various properties of Blockene, i.e., safety, liveness and fairness, in §7.

5.6.1 Consensus Protocol

For consensus (Step 10), we use the Byzantine Agreement (BA) algorithm for string consensus (that is based on [35]) which calls upon the bit consensus algorithm BBA [26] in a black-box manner. These are the same consensus algorithms used by Algorand. Citizens enter the consensus protocol with list of commitments in local winning block, as input. Two scenarios are relevant here. If the winning proposer (i.e., the one with the lowest VRF) was honest, which would happen at least two-thirds of the time, all honest Citizens in the committee would enter consensus with this proposal except with small probability (Lemma 10), and the protocol will terminate in 5 rounds. However, if the winning proposer was malicious, it can collude with malicious Politicians to partition the view of honest Citizens. In general, the consensus protocol would take an expected 11 rounds [21].

6 Optimizations

In this section, we present two key optimizations crucial to achieving high transaction throughput in Blockene.

6.1 Prioritized Gossip

Problem. The guarantee we require in Blockene is that if one honest Politician has a message, all honest Politicians receive the message. Because of the high fraction of dishonesty among Politicians, standard multi-hop gossip with a small number of neighbors (e.g., 10) cannot provide this guarantee, because there is a non-trivial probability that all of them were dishonest, and drop the message. Hence the safe thing to do is a full broadcast to all other Politicians, which is expensive; when Politicians need to gossip tx_pools that were re-uploaded by Citizens in the committee, each Politician may have up to 45 tx_pools to gossip; with full broadcast, it would send $0.2MB \times 45 \times 200 = 1.8GB$ which would take 45 seconds in the critical path (@40MB/s).

Key idea. We leverage the fact that messages being gossiped by the different Politicians have a high overlap; each Politician has a subset of the same tx_pools as Citizens pick a random Politician to re-upload a subset of tx_pools. Moreover, given the nature of re-upload, in expectation, any Politician would be missing only a few tx_pools, and honest Politicians wouldn’t lie about state.

1. Handshake. Each Politician asks recipients $B_i$ which tx_pools they already have, and send only the missing ones. While this works with honest Politicians, the 80% malicious ones could always lie that they don’t have any, to cause a higher load/latency on the system.

2. Selfish gossip. As malicious Politicians can lie that they have no tx_pools, we assign a soft-penalty to Politicians that miss a lot of tx_pools. Each sender Politician $A$ favors the peer $B$ that has the maximum number of tx_pools that $A$ needs. In each round, $A$ sends a tx_pool to $B$, and receives one in return. Given the random re-uploads by Citizens, each honest Politician would be missing only a small number of tx_pools, and hence would get prioritized. The list of what $B$ has to offer keeps getting updated as $B$ gets tx_pools from other peers; note that this list can only grow, not shrink.

3. Incentivize frugal nodes. Selfish gossip loses its ability to discriminate between honest and malicious recipients, once the sender receives all tx_pools. To address this, after getting all tx_pools, the sender changes its priority function for destinations $B_i$ to be the number of tx_pools that $B_i$ claims to have; thus honest nodes which will have large fraction of tx_pools are favored. Again, the list of tx_pools that $B$ advertises can only grow, not shrink, as shrinking would mean that $B$ lied.
Further, each honest $B_i$ requests its missing chunk from at most $k = 5$ peers simultaneously; $k = 1$ will be data-frugal, but incur high latency if the peer dishonestly delays response.

### 6.2 Sampling-based Merkle Tree Read/Write

**Problem.** The Merkle tree validation in Step 11 is expensive. In a 1-billion node Merkle-tree (30-levels deep), a challenge path is 300 bytes (10-byte hashes); downloading 270K challenge paths is 81 MB (81 sec latency) ignoring compression. The compute at Citizens is also high (total 16.2 million hash computations for challenge path verification during read and for computing new root post update).

**Key idea.** We offload most of this work to Politicians, in a verifiable manner. Since the Merkle tree validation is done after the conclusion of the consensus run using gossip through the Politicians, Politicians know the tx_pools that are considered for constructing the block. Hence, all Citizens in committee and Politicians know the keys whose values need to be read and updated. We first discuss the optimization for reading values correctly from the Merkle tree.

**1. Get Values.** Each Citizen gets just the values for all 270K keys (no challenge path, 1 MB instead of 81 MB) from one Politician, and then asks a safe sample of Politicians whether those values were correct. As at least one of these Politicians is honest, it alerts the Citizen to incorrect values through an exception list. The Politician can “prove” an incorrect value by providing a challenge path from the signed Merkle root that indicates a different value for the key.

**2. Spot-checks.** If many values were wrong, the exception list would be quite large and eat into the savings. To avoid this, Citizen picks a small random subset of $k' = 4500$ keys to initially spot-check using the challenge paths. If the spot-checks pass for a sufficiently large $k'$, a Politician could have lied only for a small number (200) of keys (except with small probability). Thus, the extra spot-checks bound the size of the exception list (Lemma 6, §D.1).

**3. Exception list protocol.** To cross-verify the values with a safe sample of Politicians, the Citizen deterministically puts these values into buckets (2000) and uploads the hashes of these buckets. When a Politician notices a mismatch for a bucket, it sends the bucket index and the correct values for all keys in that bucket. Citizen gets challenge paths only for keys that disagree (from first Politician). Our spot-checks ensure that only a small number of buckets can mismatch.

**Corner case.** Even after doing the above, there is a small probability ($< 2^{-10}$) that a Citizen may obtain an incorrect value; we count such Citizens nodes as malicious and account appropriately (Lemma 7). The full protocol and all proofs are provided in Algorithm 2 of §D.1.

**Writes: Updating the Merkle tree is a trickier problem. Due to lack of old challenge paths for the all keys being updated, the Citizen cannot construct the root of the updated Merkle tree $T'$, we solve this problem by making the Politicians compute $T'$, but now the Citizen must verify that the Politicians performed the computation correctly, i.e., $T'$ is consistent with the new values of updated keys and old tree $T$ for unmodified keys. We achieve this by breaking $T'$ at a level called the frontier level (the nodes at this level are frontier nodes). Citizens obtain the values of the frontier nodes of $T'$ from a safe sample of the Politicians. The Citizens then run a spot checking algorithm - they pick a random subset of frontier nodes and ask a Politician to prove the correctness of that frontier node. Next, Citizens create exception lists with the help of the rest of the selected Politicians. This list denotes which frontier nodes are incorrect with the Citizen. The Citizen then proceeds to sequentially correct the incorrect frontier nodes and then finally compute the correct root of $T'$ from the frontier nodes.

**Proof Overview:** In Appendix D, we prove (in Lemma 6) that for a good Citizen, after successfully spot-checking only $\mu$ fraction of key-values, only (a small number of) $\tau$ values are incorrect with probability $1 - \epsilon_1$ (here, $\mu$, $\tau$ and $\epsilon_1$ are appropriately chosen parameters). Moreover, these values will get corrected by processing exception lists of size at most $\tau$. Hence, a good Citizen gets correct values with probability $1 - \epsilon_1$ (Corollary 3). We pick our parameters (Lemma 7) such that at most 18 good Citizens will obtain incorrect values during read, and account for these 18, by counting them as bad Citizens in the committee. In the write protocol, we can show that the sizes of exception lists can be bounded (Lemma 8) and that no more than 18 Citizens accept an incorrectly updated Merkle tree $T'$ (Lemma 9), which we once again factor in to the set of bad Citizens. We additionally also show that our algorithms are between $3 - 18 \times$ more communication efficient and between $10 - 66 \times$ computationally faster than the naive algorithm for global state read/write.

### 7 Proofs of Safety, Liveness, and Fairness

In this section, we provide a brief overview of the proofs detailed in the appendix for the safety, liveness, and fairness guarantees of Blockene.

A committee round $N$ ends when a new block gets signed and committed by a threshold number ($T^*$), of committee members for $N$. $T^*$ will be set to be 850 (done taking into account maximum number of bad citizens in any committee as well as the 36 good citizens who might have read/written an incorrect global state).

First, we show (in Lemma 10) that for a block, if a good Citizen is the winning proposer, then (except with bounded constant probability) all good Citizens will output the proposal of this Citizen as the output of the consensus protocol. In Lemma 11, we show that, on the contrary, if a malicious Citizen is the winning proposer and the consensus results in a non-null value, then all good Citizens will be able to download the transactions committed in the proposal. Using Lemmas 7 and 9 (see Proof Overview of § 6), we then show (Lemma 12) that at the end of the block commit protocol all,
except 36, good citizens will sign the same block hash and new global state root and that the new block is consistent with the entire blockchain and global state. Now, using Lemma 12, safety (i.e. all honest Citizens agree upon all committed blocks and all blocks are consistent with a correct sequence of transactions) follows via an inductive argument. Next, to argue liveness (that adversarial entities cannot indefinitely stall the system and that the empty-block probability is bounded by a small constant), we use Lemmas 12 and 10.

Additionally, we also prove bounds on throughput in Lemma 13 (in expectation, committed blocks have a threshold number of transactions in them) and fairness in Lemma 14 (all valid transactions will eventually be committed).

8 Implementation

We have built a prototype of Blockene, that is spread across two components, Citizen nodes and Politician nodes.

8.1 Citizen nodes

The Citizen node is implemented as an Android app on SDK v23 and has 10,200 lines of code. It is built to optimize battery use and runs as a background app, without user involvement after initial setup. The application caters to two main phases of the protocol that a Citizen participates in: passive and active. In the passive phase, a service using Job-Scheduler [9] periodically polls Politicians for getLedger calls. In the active phase, when the Citizen is part of a committee, the application runs the steps of the protocol, handling failures, timeouts and retries to deal with corrupt Politicians.

The implementation for the active phase uses a multi-threaded event-driven model and is built on top of EventBus to parallelize and pipeline network and compute intensive crypto tasks such as signature validation.

8.2 Politician nodes

The Politician node is implemented in C++ (11K lines of code). The implementation scales to load from thousands of Citizens, and handles bursty load during gossip. Given the state-machine nature of the protocol, we have built it on top of the convenient C-Actor-Framework [16], which is based on “actors” that transition the state of the Politician through the steps of the protocol. For instance, the BBA actor, apart from storing and serving the votes that Citizens submit, also reads the votes to determine the result of consensus. Based on this, it emits an event to build the updated Merkle tree.

For the global state, we have built a SparseMerkleTree (SMT), where the leaf index is deterministically computed using the SHA256 of the key. Since the tree is of bounded depth, we allow for (a small number of) collisions in the leaf node. The challenge path of any key includes all the collisions co-located with this key, so the leaf hash can be computed. To prevent targeted flooding of a single leaf node, we reject key additions that take a leaf node beyond a threshold, forcing the transaction originator to use a different key. We also implement a DeltaMerkleTree, which allows us to efficiently create an updated version of the SMT using memory proportional only to the touched keys.

Our gossip implementation does simple broadcast for regular messages, and runs a stateful protocol for tx_pool gossip. We segregate these messages into different ports/queues so the bursty gossip messages are isolated from small messages (e.g., BBA votes) that are broadcast. To prevent malicious Citizens from flooding an honest Politician with the responsibility of gossiping their writes, we limit the set of Politicians for a Citizen to be deterministic based on its VRF. Politicians do not gossip messages from non-conforming Citizens.

9 Evaluation

We evaluate our Blockene prototype under several dimensions. The main questions we answer in our evaluation are:

- What throughput and latency does Blockene provide?
- How well does Blockene handle malicious behaviors?
- Are the optimizations on Merkle tree & gossip useful?
- What is the load on Citizen nodes (battery/data usage)?

9.1 Experimental setup

In our experiments, we use a setup with 2000 Citizen nodes and 200 Politician nodes. Citizen nodes are 1-core VMs on Azure with a Xeon E5-2673, 2GB of RAM, and are spread across three geographic regions across WAN: 700 VMs in SouthCentralUS, 600 VMs in WestUS, and 700 VMs in EastUS. Each Citizen runs an Android 7.1 image, and is rate-limited to 1MB/s network upload and download. Politician nodes run on 8-core Azure VMs with a Xeon E5-2673, 32 GB of RAM, and are spread as 100 VMs each in EastUS and WestUS. They are rate limited to 40MB/s network bandwidth.

Given the random safe sampling, the Citizen-Politician communication spans across WAN regions. Similarly, the gossip between Politicians happens across WAN regions. As our committee size is 2000, every Citizen is in the committee for every block. With a higher number of Citizens, say 1 million, a particular Citizen will be in the committee only once every 500 blocks. Except the per-Citizen load, the system performance is independent of the total number of Citizens and is just a function of committee size, so the numbers are representative of a large setup.

9.2 Transaction Throughput and Latency

Figure 2 shows the timeline of block commits in Blockene under fully honest and malicious configurations, for 50 consecutive blocks. In the fully honest (0/0) case, 4.6 million transactions get committed in 4403 seconds, corresponding to a throughput of 1045 transactions per second, or 114 KB/s.
Table 2: Transaction throughput under malicious configs.

| Citizen dishonesty | Politician dishonesty |
|--------------------|-----------------------|
| 0%                 | 0% 1045 757 390       |
| 10%                | 969 675 339           |
| 25%                | 813 553 257           |

Figure 3: Transaction Latency under different malicious configs. Dots show 50th, 90th, 99th percentiles.

Figure 4 shows the network load at a typical Politician node during 10 blocks (each of the repetitive patterns is a block). The two large spikes in uploaded data correspond to rounds where this Politician was one of the 45 chosen to provide tx_pools. For each block, there are two small spikes of transmitted data; the first spike corresponds to gossip of tx_pools through prioritized gossip, and the second spike is due to gossip of votes from Citizens in the BBA consensus.

We also show the breakup of the 89-sec block latency by plotting the time taken in Citizen nodes during a typical block. Figure 5 shows the progress of the 2000 Citizen nodes during one of the blocks, separating out the key phases of the protocol; the bulk of the time goes in the transaction validation phase, and in fetching tx_pools from Politicians.
Table 3: Cost of gossip per honest Politician before all honest Politicians receive all tx_pools.

| Config | Percentile | Upload (MB) | Download (MB) | Time (sec) |
|--------|------------|-------------|---------------|------------|
| 0/0    | 50         | 23.1        | 22.4          | 3.6        |
| 0/0    | 90         | 30.5        | 27.5          | 4.8        |
| 0/0    | 99         | 36.7        | 30.1          | 5.2        |
| 80/25  | 50         | 35.4        | 23.8          | 3.5        |
| 80/25  | 90         | 47.6        | 27.6          | 4.1        |
| 80/25  | 99         | 53.4        | 28.9          | 4.5        |

9.4 Impact of Optimizations

We now evaluate the prioritized gossip and the sampling-based Merkle tree optimizations. For gossip, we consider how much upload/download each Politician incurs before all other honest Politicians get all the tx_pools. For example, in the 0/0 case, we have 10K data points (across 50 blocks and 200 Politicians each). Across these samples, we plot the 50th, 90th, and 99th percentiles. The malicious strategy we model in the 80/25 case is where only the bare minimum number of honest Citizens have tx_pools of malicious Politicians (Δ from § 5.5.2) and all malicious Politicians ask for the full set of tx_pools from all honest nodes. As Table 3 shows, the network load of prioritized gossip is robust to dishonest behavior. Even in the malicious setting, the data transmitted is quite small before all honest Politicians get all tx_pools.

Table 4 compares the performance of our sampling based Merkle-tree reads and updates, with the simple solution of downloading challenge paths for all keys referenced in the block. The simple solution incurs much higher network cost (the numbers are after gRPC compression), and a significant compute cost at the Citizen. With our optimization, the network cost drops by 10.8× while the CPU cost drops by nearly 31×, thus significantly improving transaction throughput.

9.5 Load on Citizens

Finally, we evaluate the load at Citizen nodes due to running Blockene. The two metrics of interest are battery usage and data usage. To get these metrics, we run an actual Android phone (a OnePlus 5) with the Citizen app, as part of the committee along with the 2000 committee members on VMs, and measure battery use. After being in the committee for 5 blocks, the battery drain was ~3%. The total network traffic incurred by a Citizen for a single block was 19.5 MB.

Now, we can extrapolate the daily cost based on the per-block cost and the number of times a single Citizen is expected to be in the committee. With 1 million Citizens, a Citizen will participate roughly every 500 blocks, which at our block latency of ~90s, translates to 2 times per day. Thus, the expected battery use is < 2% per day, and the data use is ~40MB/day. In addition, we also measured on the same OnePlus5 that waking up the phone every 10 minutes and performing getLedger costs about 0.9% battery and 21MB data download. Waking up every 5 minutes costs 1.7% battery and 42MB data download. With a total of 3% battery usage and 61MB data/day, a user running the Blockene app will hardly notice it running.

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References

[1] Aadhaar identity ecosystem. In https://uidai.gov.in/aadhaar-eco-system/authentication-ecosystem.html.

[2] AWS Shield: Managed DDoS Protection. In https://aws.amazon.com/shield/.

[3] Azure DDoS Protection. In https://azure.microsoft.com/en-in/services/ddos-protection/.

[4] Carrier-grade NAT: Wikipedia. In https://en.wikipedia.org/wiki/Carrier-grade_NAT.

[5] Ethereum blockchain. In https://www.ethereum.org/.

[6] Apple Platform Security: Secure Enclaves Overview. In https://support.apple.com/en-in/guide/security/sec59b0b31ff/web, 2017.

[7] Giving in Europe country reports available. In https://ernop.eu/giving-in-europe-launched-at-spring-of-philanthropy/, 2017.

[8] India Philanthropy Report 2017. In https://www.bain.com/insights/india-philanthropy-report-2017/, 2017.

[9] Android Docs: JobScheduler. In https://developer.android.com/reference/android/app/job/JobScheduler, 2018.

[10] Charitable Giving Statistics. Americans gave $410 billion to charities in 2017. In https://nonprofitssource.com/online-giving-statistics, 2018.

[11] Android Keystore System: Hardware Security module. In https://developer.android.com/training/articles/keystore#HardwareSecurityModule, 2019.

[12] Ronald Abraham, Elizabeth S Bennett, Noopur Sen, and Neil Buddy Shah. State of aadhaar report 2016-17. IDin-sight. Available at: http://stateofaadhaar.in, 2017.

[13] Elli Androulaki, Artem Barger, Vita Bortnikov, Christian Cachin, Konstantinos Christidis, Angelo De Caro, David Enyeart, Christopher Ferris, Gennady Laventman, Yacov Manevich, et al. Hyperledger fabric: a distributed operating system for permissioned blockchains. In Proceedings of the Thirteenth EuroSys Conference, page 30. ACM, 2018.

[14] Christian Badertscher, Peter Gazi, Aggelos Kiayias, Alexander Russell, and Vassilis Zikas. Ouroboros Genesis: Composable Proof-of-Stake Blockchains with Dynamic Availability. In Proceedings of the 2018 ACM SIGSAC Conference on Computer and Communications Security, CCS 2018, Toronto, ON, Canada, October 15-19, 2018, pages 913–930, 2018.

[15] Miguel Castro, Barbara Liskov, et al. Practical byzantine fault tolerance. In OSDI, volume 99, pages 173–186, 1999.

[16] Dominik Charrouset, Thomas C. Schmidt, Raphael Hiesgen, and Matthias Wählisch. Native Actors – A Scalable Software Platform for Distributed, Heterogeneous Environments. In Proc. of the 4rd ACM SIGPLAN Conference on Systems, Programming, and Applications (SPLASH ’13), Workshop AGERE!, pages 87–96. ACM, Oct. 2013.

[17] John R Douceur. The sybil attack. In International workshop on peer-to-peer systems, pages 251–260. Springer, 2002.

[18] Forbes. The cost of mobile internet around the world. In https://blogs-images.forbes.com/niallmccarthy/files/2019/03/20190305_Data_Cost.jpg, 2019.

[19] IOTA Foundation. Differences between the tangle and blockchain. In https://docs.iota.org/docs/getting-started/1.1/the-tangle/tangle-vs-blockchain.

[20] IOTA Foundation. Tangle: The coordinator. In https://docs.iota.org/docs/getting-started/1.1/the-tangle/the-coordinator.

[21] Yossi Gilad, Rotem Hemo, Silvio Micali, Georgios Vlachos, and Nickolai Zeldovich. Algorand: Scaling byzantine agreements for cryptocurrencies. In Proceedings of the 26th Symposium on Operating Systems Principles, SOSP ’17, pages 51–68, New York, NY, USA, 2017. ACM.

[22] Aggelos Kiayias, Alexander Russell, Bernardo David, and Roman Oliynykov. Ouroboros: A Provably Secure Proof-of-Stake Blockchain Protocol. In Advances in Cryptology - CRYPTO 2017 - 37th Annual International Cryptology Conference, Santa Barbara, CA, USA, August 20-24, 2017, Proceedings, Part I, pages 357–388, 2017.

[23] S King and S Nadal. Peercoin–secure & sustainable cryptocurrency. https://www.peercoin.net/whitepapers/peercoin-paper.pdf, 2012.
Silvio Micali, Michael O. Rabin, and Salil P. Vadhan. 
Gary Rong and Felix Lange. Light ethereum
Rafael Pass and Elaine Shi. Hybrid Consensus: Efficient
Satoshi Nakamoto. A peer-to-peer electronic cash sys-
Andrew Miller, Yu Xia, Kyle Croman, Elaine Shi, and
Michael Mitzenmacher and Eli Upfal. 
Eleftherios Kokoris-Kogias, Philipp Jovanovic, Nicolas 
Mark Russinovich, Edward Ashton, Christine Avanes-
sians, Miguel Castro, Amaury Chamayou, Sylvan Cleb-
sch, Manuel Costa, Cédric Fournet, Matthew Kerner, Sid Krishna, et al. Ccf: A framework for building confidential verifiable replicated services. Technical report, Technical Report MSR-TR-2019-16, Microsoft, 2019.

Asian Nakamoto. A peer-to-peer electronic cash system. In https://bitcoin.org/bitcoin.pdf, 2008.

Rafael Pass and Elaine Shi. Hybrid Consensus: Efficient Consensus in the Permissionless Model. In 31st International Symposium on Distributed Computing, DISC 2017, October 16-20, 2017, Vienna, Austria, pages 39:1–39:16, 2017.

Gary Rong and Felix Lange. Light ethereum sub-protocol (les). In https://github.com/ethereum/devp2p/blob/master/caps/les.md, 2019.

Mark Russinovich, Edward Ashton, Christine Avanes-
sians, Miguel Castro, Amaury Chamayou, Sylvan Cleb-
sch, Manuel Costa, Cédric Fournet, Matthew Kerner, Sid Krishna, et al. Ccf: A framework for building confidential verifiable replicated services. Technical report, Technical Report MSR-TR-2019-16, Microsoft, 2019.

Appendix

A Preliminaries

Notation. All notation that we use to describe our protocol and proofs are provided in Figure 6.

B Committee Selection

In our protocol, every citizen is in any particular committee with probability \( p = \frac{n}{N} \). This means that the expected size of every committee is \( n' \). As described in Section 5.2, our cryptographic sortition mechanism of selecting committee members for round \( N \) is performed by computing a VRF on the hash of the block at \( N - 10 \), concatenated with round number \( N \). Similar to Algorand [21], we require the public keys of the VRF of citizens to be added to the blockchain at least \( k \) (\( k = 40 \)) rounds before the round in which they are eligible to be in a committee (see Section 5.3). Additionally, since in our attack model, an adversary cannot change the set of corrupted citizens of round \( N \) after round \( N - 10 \) (see Section 4.2), it is easy to see (using a similar proof as Algorand [21]), that the adversary, has no information about whether an honest citizen will be in the committee at round \( N \) or not, when it chooses the citizens who will be corrupted at round \( N \). Hence, from the adversary’s perspective, every citizen is in the committee of round \( N \) with probability \( p \) (as defined above). We can now utilize this fact below in all our lemmas and proofs. Similarly, a committee member is also chosen to be a proposer with appropriate probability so that on average each round has \( nH \) number of block proposers (by the choice of our function to select proposers, this is hidden and uniformly random to an adversary until round \( N - 1 \)).

Lemma 1 proves a lower and an upper bound on the number of citizens in any committee sampled using above probability. Let \( \text{KL}(x,y) = x \ln \frac{x}{y} + (1 - x) \ln \frac{1-x}{1-y} \) be the Kullback-Leibler
1. Politicians
   - $S$: set of politicians.
   - $S$: Number of politicians; i.e., $|S| = S$.
   - $\gamma$: upper bound on fraction of corrupt politicians.

2. Citizens
   - $M$: Number of citizens.
   - $\alpha$: lower bound on fraction of honest citizens.

3. Committee
   - $n$: Number of citizens in a committee in a given round.
   - $n^*$: Lower bound on the number of citizens in a committee in any round.
   - $\tilde{n}$: Upper bound on the number of citizens in a committee in any round.
   - $n'$: Mean value of number of citizens in a committee in any round.
   - $n_H$: Number of block proposers in a committee in a given round.

4. Protocol Specific
   - $m$: Fan-out of read/write from citizens to politicians.
   - $\mathcal{K}$: Set of all keys that are part of the global state. $|\mathcal{K}| = k$.
   - $d$: Depth of the merkle tree used for global state, i.e., number of leaves in the tree is $2^d$.
   - $h$: Size of the hash function used in merkle tree in bytes.
   - $\theta$: All leaves in the Merkle tree will have $< \theta$ number of keys (except with tiny probability).

5. Parameters
   - Size of keys and values is 4 bytes.
   - Size of transaction UUID is 8 bytes.
   - $\kappa$: Security parameter for probabilistic events; when we say that a quantity is negligible in $\kappa$, we mean $2^{-\kappa}$ with $\kappa$ set to 30.

Figure 6: Notation
Lemma 1 (Bound on committee size). Let \( \varepsilon_c > 0 \). Then, except with probability \( p_c := \exp(-K(p-\varepsilon_c, p)M) \), \( n \geq n^* := M(p-\varepsilon_c). \) Similarly, except with probability \( p'_c := \exp(-K(p+\varepsilon_c, p)M) \), \( n \leq n := M(p+\varepsilon_c). \) In particular, with \( M = 2000 \), we can choose \( \varepsilon_c > 0 \) such that \( 1700 \leq n \leq 2300 \), except with probability \( 2^{-K} \).

Proof. This follows from standard Chernoff bounds.

For the second part, Lemma 1 shows that \( n \geq n^* \), except with probability \( p_c \). Combined with the first part, we conclude that \( n_g \geq (1-\gamma^m - \varepsilon_f)(\alpha - \varepsilon_g)n^* \), except with probability \( p_{tg} := \exp(-K(\alpha - \varepsilon_g, \alpha)n^*) + \exp(-K(\gamma^m + \varepsilon_f, \gamma^m)n^*) + p_c \). The second part now follows since \( n^* \leq 1700 \) for the probable range of \( n \) from Lemma 1 and we can choose small enough \( \varepsilon_f, \varepsilon_g > 0 \) to make \( p_{tg} \) negligible.

Lemma 3 (Lower bound on gap). Let \( \varepsilon_m > 0 \). Except with probability \( p_{gap} := \exp(-K(1-\alpha+\varepsilon_m, 1-\alpha)n) + 2p_{tg} \), gap \( \geq (\alpha(1-3\gamma^m - 3\varepsilon_f) + 2\alpha - 2 - \varepsilon_g - 2\varepsilon_m + \varepsilon_g)\) except with probability \( p_{fg} \). In particular, gap \( \geq 1 \), except with negligible probability.

Proof. Let \( n \) be the committee size. Now, from Lemma 2, we have that \( n_g \geq (1-\gamma^m - \varepsilon_f)(\alpha - \varepsilon_g)n \), except with probability \( p_{tg} \). Now, a citizen in the committee is bad if it is either malicious or if the citizen spoke only to malicious politicians through the read/write. Except with probability \( \exp(-K(1-\alpha+\varepsilon_m, 1-\alpha)n) \), the number of malicious politicians in the committee is \( \leq (1-\alpha+\varepsilon_m)n \). To additionally bound the number of citizens that speak only to malicious politicians through the fanout read/write, note that this value is \( \leq (\alpha + \varepsilon_g)(\gamma^m + \varepsilon_f)n \), except with probability \( \exp(-K(1-\alpha+\varepsilon_m, 1-\alpha)n) + \exp(-K(\gamma^m + \varepsilon_f, \gamma^m)n) \), which is \( \leq p_{fg} \). Hence, \( n_b \leq (1-\alpha+\varepsilon_m + (\alpha + \varepsilon_g)(\gamma^m + \varepsilon_f))n \), except with probability \( \exp(-K(1-\alpha+\varepsilon_m, 1-\alpha)n) + \exp(-K(\gamma^m + \varepsilon_f, \gamma^m)n) \). This gives us that gap \( = n_g - 2n_b \geq n_g - (1-\gamma^m - \varepsilon_f)(\alpha - \varepsilon_g) - 2(1-\alpha+\varepsilon_m + (\alpha + \varepsilon_g)(\gamma^m + \varepsilon_f))n = (\alpha(1-3\gamma^m - 3\varepsilon_f) + 2\alpha - 2 - \varepsilon_g - 2\varepsilon_m + \varepsilon_g)\) except with probability \( p_{gap} \). The lemma follows from Lemmas 1 and 2 and choosing a small enough \( \varepsilon_m > 0 \) to make \( p_{gap} \) negligible.

Corollary 1. Above lemma shows that gap increases monotonically with committee size \( n \). Moreover, for any committee size, since \( gap \geq 1 \), it holds that \( n_g > 2n/3 \) and \( n_b < n/3 \).

Lemma 4 (Upper bound on malicious citizens). Let \( n_b \) denote the maximum number of bad nodes in any committee. Then, except with negligible probability, \( n_b \leq 772 \).

Proof. In the proof of Lemma 3, we already saw that \( n_b \leq (1-\alpha+\varepsilon_m + (\alpha + \varepsilon_g)(\gamma^m + \varepsilon_f))n \), except with probability \( \exp(-K(1-\alpha+\varepsilon_m, 1-\alpha)n) + p_{fg} \). Lemma 1 shows us that \( n \leq 2300 \) for the probable range of committee size except with negligible probability. Combining these two estimates and choosing suitably small \( \varepsilon \)’s, we conclude the claimed upper bound on \( n_b \).

In Table 5 we show how the committee size varies with some candidate choice of corruption thresholds and size of random fan-out read/writes at the Politicians.
Corruption threshold of Citizens | Corruption threshold of Politicians | Mean Committee size
---|---|---
0.2 | 0.8 | 820
0.2 | 0.75 | 700
0.25 | 0.8 | 2000
0.25 | 0.75 | 1850
0.3 | 0.8 | 14000
0.3 | 0.75 | 12000

Table 5: Average Committee size with varying corruption thresholds; \( m = 25 \).

Sub Protocols

We now describe some building block protocols that we will use in our final blockchain protocol.

C Get Ledger Protocol

We will denote by \( tk \) the public key of the TEE of a citizen and by \( vk \) the signature verification key of the same citizen on the blockchain. The signature key pair is generated within the TEE and \( vk \)'s certification by \( tk \) is verified at the time the citizen is added to the blockchain with the \( \text{addNewNode} \) transaction.

In Blockene, we have a chain of blocks of transactions and an implicit chain of valid identities (public keys and certificates on them) and previous block's hashes. Denote by \( B_i \) the sub-block in \( B_i \) containing new citizen identities added in \( B_i \), \( \text{Hash}(B_{i-1}) \), and \( \text{Hash}(SB_{j-1}) \). Here, an identity is defined by a tuple \((tk, cert(tk), vk, cert(vk))\), where \( cert(k) \) is a suitable certificate for public/verification key \( k \). Also, a committee member of block \( B_i \) signs \((\text{Hash}(B_i), \text{GSRoot}, \text{Hash}(SB_i))\), where \( \text{GSRoot} \) is the root of global state Merkle tree after \( B_i \), and \( SB_i \) is the sub-block in \( B_i \) defined as above.

Most of our sub-protocols and main blockchain protocol assume that a good citizen can reliably learn the height of the blockchain and the set of all valid public keys on the blockchain at that height. Here, we describe a protocol \( \text{getLedger} \) that realizes this assumption.

Define

\[
\begin{align*}
\text{Id-PK}_i := \{(tk, vk, i) : \text{identity } (tk, vk) \text{ is added by } SB_i\}, \\
\text{GS-PK}_i := \text{Id-PK}_0 \cup \cdots \cup \text{Id-PK}_i, \\
\text{HC}_i := \{\text{Hash}(B_{i-9}), \ldots, \text{Hash}(B_{i-1})\}.
\end{align*}
\]

(1) (2) (3)

So, \( \text{GS-PK}_i \) is the set of all (TEE public key, verification key) pairs added to Blockene by the time \( B_i \) is committed, including the block number when the citizen with that pair is added and \( \text{HC}_i \) is the set of hashes of “skipped” blocks between successive calls to \( \text{getLedger} \) described below.

Our citizen nodes are stateful and maintain a local state of last verified height of blockchain and identities. If the last verified height of the blockchain by a citizen \( v \) is \( i \), then local state \( \text{LS}(v, i) \) of that citizen is defined as follows.

\[
\text{LS}(v, i) := (\text{Hash}(B_i), \text{GSRoot}, \text{Hash}(SB_i), \text{GS-PK}_i, \text{HC}_i).
\]

(4)

Committee Membership: As described in Section 5.2, an identity \((tk_j, vk_j) \in \text{GS-PK}_{i-10}\) is in committee for block \( B_i \) if \( \text{Sortition}(sk_j, \text{Hash}(B_{i-10}), i) \) outputs 1 and this can be verified without knowing \( sk_j \) given \( vk_j \).

We describe in Algorithm 1 below the \( \text{getLedger} \) protocol for verifying ledger height \( i + 10 \), given the verifier \( v \) has last verified height \( i \), without an explicit brute-force verification of signatures of all 10 blocks. The algorithm naturally generalizes to verifying any height \( i + j \) for \( 1 \leq j \leq 10 \). The jump of “10” here is due to the way we define the cryptographic sortition function to determine the committee membership.

Recall (Definition 1) that a good citizen is an honest committee member who talks to at least one honest politician.

The following lemma captures the correctness of \( \text{getLedger} \).

Lemma 5. Suppose \( v \) has the correct local state for height \( i \), i.e., \( \text{LS}(v, i) \) in (4) is consistent with the current blockchain up to height \( i \).

If \( v \) is a good citizen for round \((i + 11)\) and calls \( \text{getLedger} \) (Algorithm 1) with local state \( \text{LS}(v, i) \) and accepts, then \( v \)'s updated local state \( \text{LS}(v, i + 10) \) is consistent with the same blockchain up to height \( i + 10 \), except with negligible probability.

Proof. Note that \( v \) talks to at least one honest politician, say \( P \), who holds the correct copy of the blockchain up to height \( i + 10 \). We will argue that if \( v \) accepts, then, except with negligible probability, \( v \)'s view of the blockchain is consistent with that of \( P \)'s from height \( i \) to height \( i + 10 \), and hence, with the unique blockchain up to height \( i + 10 \) as maintained by \( P \). From Theorem 1 proved in Section E, except with negligible probability, there is a unique sequence of blocks \((B_{i+1}, \ldots, B_{i+10})\) and global state root \( \text{GSRoot}_{i+10} \) that extend the blockchain up to \( B_{i+10} \) and \( \text{GSRoot}_i \). Since \( \text{LS}(v, i) \) is correct and the committee for \( B_{i+10} \) is determined by height \( i \) prefix, in step (2), the committee that \( v \) evaluates signatures of and the committee that blessed \( B_{i+10} \) in
Algorithm 1 `getLedger` by a citizen node \( v \)

**Input:** Citizen \( v \) has verified ledger height \( i \) and stores local state \( LS(v, i) \) as in (4). Citizen \( v \) talks to a politician node claiming to have a correct copy of the blockchain up to block \( B_{i+10} \).

**Output:** Citizen \( v \) either rejects or accepts and updates local state to \( LS(v, i+10) \).

1. Download Hash\((B_{i+10})\), global state root GSRoot\(_{i+10}\), sub-block hash Hash\((SB_{i+10})\). T* block commit signatures (\( T^* = 850 \) as set in Section E.1), and membership proofs for these T* committee members for \( B_{i+10} \). By traversing the sub-blockchain, also download \( SB_{i+10}, \ldots, SB_{i+1} \).

2. For each of the \( T^* \) citizens \((tk, \text{vk})\) who signed the block commit signatures for \( B_{i+10} \), the verifier \( v \) checks that \((tk, \text{vk}) \in \text{GS-PK}_{i+10} \cdot 40 \). Given \( v \) has Hash\((B_{i})\) in its local state, committee membership proofs for \( B_{i+10} \) for each such \((tk, \text{vk})\) can be verified. Finally, signatures on \( \{\text{Hash}(B_{i+10}), \text{GSRoot}_{i+10}, \text{Hash}(SB_{i+10})\} \) can be validated for each of these committee members.

3. The verifier \( v \) checks that \( SB_{i+j} \) contains Hash\((SB_{i+j-1})\), for \( 10 \geq j \geq 1 \); note that \( v \)’s local state contains Hash\((SB_{i})\). Next, \( v \) extracts sets of \((tk, \text{vk})\) in Id-\text{PK}_{i+j} from \( SB_{i+j} \), for \( 1 \leq j \leq 10 \). Then, \( v \) checks certificates in all the tuples \((tk, \text{cert}(tk), \text{vk}, \text{cert}(\text{vk}))\) for \((tk, \text{vk})\) added in Id-\text{PK}_{i+1}, \ldots, Id-\text{PK}_{i+10} and accumulates them into \( \text{GS-PK}_{i+1}, \ldots, \text{GS-PK}_{i+10} \). Finally, it verifies that \( SB_{i+1} \) contains Hash\((B_{i})\) and also extracts Hash\((B_{i+j-1})\) from \( SB_{i+j} \) for \( 2 \leq j \leq 10 \). In particular, the verifier now has \( \text{GS-PK}_{i+10} \) and HC\(_{i+10} \).

4. If any of the checks in the above steps fails, \( v \) rejects. Otherwise, \( v \) accepts and updates the new local state to \( \text{LS}(v, i+10) = \{\text{Hash}(B_{i+10}), \text{GSRoot}_{i+10}, \text{Hash}(SB_{i+10}), \text{GS-PK}_{i+10}, \text{HC}_{i+10}\} \).

\[ P \]'s copy are identical. Hence, among all politicians, there is a unique tuple \((\text{Hash}(B_{i}), \text{GSRoot}_{i}, \text{Hash}(SB_{i}))\) in step (2) that would make \( v \) accept and this must be consistent with \( P \)'s copy of the blockchain and global state. As argued above, Theorem 1 implies that blocks \( B_{i+1}, \ldots, B_{i+10} \), and hence their sub-blocks, also must be unique. By collision resistance of hash functions, Hash\((B_{i+j})\) and Hash\((SB_{i+j})\) are also uniquely determined for \( 1 \leq j \leq 10 \). It follows that the sub-blocks \( SB_{i+j}, 1 \leq j \leq 10 \) that \( v \) downloaded in step (1) using the sub-block hash chain are correct; note that \( v \) checks \( SB_{i+10} \) with committee’s signatures on Hash\((SB_{i+10})\) and containment of Hash\((B_{i})\) in \( SB_{i+1} \). In particular, \( v \) obtains the correct values – according to \( P \)'s copy of the blockchain – for Hash\((B_{i+1})\), \ldots, Hash\((B_{i+10})\) and the identity tuples \((tk, \text{cert}(tk), \text{vk}, \text{cert}(\text{vk}))\) added in these sub-blocks. Finally, in step (3), \( v \) would validate the same identity certificates as the respective committees would have verified before adding them to these sub-blocks. Hence, if \( v \) accepts, it would correctly compute \( \text{Id-PK}_{i+j}, \text{GS-PK}_{i+j}, \) and \( \text{HC}_{i+j} \) for \( 1 \leq j \leq 10 \).

An easy inductive argument proves the following corollary.

**Corollary 2.** Let \( v \) be a good citizen for \( B_{i+1} \) for \( i \geq 40 \). Then, except with negligible probability, \( v \) can acquire the correct local state \( \text{LS}(v, i) \) for ledger height \( i \) as in (4). In particular,

(i) \( v \) obtains the correct global state root \( \text{GSRoot}_{i} \), and

(ii) \( v \) downloads \( \text{GS-PK}_{i} \) into its local state, i.e., knows all the valid citizen identities \((tk, \text{vk})\) registered up to \( B_{i} \).

**Communication cost of getLedger:** The verifier \( v \) downloads the following from a politician. 850 signatures of 64-bytes each on the triple \((\text{Hash}(B_{i}), \text{GSRoot}_{i}, \text{Hash}(SB_{i}))\) (less than 0.1KB) and for each of the 850 committee members that signed, we need their verification keys, VRF values, and VRF proofs. This gives a total of about 136 KB. In addition, \( v \) also downloads 10 subblocks and the id’s and hashes in them. For concreteness, we assume each block allows one identity to be added. An identity \((tk, \text{cert}(tk), \text{vk}, \text{cert}(\text{vk}))\) along with the certificates is about 3.5KB. Hence a subblock \( SB_{j} \) with its id’s, Hash\((B_{j-1})\), and Hash\((SB_{j-1})\) is about 3.6KB. Hence, the 10 sub-blocks cost about 36KB. So, from each politician, \( v \) downloads a total of about 172KB. Since a politician is blacklistable if the verification fails, in the most common case, \( v \) needs to download only from one politician making getLedger’s download cost is less than 0.18MB in the common case. Since a citizen makes about 150 calls to getLedger in a day, the total download cost for a citizen node is roughly 27MB per day.

## D Merkle tree of Global State

All the politicians maintain the up-to-date global state in the form of a Merkle tree whose root is signed by the committee in each round. The depth of this tree is \( d = 30 \). Keys are mapped to random leaves and we assume that at most \( \theta = 10 \) keys can get mapped to a single leaf. In this section, we describe formally our optimized protocols for global state read and update by the light-weight citizens for the keys referenced in a tentative block of transactions. In our overall
protocol (as described in Appendix E), these steps are executed after the completion of the consensus protocol. Hence, as proved formally in Appendix E.2, we can safely assume that all good citizens as well as politician nodes have access to the transaction pools referred by the output of the consensus. This ensures that both the citizens and the politicians know the keys that are being referenced in the proposed block. First, we describe our protocol for global state read that is used by citizen nodes to learn the correct values corresponding to these keys. Next, the citizen will apply relevant transactions on these key-values to obtain updated values for each of these keys. Finally, we describe our protocol for global state update that is used by citizens to obtain the merkle root of the tree that has updated values of each of these keys. For both of our protocols we prove that all good citizens except 36 will learn the correct values during global state read and correct new global state Merkle root in global state update except with negligible probability. We use this to define effective good citizens that would sign the correct block.

**D.1 Sampling based Merkle Tree Read**

Here, we describe a protocol to realize the following task. A citizen and politicians hold a set of keys \( \mathcal{K} \) and the citizen wants to read the corresponding values from the global state. Let \( k = |\mathcal{K}| \). We describe our optimized protocol for reading values from global state in Algorithm 2.

At a high level, as described in § 6.2, citizen first does a spot-check on small number of keys by downloading the complete challenge paths and then corrects the incorrect key-values by cross validating across \( m \) politicians.

First, we prove that for a good citizen, after successfully spot-checking only \( \mu \) fraction of key-values in Steps 4, 5, 6 only (a small number of) \( \tau \) values are incorrect with probability \( 1 - \epsilon_1 \) (here, \( \epsilon_1 \) is a function of \( \mu \) and \( \tau \)). Moreover, these values will get corrected by processing exception lists of size at most \( \tau \) in Steps 8, 10, 11, 12. Hence, a good citizen gets correct values with probability \( 1 - \epsilon_1 \). More formally,

**Lemma 6.** For an honest citizen, if verification in step 6 succeeds, then at most \( \tau \) values can be incorrect in Step 4, except with probability at most \( \epsilon_1 = e^{-\mu \tau} \).

**Proof.** The lemma follows from a standard probability argument. Let \( \epsilon > \tau \) values be incorrect in Step 4. Then the probability with which an honest citizen does not pick an incorrect value for verification is at most \( (1 - \frac{\epsilon}{\tau})^{\mu \tau} \leq e^{-\mu \tau} \), for \( \epsilon > \tau \).

**Corollary 3** (Upper bound on failure probability of Global State Read). A good citizen learns the correct values for all keys \( \mathcal{K} \), except with probability at most \( \epsilon_1 \).

**Proof.** It follows from the above lemma and the fact that for a good citizen at least one of \( S_1, \ldots, S_m \) is honest. This honest politician node would provide the correct exception list that is used by citizen node to correct the incorrect values received in Step 4.

Next, we upper bound the number of good citizens that can be fooled into accepting incorrect values.

**Lemma 7** (Upper bound on number of good citizens fooled in Global State Read). Let \( n_c \) denote the number of good citizens that have at least one incorrect key-value pair at the end of Algorithm 2. Then, for \( n_c \leq 2300 \) and \( \epsilon_1 \leq 2^{-10} \), \( n_c < 18 \), except with negligible probability.

**Proof.** Let \( E_c \) denote the event where a good citizen \( v \) has incorrect key-value pairs at the end of Algorithm 2. From Corollary 3, we have probability of \( E_c \) is upper bounded by \( \epsilon_1 \). Hence, the probability with which \( E_c \) occurs for at least 18 citizens is upper bounded by \( (\frac{n}{18})^{18} \times 1 \), which is \( < 2^{-18} \) using \( n \leq 2300 \) and \( \epsilon_1 \leq 2^{-10} \).

**Total Communication.** We calculate concrete communication of our protocol in our setting. For our setting, \( k \leq 300,000 \), \( d = 30 \), \( m = 25 \), \( \theta = 10 \), \( h = 10 \). We need \( \mu \tau > 7 \) to achieve \( \epsilon_1 \leq 2^{-10} \). Recall the major upload and download cost in the above protocol.

- Upload: \( B \cdot h \cdot m \) (Step 8).
- Download: \( \mu \cdot k \cdot (h \cdot d + \theta \cdot 8) \) (Step 5) + \( \tau \cdot (k/B) \cdot 4 \cdot m \) (Step 11) + \( (\epsilon + m) \cdot (h \cdot d + \theta \cdot 8) \) (Step 12).

We set \( \mu = 0.015 \) (i.e., \( k' = 4500 \)), \( \tau = 500 \), and \( B = 2000 \). This gives us upload of 0.5MB and download of 1.71MB (in Step 5), 7.5MB (in Step 11) and 0.19MB (in Step 12).

**D.2 Sampling based Merkle Tree Write**

In our protocol, the Politicians will compute the updated Merkle tree \( T' \). Naturally, they cannot be trusted to do this computation correctly - so we construct a protocol that will enable Citizens to verify the correctness of the updated Merkle tree without downloading all challenge paths. The high level idea is as follows. Let the original tree be \( T \) and the updated tree be \( T' \). We break \( T' \) at a level, say \( a \), that has \( 2^a \) nodes. We call this level the frontier level and the nodes at this level as frontier nodes. Now Citizens will obtain the values of the frontier nodes of \( T' \) from a random subset of the Politicians. The Citizens then run a spot checking algorithm - they pick a random subset of frontier nodes and ask a Politician to prove the correctness of that frontier node. The Politician does this by showing the challenge paths (up to the frontier node) in \( T' \) for all leaves that have changed and the challenge paths in \( T \) for all (potentially internal) nodes that havent changed. Next, Citizens create exception lists with the help of a random subset of Politicians. This list denotes which frontier nodes are incorrect with the Citizens. The Citizens then proceed to sequentially correct the incorrect frontier nodes and then
Algorithm 2 Global State Read by a citizen node

Input: The citizen has the correct root of the Merkle tree corresponding to the global state (using our Get Ledger protocol in Appendix C). Citizen and politicians hold a set of keys $\subset K$. Let $k = |\text{keys}|$.

Output: Citizen outputs values corresponding to all keys in $\text{keys}$.

1. (If not already picked) Pick a subset $S = (S_1, \ldots, S_m) \subset S$ at random.
2. Ask for values from $S_1$.
3. Receive a signed ordered list of $k$ values from $S_1$. (Comm. cost: Download $k \cdot 4$ bytes.)
4. Pick a random subset $\text{keys}' \subset \text{keys}$ of size $k' = \mu \cdot k$ for appropriate $\mu < 1$ and send to $S_1$. (Comm. cost: Upload $\mu \cdot k \cdot 4$ bytes.)
5. Receive signed list of $k'$ challenge sibling paths in the merkle tree corresponding to keys in $\text{keys}'$ from $S_1$. (Comm. cost: Download $\mu \cdot k \cdot (h \cdot d + \theta \cdot 8)$ bytes.)
6. Verify all the challenge sibling paths against the root of merkle tree. If verification of one of the paths fails, then it can be used as a witness to blacklist $S_1$.
7. Citizens as well as the politicians $(S_1, \ldots, S_m)$ deterministically arrange keys into $B$ buckets and compute hash of keys and values in each bucket. Each bucket would contain $k/B$ keys. Let us denote these hashes computed by the citizen as $(hv_1, \ldots, hv_B)$.
8. Upload $(hv_1, \ldots, hv_B)$ to $(S_1, \ldots, S_m)$. (Comm. cost: Upload $B \cdot h \cdot m$ bytes.)
9. A politician $S_i$ checks these hash values against its locally computed list. It creates a list of indices for which these don’t match. We call this the exception list $E_i$.
10. Citizen receives exception lists from all politicians. Let $\tau$ be a parameter fixed later such that it is guaranteed that at most $\tau$ values can be incorrect in Step 3 with probability at least $1 - \varepsilon_1$. An exception list is considered valid if it is of size at most $\tau$. (Comm. cost: Download tiny.)
11. If exception list $E_i$ is valid, ask $S_i$ for values for all the keys in bucket whose index is in $E_i$ and receive the same. (Comm. cost: Download $\tau \cdot (k/B) \cdot 4 \cdot m$ bytes.)
12. Now, process these claimed incorrect buckets sequentially as follows: Pick a key for which value from Step 3 does not match the claimed value in Step 11, ask the corresponding politician for the signed challenge path to the root. Continue till the citizen corrects $\tau$ keys or exhausts all unmatched values. Moreover, if a politician provides an incorrect challenge path, consider that politician as malicious and move to the list of the next politician. (Comm. cost: Download $(\tau + m) \cdot (h \cdot d + \theta \cdot 8)$ bytes.)
D.3 Savings from optimized global state protocols

First, we compare the communication cost of our optimized global state read/write w.r.t. naive protocol that downloads the challenge paths in the Merkle tree for all relevant keys, computes partial Merkle tree with new updated values to create the new root. We note that if a politician note lies in either GSRead protocol (Algorithm 2) or GSUpdate protocol (Algorithm 3), it is a detectable offence, i.e., there is a short proof that can be used to consistently blacklist the politician node for all honest politicians as well as honest committee members of this round. Hence, the committee can additionally sign the blacklisting of this malicious politician. With this observation, we compare our costs with the naive solution in both best case (that is all politicians behave honestly) and worst case (there exists a politician that lies either in spot check or exception list phase).

The communication cost of naive GSRead/GSUpdate is downloading 300,000 challenge paths in a Merkle tree with 2^30 leaves of size at most 10 bytes. This amounts to 108MB (modulo compression). In contrast, communication cost of our GSRead/Write in best case (with no exceptions) is 5.9MB and in worst case is 32MB (for citizens that are not fooled, i.e., all except 36 citizens). Hence, we are at least 18× better in best case and 3× better in worst case. Note that in the worst case, at least one malicious politician gets blacklisted.

Next, we compare the number of hash evaluations of both solutions. Verifying a challenge path requires computing 30 hashes. Hence, for both read and update, naive solution requires 300,000 · 30 · 2 = 18 million hashes to be computed. Our optimized protocol for read checks 4500 and 5025 challenge paths in a Merkle tree with 2^18 leaves of size at most 10 bytes. This amounts to 3000 hashes in best case and 3200 hashes in worst case. Verifying a challenge path requires computing 30 hashes. Hence, for both read and update, naive solution requires 300,000 · 30 · 2 = 18 million hashes to be computed. Our optimized protocol for read checks 4500 and 5025 challenge paths in a Merkle tree with 2^18 leaves of size at most 10 bytes. This amounts to 3000 hashes in best case and 3200 hashes in worst case.

Our optimized protocol for global state update computes 2d · a hashes per key that has changed under a frontier node. Once it learns the correct value of all frontier nodes, it computes 2^d hashes to compute the root. We check 2637 keys in best case (123,925 hashes) and 32,849 keys (1.5 million hashes) in worst case. Global state update additionally needs 8192 hashes to compute the root from the correct frontier nodes. In total over both global state read and update, using our optimized protocols, we need 269,117 hashes in best case and 1.7 million hashes in worst case. Hence, we are 66× and 10× better in best and worst case, respectively.

E Committing blocks

E.1 Protocol Description

In this section, we describe our protocol to commit new blocks to the blockchain. This protocol builds on the sub-protocols described in the previous section and a Byzan-
Algorithm 3 Global State Update by a citizen

**Input:** The citizen has the correct root of the Merkle tree corresponding to the global state. Citizen and politicians hold set of keys $\mathcal{K}$ (as well as their corresponding new values) that have to be updated. Let $k = |\mathcal{K}|$.

**Output:** If a good citizen accepts then with probability at least $1 - \epsilon$, new Merkle root is correct for that citizen (for a constant $\epsilon$ to be specified later.)

1. All politicians use the new key-value pairs to construct the new merkle tree. Let us denote the old tree by $T$ (that is authenticated by threshold number of citizens from previous committee) and the new tree by $T'$.
2. Citizen picks a subset $S = (S_1, \ldots, S_m) \subset S$ at random (if not already picked) and queries $S_1$ for frontier node values in new tree $T'$.
3. Citizen receives signed frontier node values in $T'$. Denote this set by $F$. (Comm. cost: Download $2^a \cdot h$ bytes.)
4. Now the citizen runs the following spot-checking algorithm for the frontier node values.
   - (a) Pick a random subset $F' \subset F$ of size $c$ and send to $S_1$. We will fix $c$ later. (Comm. cost: Upload $2^a - 3$ bytes, tiny.)
   - (b) For each $f \in F'$, $S_1$ computes the following: 1) for all the keys that have changed in the subtree rooted at $f$ it computes their challenge sibling path from leaf to $f$. 2) For all the internal nodes that are part of some challenge sibling path and are unchanged in $T$ and $T'$, it computes the challenge path for this (potentially internal) node in the tree $T$. It sends all this data signed to the citizen. Note that challenge paths for all the unchanged siblings are perfectly overlapping and can be sent together. (Comm. cost: Download $\frac{k_c \cdot \epsilon}{2^r} \cdot ((d - a) \cdot h + \theta \cdot 8) + \frac{k_c \cdot \epsilon}{2^r} \cdot (h \cdot d + \theta \cdot 8)$ bytes.)
   - (c) Note that the citizen knows the keys that have changed as well as their location in global state merkle tree. Hence, it knows all the challenge paths that need to be provided in $T'$ and $T$. After receiving all these challenge paths, it runs the appropriate verification procedure. If some verification fails, then it can be used as a witness to blacklist $S_1$.
5. Next, the citizen runs the following steps to learn exception list of incorrect frontier nodes and proofs to correct them. Let $\tau$ be a parameter to be fixed later such that the citizen would try to correct at most $\tau$ frontier nodes.
   - (a) Download the signed frontier nodes from remaining politicians $(S_2, \ldots, S_m)$. (Comm. cost: Download $2^a \cdot h \cdot (m - 1)$ bytes.)
   - (b) Based on information obtained above, the citizen would create an exception list $E_i$ corresponding to each politician $S_i$. Discard a politician if the exception list is longer than $\tau$.
   - (c) Now similar to spot-checking step above, the citizen sequentially verifies sub-trees under $\tau$ frontier nodes in the cumulative exception lists. If data provided by a politician does not verify, declare that politician as malicious. Hence, the citizen downloads data corresponding to at most $c' = \tau + m$ subtrees. (Comm. cost: Download: $\frac{k_c \cdot \epsilon'}{2^r} \cdot ((d - a) \cdot h + \theta \cdot 8 + h \cdot d + \theta \cdot 8)$ bytes.)
6. Finally, the citizen computes the root of the new merkle tree $T'$ using final frontier node values.

†This can be ensured using the signatures on the root by the previous committee. We will include the communication required to realize this in the main protocol.
tine agreement or consensus protocol for strings [21, 26, 35].

Define a committee round \( N \) to start when the first honest
citizen that is a member of that committee downloads the
Merkle root of global state corresponding to committee round
\( N - 1 \). The committee round \( N \) ends when a new block gets
signed and committed by a threshold number, say \( T^* \), of
committee members for \( N \). We will fix \( T^* \) later such that
\( \n_b + 36 < T^* \leq n^*_b - 36 \) (because 36 good citizens can be
fooled during global state read/write, Appendix D). Here,
recall that \( \n_b \leq 772 \) is the upper bound on malicious citi-
zens (Lemma 4) and \( n^*_g \geq 1137 \) is minimum number of good
citizens in any committee (Lemma 2). In particular, we set
\( T^* = 850 \). We present our the protocol for committing a block
number \( N \) formally in Algorithm 4. This builds on the intu-
itive protocol description in \S 5.6 and uses our optimized
protocol separately for the case when the winning proposer is
an empty block. An empty block could be committed in one of
the following cases: a) The proposer was a malicious citizen;
b) The proposer was a good citizen, but all good citizens did
not start the consensus protocol with the proposal of the win-
er (the exception case of Lemma 10). The former happens
with probability at most \( \frac{1}{3} \) because in any committee \( \n_b < n/3 \).
And, the latter probability is bounded by 0.017 as shown in
Lemma 10. Hence the lemma follows.

We also prove bounds on throughput Lemma 13 and fair-
ness Lemma 14. First, we prove lemmas needed to prove safety and liveness.

**Theorem 2 (informal, Liveness).** An adversary colluding
with malicious politicians and citizens cannot indefinitely
stall the system. Moreover, in any block-commit round, the
probability that an empty block is committed is at most
\( \frac{1}{3} + 0.017 < 0.35 \).

**Proof.** From the safety property, it is clear that at the begin-
ing of a round, all good citizens have a consistent view of
the blockchain and global state. Next, from the design of
the block-commit protocol, it is easy to see that since all
good citizens talk to at least one honest politician, they will
make progress and enter the consensus protocol. Moreover,
Lemma 12 shows that in all cases, at the end of a round, a
block consistent with the existing blockchain will be signed
by all good citizens (except at most 36). This meets the thresh-
old of block commitment, i.e., \( T^* = 850 \). Hence, an adver-
sary cannot stall the system indefinitely. Next, to argue live-
ness/progress, we need to prove that not all blocks can be
empty blocks. An empty block could be committed in one of
the following cases: a) The proposer was a malicious citizen;
b) The proposer was a good citizen, but all good citizens did
not start the consensus protocol with the proposal of the win-
er (the exception case of Lemma 10). The former happens
with probability at most \( \frac{1}{3} \) because in any committee \( \n_b < n/3 \).
And, the latter probability is bounded by 0.017 as shown in
Lemma 10. Hence the lemma follows.

We prove the following theorems about our protocol above.
All statements below hold except with negligible probability.
Let the number of proposers in the committee be \( n_H \).

**Theorem 1 (informal, Safety).** After block \( N \) gets committed,
the blockchain, agreed upon by all honest citizens and politi-
cians consists of a sequence of blocks and a authenticated
global state s.t. the following holds.

1. This sequence of blocks \( B_1, \ldots, B_N \) forms a ledger with
   a sequence of correct transactions.

2. Committed global state, say GSRoot\(_N\), contains the cor-
   rect values for all the keys.

**Proof.** Note that for a block to be valid, its hash needs to
be signed by \( T^* \) number of committee members. Lemma
12 shows that at the end of each round a block and global
state consistent with existing blockchain is signed by all good
citizens except 36. First, note that \( n_g - 36 \geq 1101 > T^* = 850 \)
meets the threshold needed for committed a block. Moreover,
Algorithm 4 Block Commit

**Input:** Committee members for block $N$ hold the authenticated GSRoot$_{N-1}$ and Hash($B_{N-1}$) signed by the corresponding committee. Let $V = v_1, \ldots, v_n$ be the committee for block $N$ with $V \supseteq U = u_1, \ldots, u_m$ as the proposers. Let $T_1, \ldots, T_b$ be the politicians that would provide the transactions in $N$.

**Output:** $T^*$ number of citizens of block $N$ will sign and “commit” a block (also containing Hash($B_{N-1}$)) along with the updated root of the global state at the end of the protocol.

1. Download transaction pools and upload witness lists: Every committee members $v \in V$ does the following:
   (a) For all $i \in [\rho]$ download a signed $tx\_pool$ (of appropriate size) $(\text{mem}_i, \sigma_i)$ from $T_v$, where $\sigma_i$ is the signature on $(\text{Hash}(\text{mem}_i), \text{Rnd})$ by $T_v$.
   (b) Pick a random subset $S(v) \subset S$ of size $m$ for the rest of the protocol. (The committee member talks to the same politicians for the whole protocol).
   (c) Create a witness list $\text{WL}_v$ of length $\rho$ as follows: $\text{WL}_v[i] = (\text{Hash}(\text{mem}_i), \sigma_i)$ if it has $i^{th}$ $tx\_pool$, and $\text{WL}_v[i] = \bot$ otherwise. We call $(\text{Hash}(\text{mem}_i), \sigma_i)$ a commitment.
   (d) It uploads $(\text{WL}_v, \sigma_v, \text{VRF}_v)$ to all $S(v)$, where $\sigma_v$ is signature on $\text{Hash(\text{WL}_v)}$ by citizen $v$.

2. Politicians gossip on these signed witness lists and VRFs using full broadcast. Within these witness lists, if a politician finds two different valid commitments by another politician, it constitutes a proof of malicious behavior by that politician that can be used to blacklist the malicious politician.

3. Block Proposal by proposers and upload of transaction pools by citizens: A proposer $u \in U$ does the following:
   (a) Downloads signed witness lists and VRFs of all committee members from $S(u)$.
   (b) Picks commitments that are non-null in witness lists of at least $n_b + \Delta$ committee members. Denote these by $((\text{Hash}(\text{mem}_{j_1}), \sigma_{j_1}), \ldots, (\text{Hash}(\text{mem}_{j_p}), \sigma_{j_p}))$.
   (c) Upload the following to $S(u)$: i) $\text{VRF}_u$ (a proof that it is a proposer for this round) ii) $\text{IDList}_u = ((\text{Hash}(\text{mem}_{j_1}), \sigma_{j_1}), \ldots, (\text{Hash}(\text{mem}_{j_p}), \sigma_{j_p}))$ iii) Signature on $\text{Hash(\text{IDList}_u)}$. We denote these by $\text{Proposal}_u$.

   In parallel, every committee member $v$ picks 5 indices $i_1, i_2, i_3, i_4, i_5 \in [\rho]$ at random s.t. for all $j \in [5]$, $\text{WL}_v[i_j] \neq \bot$ and uploads all $(\text{mem}_{j_1}, \sigma_{j_1})$ to a random politician.

4. Politicians sync on the block proposals, i.e., $\{\text{Proposal}_u\}_{u \in U}$ using full broadcast and sync on $tx\_pools$ uploaded by last step using our prioritized gossip protocol (see § 6.1).

5. Compute winner of block proposal and initial value in consensus. Every committee members $v \in V$ does the following:
   (a) Download block proposals, i.e., $\{\text{Proposal}_u\}_{u \in U}$ from $S(v)$. Winner $\text{win}(v)$ is the one with least value of $\text{VRF}_u$.
   (b) Try downloading $tx\_pools$ that are missing after Step 1a from $S(v)$. If successful in downloading all $tx\_pools$ committed in $\text{IDList}_{\text{win}(v)}$, set the initial value for consensus protocol $\text{initial}_v = \text{Proposal}_{\text{win}(v)}$, else set $\text{initial}_v = \text{NULL}$.

6. Consensus and second round of upload-download of $tx\_pools$
   (a) Committee members run the consensus protocol [21, 26, 35], where committee member $v$ enters consensus with value $\text{initial}_v$, to reach consensus on value out.
   (b) In parallel, every committee member $v$ picks 10 out of $\rho$ $tx\_pools$ it has at random and uploads them to a random politician.
   (c) Politicians sync on the $tx\_pools$ uploads using our protocol for prioritized gossip.
   (d) Committee members try downloading the $tx\_pools$ that are still missing after Step 5b.

Contd....
When we set $\Delta$

Applying a union bound over all $\rho$
The lemma then follows from the correctness of the consensus †

bility that a $\rho$

izens started the consensus with that initial value and had $\left\lceil \frac{\gamma}{5} \rho \right\rceil$

Proof.

By Property 1, we know that if the consensus results in non-null, then at least $\left\lceil \frac{n-1}{3} \right\rceil$ number of good citizens started the consensus with that initial value and had all the required $tx_pools$. With this, for step 6b, the probability that a $tx_pool$ is not re-uploaded by any good citizen to an honest politician is bounded by $\left( \frac{\rho - 10}{\rho} + 10 \gamma \right)^{(n-1)/3}$ and the probability that there exists such a $tx_pool$ among the all of $\rho$ $tx_pools$ is bounded by $\rho \left( \frac{\rho - 10}{\rho} + 10 \gamma \right)^{(n-1)/3}$.

Since $n \geq 1700$, we have $\left\lceil \frac{(n-1)}{3} \right\rceil \geq 566$, and hence, for $\rho = 45$ we have that this probability is negligible. Once the politicians gossip the $tx_pools$, all honest politicians will have the $tx_pools$ and hence, every good citizen can download all $tx_pools$ in step 6d of Algorithm 4.

Lemma 12 (Block Consensus). Except with negligible prob-

ability, (i) at the end of the block commit protocol, all good citizens except 36 sign the same block hash and new global state root and (ii) moreover, this block is consistent with the entire block chain and global state.

Proof. We consider the following two cases:

- (Good citizen is winner of block proposal): From Lemma 10, all good citizens hold all the required $tx_pools$ and agree on honest proposer’s block except with probability 0.017. When this happens, all good citizens and honest politicians construct the same block. Moreover, by Lemma 7 and Lemma 9, we know that at least $n_g - 36 \geq 1101$ good citizens are able to do global state read/write operations correctly and compute correct new global state root. Finally, good citizens follow a deterministic procedure to create a valid block. Hence, all good citizens except 36 will sign the same block hash and new global state root.

With probability 0.017, all good citizens do not enter the consensus with proposer’s block. This case is identical to an honest politician is bounded by $\left( \frac{\rho - 10}{\rho} + 10 \gamma \right)^{(n-1)/3}$ and the probability that there exists such a $tx_pool$ among the all of $\rho$ $tx_pools$ is bounded by $\rho \left( \frac{\rho - 10}{\rho} + 10 \gamma \right)^{(n-1)/3}$.

Since $n \geq 1700$, we have $\left\lceil \frac{(n-1)}{3} \right\rceil \geq 566$, and hence, for $\rho = 45$ we have that this probability is negligible. Once the politicians gossip the $tx_pools$, all honest politicians will have the $tx_pools$ and hence, every good citizen can download all $tx_pools$ in step 6d of Algorithm 4.

Lemma 11 (Malicious Proposer). If a malicious citizen is

the winning proposer, and consensus results in non-null, then all good citizens will be able to download the $tx_pools$ committed in the proposal, except with negligible probability.

Proof. By Property 1, we know that if the consensus results in non-null, then at least $\left\lceil \frac{(n-1)}{3} \right\rceil$ number of good citizens started the consensus with that initial value and had all the required $tx_pools$. With this, for step 6b, the probability that a $tx_pool$ is not re-uploaded by any good citizen to an honest politician is bounded by $\left( \frac{\rho - 10}{\rho} + 10 \gamma \right)^{(n-1)/3}$ and the probability that there exists such a $tx_pool$ among the all of $\rho$ $tx_pools$ is bounded by $\rho \left( \frac{\rho - 10}{\rho} + 10 \gamma \right)^{(n-1)/3}$.

Since $n \geq 1700$, we have $\left\lceil \frac{(n-1)}{3} \right\rceil \geq 566$, and hence, for $\rho = 45$ we have that this probability is negligible. Once the politicians gossip the $tx_pools$, all honest politicians will have the $tx_pools$ and hence, every good citizen can download all $tx_pools$ in step 6d of Algorithm 4.

Lemma 10 (Honest Good Proposer). If a good citizen is

the winning proposer, then, except with probability 0.017, all good citizens will enter the consensus protocol with the proposal of the winner and output the proposal of the winner as output of the consensus protocol.

Proof. In the case of a proposer who is a good citizen, since any $tx_pool$ is picked in the proposal iff it is present in the witness lists of $n_b + \Delta$ citizens, it is definitely the case that at least $\Delta$ good citizens have this $tx_pool$ after Step 1a. Now, in Step 3, the probability that $tx_pool$ is not re-uploaded by any good citizen to any honest politician is bounded by $\left( \frac{\rho - 5}{\rho} + \frac{10 \gamma}{\rho} \right)^{\Delta}$.

Applying a union bound over all $\rho$ $tx_pools$, the probability that there exists such a $tx_pool$ is bounded by $\rho \left( \frac{\rho - 5}{\rho} + \frac{10 \gamma}{\rho} \right)^{\Delta}$.

When we set $\Delta = 350$, and $\rho = 45$, this probability is $\leq 0.017$.

Now, from the correctness of our prioritized gossip protocol, it follows that if a $tx_pool$ is uploaded by a good citizen, it is learnt by all honest politicians and hence, by all good citizens during the download in step 5b of Algorithm 4. Hence, all good citizens will enter consensus with this proposed block. The lemma then follows from the correctness of the consensus algorithm.

\[\square\]

Lemma 11 (Malicious Proposer). If a malicious citizen is

the winning proposer, and consensus results in non-null, then all good citizens will be able to download the $tx_pools$ committed in the proposal, except with negligible probability.

Proof. By Property 1, we know that if the consensus results in non-null, then at least $\left\lceil \frac{(n-1)}{3} \right\rceil$ number of good citizens started the consensus with that initial value and had all the required $tx_pools$. With this, for step 6b, the probability that a $tx_pool$ is not re-uploaded by any good citizen to an honest politician is bounded by $\left( \frac{\rho - 10}{\rho} + 10 \gamma \right)^{(n-1)/3}$ and the probability that there exists such a $tx_pool$ among the all of $\rho$ $tx_pools$ is bounded by $\rho \left( \frac{\rho - 10}{\rho} + 10 \gamma \right)^{(n-1)/3}$.

Since $n \geq 1700$, we have $\left\lceil \frac{(n-1)}{3} \right\rceil \geq 566$, and hence, for $\rho = 45$ we have that this probability is negligible. Once the politicians gossip the $tx_pools$, all honest politicians will have the $tx_pools$ and hence, every good citizen can download all $tx_pools$ in step 6d of Algorithm 4.

\[\square\]

Lemma 12 (Block Consensus). Except with negligible prob-

ability, (i) at the end of the block commit protocol, all good citizens except 36 sign the same block hash and new global state root and (ii) moreover, this block is consistent with the entire block chain and global state.

Proof. We consider the following two cases:

- (Good citizen is winner of block proposal): From Lemma 10, all good citizens hold all the required $tx_pools$ and agree on honest proposer’s block except with probability 0.017. When this happens, all good citizens and honest politicians construct the same block. Moreover, by Lemma 7 and Lemma 9, we know that at least $n_g - 36 \geq 1101$ good citizens are able to do global state read/write operations correctly and compute correct new global state root. Finally, good citizens follow a deterministic procedure to create a valid block. Hence, all good citizens except 36 will sign the same block hash and new global state root.

With probability 0.017, all good citizens do not enter the consensus with proposer’s block. This case is identical to an honest politician is bounded by $\left( \frac{\rho - 10}{\rho} + 10 \gamma \right)^{(n-1)/3}$ and the probability that there exists such a $tx_pool$ among the all of $\rho$ $tx_pools$ is bounded by $\rho \left( \frac{\rho - 10}{\rho} + 10 \gamma \right)^{(n-1)/3}$.

Since $n \geq 1700$, we have $\left\lceil \frac{(n-1)}{3} \right\rceil \geq 566$, and hence, for $\rho = 45$ we have that this probability is negligible. Once the politicians gossip the $tx_pools$, all honest politicians will have the $tx_pools$ and hence, every good citizen can download all $tx_pools$ in step 6d of Algorithm 4.

\[\square\]
to malicious proposer discussed below.

- (Malicious citizen is winner of block proposal): In this case, if the consensus results in an empty block, then all good citizens \( (n_g \geq 1137) \) will sign the empty block and previous global state root. If the consensus results in non-null, then from Lemma 11, all good citizens will be able to download the \( tx\_pools \) committed in the proposal (except with negligible probability) in Step 6d. Hence, using same arguments as above, all good citizens except 36 will will compute the same block hash and new global state root and sign this. This number is clearly more than \( T^* \).

To prove consistency of the block and global state with the entire block chain, observe that at most 36 good citizens could have obtained either an incorrect \((\text{key}, \text{val})\) pair or an incorrect frontier node \( F \) (Lemmas 7 and 9). All other good citizens download the correct global state, verify all transactions honestly and only sign blocks with valid transactions that are consistent with the global state. They also update the global state honestly.

Lemma 13 (Lower bound on throughput). The system does not stall in the presence of adversarial behavior and in expectation, committed blocks will have at least \( 0.65(1 - \gamma)\rho \) \( tx\_pools \) in them.

Proof. First, note from Theorem 2 (Liveness), we have that the system does not stall and a non-empty block gets committed to the blockchain with probability at least 0.65, and in particular, this happens with an honest citizen as the proposer. Now, note that malicious politicians can refuse to provide \( tx\_pools \), provide them to only a few honest mobile nodes, or provide \( tx\_pools \) that have transactions that do not verify (the last attack however, will get a politician blacklisted because \( tx\_pools \) are signed.). However, since, \( T_1, \ldots, T_\rho \), which are the politicians that would provide the transactions for the block in round \( Rnd \) are chosen at random, the expected number of honest politicians in this set of \( \rho tx\_pools \) is \( (1 - \gamma)\rho \). Furthermore, the \( tx\_pools \) corresponding to these politicians are non-intersecting from the way transactions are assigned to politicians. For all honest politicians’ \( tx\_pools \) in this set, the condition in Step 3b of Algorithm 4 will be met since \( n_g \geq n_g^* > n_b + \Delta \). Hence, the protocol would result in committing this block with at least \( (1 - \gamma)\rho \) \( tx\_pools \) in them. Combining this with the probability of a non-empty block, we obtain the proof of the lemma.

Lemma 14 (informal, Fairness). All valid transactions will eventually be committed.

Proof. As in the proof of Lemma 13, from Theorem 2, we know that the system does not stall and that non-empty blocks get committed with probability at least 0.65. A malicious block proposer could only pick \( tx\_pools \) provided by malicious politicians or always creates an empty block. However, for a block constructed by an honest proposer, since the politicians that would provide the transactions for the block in round \( Rnd \) are chosen at random, eventually every valid transaction held by honest politicians will be selected by an honest proposer. Hence, we can argue that all valid transactions are eventually committed.