SURFACE: A Practical Blockchain Consensus Algorithm for Real-World Networks

Zhijie Ren and Ziheng Zhou
VeChain
zhijie.ren, peter.zhou@vechain.com
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ABSTRACT

SURFACE, standing for Secure, Use-case adaptive, and Relatively Fork-free Approach of Chain Extension, is a consensus algorithm that is designed for real-world networks and enjoys the benefits from both the Nakamoto consensus and Byzantine Fault Tolerance (BFT) consensus. In SURFACE, a committee is randomly selected every round to validate and endorse the proposed new block. The size of the committee can be adjusted according to the underlying network to make the blockchain mostly fork-free with a reasonable overhead in communication. Consequently, the blockchain can normally achieve fast probabilistic confirmation with high throughput and low latency. SURFACE also provides a BFT mechanism to guarantee ledger consistency in case of an extreme network situation such as large network partition or being under a massive DDoS attack.

Keywords Blockchain · Consensus · Byzantine Fault Tolerance · Bitcoin · VeChain

1 Introduction

Blockchain, originated from Bitcoin [37], has received great attention recently since it can be used to create a trusted ledger/system amongst multiple untrusted parties and replace a central authority or a third party. One of the mostly discussed and vastly studied problems in blockchain is improving the throughput and latency, or in particular, the Bitcoin POW scheme, which is called the scalability problem [14]. Briefly speaking, the traditional Bitcoin POW is sub-optimal due to various reasons, one of which is the dependency between the Bitcoin POW’s consensus and the synchrony of the network [14, 16]. More precisely, forks would be created due to the asynchrony of the network, which waste bandwidth to be transmitted, reduce the security, and thus reduces the throughput and increases the confirmation time, i.e., the latency. One way to mitigate this problem is to transform the chain structure to a Directed Acyclic Graph (DAG) so that all branches of blocks could be counted in the consensus. As a result, the mining power as well as the transactions on the forks are all taken into account and thus the throughput and the security would not be degraded [49, 44, 33, 8]. Another approach is to prevent forks, i.e., using Byzantine Fault Tolerant (BFT) algorithms to reach consensus for each block [38, 28, 23].

In this paper, we introduce SURFACE, which is the abbreviation of Secure, Use-case adaptive, and Relatively Fork-free Approach of Chain Extension. The name suggests some of the major features of SURFACE, one of which is “relatively folk-free”. In SURFACE, we focus on practical networks in real-world and propose a blockchain consensus algorithm that is “mostly” fork-free by introducing a committee to validate the proposed block. At the meantime, the validation process of the committee is much simpler than running BFT algorithms in the whole network, thus it causes lower latency and communication overhead. As a result, the bandwidth will not be wasted due to transmitting forks that are eventually discarded and the latency will not be increased comparing to the schemes without committee. Moreover, the performance is adaptive as we could adjust the committee size according to the network condition to achieve the best throughput/latency performance for specific use cases. In addition to the committee based block validation scheme, a BFT scheme is also included in SURFACE to achieve finality, i.e., uncompromised consistency (security), even under the strict asynchronous assumption.
1.1 Background

Whether forks are allowed in the blockchain is in fact depending on the types of consensus algorithms, i.e., whether it achieves Nakamoto consensus [22, 51] or BFT consensus [32, 11]. Bitcoin and Ethereum [46], as well as many blockchains following their paths [4, 3, 27] achieve Nakamoto consensus. The achieved consistency is probabilistic, i.e., the probability that a block is immutable is not definitive but increases exponentially as more blocks appending to it. Some other blockchains use BFT algorithms to achieve deterministic consistency [23, 2, 26, 34], that is, blocks can be proven to be definitively immutable once they reach consensus.

Blockchain consensus algorithms could also be categorized into permissioned and permissionless by whether some permission from a trusted source is required for a node to participate in the consensus process. For example, Bitcoin’s POW is a permissionless consensus scheme as participants only need to solve a hash function based Proof-of-Work (PoW) puzzle to participate in the consensus process without needing permissions from any party. On the other hand, EOS [1], using the Delegated-Proof-of-Stake (DPoS) as its consensus scheme, is permissioned. In DPoS, all stakeholders vote for a certain number of “super nodes” to participate in the consensus. However, eventually, the elected super nodes are permissioned by the trusted authority who initiated the vote.

1.2 State-of-the-art

In this paper, we focus on the consensus algorithm for permissioned blockchain that functions in large real-world networks, some of the favorable choices are BFT algorithms and Proof-of-Authority (PoA) based consensus schemes. Alternatively, we could modify permissionless consensus algorithms to our scenario.

BFT algorithms are originated from [32] and has already been developed for decades [11, 9, 13] before the blockchain era. However, these algorithms are either too theoretical to be used in practice or not designed for scenarios of blockchains and have poor scalability in large networks. Some novel BFT algorithms designed for blockchains like Byzcoin [28], Tendermint [31], Algorand [23], and HotStuff BFT [48] reduce the message complexity of classical BFT algorithms. However, the block interval has to be set in such a way that the consensus could be reached via multiple rounds of communication, or at least the messages from the super majority (more than 2/3 of the population) could be received, which brings a relatively high latency than PoA.

PoA is a type of permissioned Nakamoto consensus schemes, which is used in several blockchains including VeChain and Parity. In general, PoA schemes enjoy the advantage of a simpler mechanism and lower latency as the block interval only needs to be sufficient for the block to be broadcast. However, it also has many drawbacks. First, probabilistic consensus is sometimes not sufficient for practical uses, in particular, for high sensitive data or law related affairs. These is also known as the “finality” problem, which has been addressed in Casper [12], Polkadots [47], and some others. However, as all these algorithms are ongoing works that are independent from our research, we will not address them here but compare SURFACE to them in Section 6.

Second, as most PoA schemes are roughly a natural extension of PoW in the permissioned setting, they also suffer from the above mentioned scalability problem. This problem has already been addressed by enormous number of works with various approaches [45, 19, 27, 44], most of which consider permissionless settings but could be modified to be applied in permissioned blockchains. Directed Acyclic Graph (DAG) based approaches [44, 33] have a rather high complexity, in particular, while dealing with problems of block ordering and transaction repetition. Then, “non-DAG” Nakamoto consensus based approaches [19, 50, 27, 10] have their dependencies on synchrony and the performances of these algorithms are thus more situational. More precisely, in BFT based blockchain consensus algorithms, the block size and intervals have to be adjusted such that the block could be broadcast and the response from the super majority could be received in each round. However, in these Nakamoto consensus algorithms, the block size and intervals only need to be suffice for the block to be broadcast. Hence, the throughput would be higher when the message delays are small and most nodes behave honestly. However, it is not safe to only consider the best scenario as otherwise malicious nodes could easily attack the blockchain by creating forks. Hence, redundancy has to be introduced in the throughput and latency to cope with the non-ideal situations, which leads to a sub-optimal performance.

1.3 Contribution

SURFACE focuses on the practicality of the consensus algorithms in real-world networks and enjoys the benefit from both worlds of Nakamoto consensus and BFT consensus. More precisely, SURFACE achieves fast probabilistic confirmation with high throughput and low latency that are comparable to the state-of-the-art algorithms with Nakamoto consensus like [50, 27]. At the meantime, SURFACE could achieve deterministic consistency (finality) as BFT algorithms like PBFT and HotStuff BFT [13, 48], and the consistency will not be compromised even if the network is asynchronous. In particular, our contributions are the following.
• We use a committee endorsing mechanism for each proposed block, where the size of the committee is adjustable to the network condition in such a way that the probability of forks is minimum in the “normal” situation of the practical network.
  – Comparing to other Nakamoto consensus algorithms without committee \[19, 27, 10\], we minimize the probability of fork and thus achieve a higher and more stable performance in terms of throughput and latency with minimum overhead in communication.
  – Comparing to BFT based algorithms, in case that the network is large, it does not take multiple rounds of messages responding from the super majority to reach consensus. Instead, a block could be probabilistically confirmed by a certain number of successive leaders and committees. At the meantime, the block interval could be set shorter as only a fraction of nodes need to respond. Hence, for transactions that do not require definitive consistency, SURFACE allows faster confirmation in large network.

• We use a BFT based consensus algorithm to achieve deterministic consistency (finality) in asynchronous networks.
  – Most Nakamoto consensus algorithms use synchronous assumptions and could not achieve consistency if the network is asynchronous, e.g., the security is not guaranteed in extreme situations. In that perspective, SURFACE achieves higher security.
  – We use an approach that is inspired by HotStuff BFT and prove that the consistency is achieved without any synchronous argument. As a result, instead of guaranteeing both liveness and consistency with some synchronous assumptions \[31, 12\], we guarantee uncompromised consistency but not liveness in asynchronous network. We will argue that this is practical in real-world applications in Section \[2\].

• We further incorporate with several novel ideas and mechanisms like block decomposition and delayed validation to further improve the performance of the consensus algorithm in practical networks.

1.4 Outline

In Section \[2\], we explain practical asynchronous networks with their network and security assumptions that will be used throughout this paper. A detailed explanation of SURFACE will be given in Section \[5\] with a high level overview followed by all the functions used in SURFACE. Then, in Section \[4\], we explain some of the novel ideas and mechanisms used in the design of SURFACE and compare them to previous works. In Section \[5\], we give numerical analysis on the security of probabilistic confirmation and theoretical proofs for the consistency and liveness of SURFACE. Then, in Section \[6\], we compare SURFACE to some closely related and recent works. At last, we conclude our paper in Section \[7\].

2 Network and Security Model

Bitcoin was described and considered as a secure value-transfer system that functions in asynchronous network as long as the majority (more than 50%) of the hashing power is rational. However, this description has already been challenged and proven wrong in many aspects. In \[20\], selfish mining is introduced, which could attack Bitcoin with merely 25% of the hashing power. In \[14, 16\], it is stated that Bitcoin is only secure if the network of Bitcoin is synchronous. Then, in \[21\], a collection of literature pointing out vulnerabilities in Bitcoin is listed \[7, 18\], etc., which leads to a conclusion that “rationality” is not a potent argument for honesty. In other words, evidences show that it is very hard to design incentive mechanism such that the rational players would only perform a certain behaviors. Hence, rational players should be considered as Byzantine players who would behave arbitrarily.

On the other hand, despite of all vulnerabilities and synchronous limitations, Bitcoin is still considered as secure and suitable for asynchronous network in the “common belief” as it functions well in real-world for years. Hence, in this paper, we take both the theoretical asynchronous network model and the practical network in real life into account.

We consider two scenarios: firstly, in a “normal” situation, we assume that the network is synchronous, the nodes are semi-trusted as their behavior is restricted by rational arguments, and the messages are propagated via gossip protocol. We argue that this is a reasonable assumption as most blockchain systems, including Bitcoin, function in this kind of networks in the practice. Then, we consider an “abnormal” situation that either the network is partitioned due to accident or attack, or the adversaries are trying to create inconsistency. In the “abnormal” situation, we use the strict asynchronous BFT assumption, i.e., the message delay as well as the behavior of the malicious nodes are arbitrary.

We assume that the network could arbitrarily switch in between these two situations. However, we assume that the abnormal situation is “temporary”, i.e., after each abnormal period of arbitrary length, there will always be a long normal period in which the transactions could be confirmed.
Then, we aim for different goals in different scenarios. In “normal” situation, we aim for high throughput, fast confirmation, and probabilistic consistency which is secure in the same fashion as Bitcoin. Then, to cope with the abnormal situation, we aim for uncompromised security such that the security of the blockchain is guaranteed without any synchronous argument. However, we do not guarantee liveness in abnormal situations.

The reason of choosing this model over traditional BFT network model or Nakamoto consensus model is purely practical. First, it is reasonable to assume that the “normal” situation is dominant as by our observation, most blockchains are working in the normal situations and rarely experienced abnormal situations, particularly, for permissioned blockchains in which the nodes are authorized to participate in the first place. At the meantime, it is crucial that the blockchain could guarantee its consistency without using any argument of synchrony or rationality, otherwise it is vulnerable to various types of attacks.

Here, we further specify our practical asynchronous network model.

2.1 Normal Situation

2.1.1 Network Assumptions

In the normal situation, we assume that the message delay is upper bounded by $\Delta$, which is determined by the network configuration and known in advance. Moreover, we consider messages are propagated to the network via gossip protocol, which is the general case for blockchains. In gossip communication model, adversaries cannot arbitrarily split the network by sending different messages to different nodes, as these messages will eventually be gossiped to all nodes. W.l.o.g., we assume that in synchronous situations, if a message is received by an honest node at time $t$, then it will be received by all honest nodes before $t + \Delta$.

2.1.2 Security Assumption

The number of malicious node is $f$ and we have $n \geq 3f + 1$, where $n$ is the total number of nodes in the network. For simplicity, we assume $n = 3f + 1$. We also assume that there exists a certain incentive mechanism to encourage honest behaviors and punish malicious behaviors. Hence, in normal situation, adversaries would mostly behave honestly with a fixed and relatively low probability of misbehave. We assume this is a parameter of fact and can be calculated in advanced.

2.2 Abnormal Situation

2.2.1 Network Assumption

In abnormal situation, the network is asynchronous, i.e., the message delay is arbitrary.

2.2.2 Security Assumption

The malicious nodes are Byzantine nodes, i.e., there could perform arbitrary behaviors, including not responding or behaving honestly. We also allow them to manipulate the network, e.g., arbitrarily delay the message. However, we assume that they have limited computation capacity such that they could not break the cryptographic primitives used in this paper. Moreover, the disconnection of the network, i.e., the losses of messages send by honest nodes, is not considered in this paper.

2.3 Situations changes

The network could change between these two situations arbitrarily and the duration of any situation is also arbitrary. However, it is guaranteed that abnormal situation is temporary, i.e., after each period of abnormal situation, there will be a relatively “long” period of normal situation, i.e., the period is sufficiently long for some transactions to be confirmed.

2.4 Differences from classical models

2.4.1 Network assumptions

Our network assumption is a strictly stronger assumption than asynchronous assumption and a strictly weaker assumption than synchronous assumption, as we assume that the network is not synchronous, but there will always be a sufficiently long period of synchrony. Our assumption is on the other hand, neither stronger nor weaker than the partial synchronous assumption, where the message delay is assumed to be bounded with an unknown bound.
2.4.2 Security assumption

Our security model is stronger than the assumption in asynchronous BFT as we assume that malicious nodes are “disciplined” and will behave honestly unless they see a possibility to perform a successful attack. This could be guaranteed by an incentive and punishment mechanism on and/or off the chain. The design of such a scheme is outside the scope of the paper.

2.5 Consensus

We propose a consensus algorithm that guarantee the following:

- **Consistency:**
  - In **normal situation**, if an honest node confirms a transaction $tx$ in a position $P$ in the blockchain, then the probability that there exists another honest node confirming a transaction $tx' \neq tx$ in the same position $P$ of the blockchain is smaller than $\epsilon$.
  - If an honest node finalizes a transaction $tx$ in a position $P$ in the blockchain, then there cannot be another honest node confirming a transaction $tx' \neq tx$ in the same position $P$ of the blockchain.

- **Liveness:** Transactions could be confirmed and finalized in **normal situation**.

2.5.1 Awareness of situation changes

In this paper, we assume that the honest nodes are rational, i.e., they will try to detect the situation of the network with the information on and off the chain. Then, they will stop using probabilistic arguments to confirm transactions when they consider the system is not in normal situation and retain confirming transactions when they see the network is back to normal. With practical concerns, we assume that rational nodes could allow false positive in detecting the abnormal situation and false negative in detecting the normal situation. In that case, the liveness is traded for consistency.

3 SURFACE

In SURFACE, we merge several schemes and concepts from existing blockchain and BFT algorithms. At the meantime, we make many improvements by proposing some additional mechanisms. In this section, we first give a high level overview on SURFACE. Then, we explain SURFACE in detail by firstly giving two core functions: a main function that is executed at the beginning of each round and a block receiving function that is used every time a new correct block is received. Then, we explain all the functions and variables used in these functions, without giving much explanation of their purposes, which we will do in Section 4.

3.1 A high level overview

SURFACE works in practical asynchronous networks, in which we define round according to Global Standard Time (GST) with a predetermined time interval. Further, we define epoch as a relatively long duration consisting many rounds. In this paper, the hash function is modeled by a random oracle.

Then, for each round, we randomly select a leader to create a block and a committee for validation. The leader is selected by a hash function and a random beacon determined by some randomness created and acknowledged by the end of the previous epoch by all nodes. The committee members of a round are determined by each node comparing a random number generated by a Verifiable Random Function (VRF) [35] to a given threshold. As a result, the leader of a round is known by all nodes by the end of the previous epoch, and the committee members of a round are only revealed when they announce their roles by revealing their proofs.

Each leader needs to first broadcast the new block and collect the endorsements from $d$ committee members to generate a valid block. There remains a possibility of forks, although the chance is much lower than the algorithms without committee and it can only be caused by an adversarial leader colluding with an adversarial committee. In case of forks, nodes will determine the valid chain by the “heaviest chain rule”. More precisely, assume that there are two chains which are identical till block $B$, and appended by $B_1$ and $B_2$ in each fork, respectively. Then, between these two blocks, honest nodes will choose the one with a heavier weight, e.g., with more nodes who have played the roles of leaders or committee members in the trailing blocks. The above-mentioned algorithm is designed to have fast confirmation and high throughput in the normal situation.

The abnormal mode of our algorithm is a BFT consensus algorithm that guarantees consistency in asynchronous network and liveness if the network regains synchrony. We introduce a “finality vector” that is included in each block.
It is a collection of new view messages, prepare messages, pre-commit messages, and commit messages that are sent by
the leader and committee together. Then, we use a chain selection and finality rule inspired by HotStuff BFT [48] to
reach BFT, which is alternatively called "finality" in this paper, for the blockchain.

3.2 Main Function

At round \( r \), a node \( u \) calls the main function MainFunction\((u, r)\).

\[
\text{Algorithm 1 Main Function MainFunction}(u, r, mode(r-1), C_0(u, r-1))
\]

\[
\begin{align*}
C_0(u, r-1) & \text{ is the finalized chain till the last round} \\
\mathcal{T} X_0(u) & \text{ the set for all unpublished valid transactions known to } u \\
\text{mode}(u, r) & \text{ SwitchMode}(u, r, mode(r-1)) \\
\mathcal{B}(u, r) & \text{ CandidateBlocks}(\mathcal{B}_{\text{non}}(u, r), \mathcal{B}_{\text{val}}(u, r), \text{mode}(u, r)) \\
C(u, r) & \text{ CanonicalChain}(\mathcal{B}(u, r), F(u, r-1)) \\
F(u, r) & \text{ Finality}(\mathcal{B}(u, r), C(u, r), F(u, r-1)) \\
\text{role}(u, r) & \text{ RoleDetermine}(u, r, C(u, r)) \\
\text{if } \text{role}(u, r) & = \text{‘leader’ then} \\
\mathcal{T} X(B(u, r)) & \text{ an ordered set of new transactions packed by } u \text{ to be published in this round} \\
(s(B(u, r)), \text{Sig}_u(s(B(u, r)))) & \text{ BlockSummary}(C(u, r), \mathcal{T} X(B(u, r))) \\
\text{broadcast } s(B(u, r)), \text{Sig}_u(s(B(u, r))) & \text{ and } \mathcal{T} X(B(u, r)) \\
\text{Receive for } d \text{ endorsements } \text{End}_u(\text{Sig}_u(s(B(u, r)))), \text{role}(v) & = \text{‘committee’ and combine it into a} \\
\text{CEnd}(B(u, r)) & \text{broadcast CEnd}(B(u, r)), \text{Sig}_u(\text{CEnd}(B(u, r))) \\
\text{else if } \text{role}(u, r) & = \text{‘committee’ then} \\
\text{Receive } s’ \text{ and sig’} \\
\text{valbs}(s’) & \text{ ValBlockSum}(s’, \text{sig’}, C(u, r)) \\
\text{if } \text{valbs}(s’) & = \text{‘valid’ then} \\
\text{End}_u(s’) & \text{ Endorsement}(s’, u) \\
\text{Send } s’, \text{sig’}, \text{End}_u(s’) & \text{ to the leader} \\
\text{Receive } \mathcal{T} X \\
\end{align*}
\]

A node \( u \) will always keep track of an unpublished valid transaction set \( \mathcal{T} X_0(u) \). At the start of each round, it detects
its mode \( \text{mode}(u, r) \) of this round and determines the set of blocks that he will consider to determine the canonical
chain \( C(u, r) \), namely the candidate blocks \( \mathcal{B}(u, r) \), according to the mode of this round. Then, he will update his own
finality vector \( F(u, r) \) according to his finality vector of the previous round as well as the finality vectors (actually the
pruned finality vectors, which will be explained later) collected in the canonical chain \( C(u, r) \).

Then, at the beginning of each round, each node determines his role by RoleDetermine\((u, r)\). If \( u \) is the leader
of this round, he makes a block summary \( s(B(u, r)) \) according to \( C(u, r) \) and \( \mathcal{T} X(B(u, r)) \subseteq \mathcal{T} X_0(u) \). He broadcasts
the block summary \( s(B(u, r)) \), a corresponding signature \( \text{Sig}_u(B(u, r)) \), along with \( \mathcal{T} X(B(u, r)) \) and waits for the
endorsements from the committee members of this round. Once \( c \) endorsements have been received, he combines these
endorsements into a collected endorsements \( \text{CEnd}(B(u, r)) \) and broadcasts it with \( \text{Sig}_u(\text{CEnd}(B(u, r))) \).

Then, if \( u \) is a committee member of this round, he waits for the block summary \( s’ \) and a signature \( \text{sig’} \). He validates the
block summary and endorses for it by signing it if it is valid. Then, he sends his endorsement \( \text{End}_u(s’, \text{sig’}) \) alongside
with \( s’, \text{sig’} \) and at the meantime receives \( \mathcal{T} X(B(u, r)) \).

3.3 Blocks

In SURFACE, the blocks are not as straightforward as they are in Bitcoin since a block is decomposed into multiple
parts that are not sent together as an actual "block", but separately. The matching parts are combined into a block by the
receiver. Then, the receivers will validate these blocks and for each round, they will select a chain according to the
canonical chain rule.

However, not all blocks are directly considered as candidate blocks for the canonical chain. Nodes will also use their
local knowledge to judge whether the block is suspicious, i.e., sent by adversaries to intentionally cause inconsistency.
When the node is in the normal mode, inconsistent blocks sent by the same leader or blocks received outside of their
rounds are all suspicious and will not be considered as candidate blocks. However, when the node is in abnormal mode,
these blocks will be also considered. Hence, nodes will keep two sets of blocks, which are called valid blocks and
honest blocks, respectively. Then, they will select the candidate blocks from these two sets accordingly to the mode.
3.3.1 Composition of blocks

A block $B(u,r)$ consists of three parts: A set of transactions $TX(B(u,r))$, a signed block summary $s(B(u,r)), \text{Sig}_u(s(B(u,r)))$, and a signed collected endorsement $C\text{End}(B(u,r)), \text{Sig}_u(C\text{End}(B(u,r)))$.

Transaction set $TX(B(u,r))$ Each node will maintain a set of valid and unpublished transactions $TX_0(u)$ according to the canonical chain that they observed. Then, if he is in turn as a leader, he will make a transaction set to publish in this turn $TX(B(u,r)) \subseteq TX_0(u)$.

Block summary A block summary is composed by the following items in the exact order.

1. A hash of the block summary and the collected endorsement of the previous block, i.e., $H(s(B(u,r))|C\text{End}(B(u,r)))$, where $B(u,r)$ is the last block of the canonical chain $C(u,r)$.
2. The current epoch and the round number.
3. A Merkle root of $TX(B(u,r))$.
4. A pruned finality vector $F_p(u,r)$.

A finality vector $F(u,r)$ is a vector including five values $H(B_{\text{rev}}(u,r)), H(B_{\text{prev}}(u,r)), H(B_{\text{pcmt}}(u,r)), H(B_{\text{cumt}}(u,r)), H(B_{\text{final}}(u,r))$, which are the indicators of the consensus status of node $u$ at round $r$ computed by function $\text{Finality}(B(u,r), C(u,r), F(u,r-1))$. A pruned finality vector $F_p(u,r)$ excludes $H(B_{\text{final}}(u,r))$.

Then, by publishing or endorsing block $B$ which includes $F_p(u,r) = F(B)$, the leaders and committee members equivalently send new view messages to block $B_{\text{rev}}(B)$, prepare messages to block $B_{\text{prev}}(B)$, pre-commit message to block $B_{\text{pcmt}}(B)$, and commit message to block $B_{\text{cumt}}(B)$ as in [48].

Collected endorsement Once $d$ endorsements are collected, they are ordered according to the ascending order of the public keys of committee members and concatenated into the collected endorsement $C\text{End}(B(u,r))$.

3.3.2 Valid blocks

We consider a block $B$ as “valid” if it is self-contained, i.e., it is consistent with itself and all previous blocks on its chain $C$. Hence, we define the correctness of a block as the following

- The leader, round number, epoch number, and the finality vector are consistent with what can be computed from $C$.
- The block summary and the collected endorsement are correctly signed by the leader.
- The Merkle root in the block summary is consistent with the transaction set.
- The transactions in the transaction set are all valid with regards to the chain that it is on.
- There are $d$ endorsements in the collected endorsements from the committee members of round $r$.
- All previous blocks on $C$ are also valid.

Throughout this paper, if we refer to a “block”, then it is a valid block. In other words, we do not take a block that is not self-contained into account when we consider the blockchain, even if it has a valid block summary, or enough endorsements from the committee, or valid transaction sets, etc. We denote all blocks that are received by node $u$ till round $r$ by $B_{\text{val}}(u,r)$.

3.3.3 Honest blocks

Nodes that are participating in the consensus will also mind the honesty of the block, i.e., whether they are sent by honest nodes. In normal situation, a block will be received by all honest nodes in that round. Hence, a block is suspicious if

- there are different blocks or block summaries generated by the same leader of that round;
- it is received outside of their round.

We define the blocks that are not suspicious as honest blocks, i.e., the honest blocks are

- received in the corresponding rounds;
with no received blocks or block summaries that are from the same leader of the same round but are different.

We denote all honest blocks that are received by node \( u \) till round \( r \) by \( B_{\text{hon}}(u, r) \). Note that honest blocks only make sense in “normal situations”. We will specify how nodes determine their current mode in Subsection 3.9.

### 3.4 Candidate Blocks

At the start of each round, node \( u \) runs the function \( \text{CandidateBlocks}(u, r) \) to determine the blocks to be considered for the canonical chain of this round. In normal mode, a node will only consider honest blocks for their chain selection and could confirm transaction using probabilistic metrics. In abnormal mode, a node will consider all blocks for their chain selection and be aware of the confirmed transactions might not be final.

**Algorithm 2** Determine the candidate blocks \( \text{CandidateBlocks}(B_{\text{hon}}(u, r), B_{\text{val}}(u, r), \text{mode}(u, r)) \)

\[
\begin{align*}
  r' & \leftarrow \text{the last round that } \text{mode}(u, r') \neq \text{'normal'} \\
  \text{if } \text{mode}(u, r) = \text{'normal'} \text{ then} \\
  B(u, r) & \leftarrow \{B : B \in (B_{\text{hon}}(u, r) \setminus B_{\text{hon}}(u, r' + 1)) \cup B_{\text{val}}(u, r') \land B \sim C_{\text{final}}(u, r - 1) \} \\
  \text{else} \\
  B(u, r) & \leftarrow \{B : B \in B_{\text{val}}(u, r), B \sim C_{\text{final}}(u, r - 1) \} \\
  \text{return } B(u, r)
\end{align*}
\]

Here, \( B \sim B \) is defined as \( B \) is not conflict with any block in \( B \), and \( C_{\text{final}}(u, r) \) is the chain that has reached finality by node \( u \) in round \( r \), which we will explain later.

### 3.5 Canonical Chain

Firstly we define the weight of block \( B \) in chain \( C \).

**Definition 1** (Block Weight). Given a block \( B \) in a chain \( C \), the weight \( W(B, C) \) is defined as the number of different nodes that are leaders and committee members in the blocks appending to \( B \). More precisely, let us denote \( C \) by \( \{B_1, B_2, \ldots, B_m\} \), where \( B_k = B \). Then, assume the set for the nodes who are the leader and the committee members of \( B_i \) is \( M_i \). The weight of block \( B \) in chain \( C \) is then defined by

\[
W(B, C) = \min(|M_{k+1} \cup M_{k+2} \cup \ldots \cup M_m|, 2f + 1).
\]

Moreover, let’s denote the set of blocks on a chain \( C \) from the genesis block to \( B_2 \) by \( C(1 : B_2) \) and a chain from \( B_1 \) to \( B_2 \) by \( C(B_1 : B_2) \).

Then, we use the following rules to determine the canonical chain:

1. \( C \) includes \( B_{\text{final}} \).
2. For two chains \( C_1, C_2 \in B(u, r) \) satisfying the first rule, let \( B \) be the last common block for both chains, i.e., \( B \in C_1, B \in C_2 \), compare \( W(B, C_1) \) and \( W(B, C_2) \). Select the chain with a larger block weight. If there is a tie, compare the block weight of the next block until the tie is broken.
3. If the block weight is tied in both chains in all blocks, select the chain with a newer block.
4. If there are multiple qualified blocks, select the one that is received first.

The function \( \text{CanonicalChain}(B(u, r)) \) is an implementation of these chain selection rules.

### 3.6 Finality

The finality vector \( F(u, r) = [H(B_{\text{nv}}(u, r)), H(B_{\text{pre}}(u, r)), H(B_{\text{pen}}(u, r)), H(B_{\text{val}}(u, r)), H(B_{\text{final}}(u, r))] \) represents the blocks that are seen as the current view, being prepared, pre-committed, committed, and finalized by node \( u \) in round \( r \), respectively. Then, we denote such a finality vector included in block \( B \) by \( F(B) = [H(B_{\text{nv}}(B)), H(B_{\text{pre}}(B)), H(B_{\text{pen}}(B)), H(B_{\text{val}}(B)), H(B_{\text{final}}(B))] \). In the context of HotStuff BFT [48], \( F(B) \) can be seen as the new view requests including a proposal of block \( B_{\text{nv}}(B) \), prepare messages for block \( B_{\text{pre}}(B) \), pre-commit messages for block \( B_{\text{pen}}(B) \), and commit messages for block \( B_{\text{val}}(B) \) sent by the leader and all signed committee members in block \( B \). Then, we say \( B \) is at view \( B_{\text{nv}}(B) \), prepares \( B_{\text{pre}}(B) \), pre-commits \( B_{\text{pen}}(B) \), and commits \( B_{\text{val}}(B) \), respectively. Further, we use the notation \( B \preceq B' \) if block \( B \) is in an earlier round than or the same round as
We then use the notation $C[B_1 : B_2]$ to represent the chain starting from block $B_1$ and ends with block $B_2$. Then, $C[B]$ is the chain from the genesis block to block $B$.

We define a counter for the prepare messages according to a block set $B$ as $N_{nv}(B, B') := |\{u : u is a leader or signed committee member of a block $B' \in B$ such that $B_{nv}(B') = B\}|$. Then, we define $N_{prepare}(B, C)$, $N_{prect}(B, C)$, and $N_{com}(B, C)$ similarly. Furthermore, we define a counter for the messages in a specific view, i.e., $N_{prepare}(B, C, V) := N_{prepare}(B, C')$ where $C'$ is the part of the chain that has $B' \in C'$, $B_{nv}(B') = V$.

Then, after the canonical chain is selected, we use Algorithm 3 to determine the finality vector $F(u, r)$, which is the consensus status that node $u$ is at in round $r$. The finality vector is initially set to $[H(b_0), H(b_0), H(b_0), H(b_0), H(b_1)]$ where $b_1$ is the genesis block and $b_0$ is an unique identifier of the “null” block.

Here, we describe the rules in Algorithm 3 in words:

- **Commit rules:**
  1. (line 4) $u$ commits a block $B$ if he has received $2f + 1$ pre-commit messages of $B$ in one view.
  2. (line 6) $u$ commits a block $B$ if he receives $f + 1$ commit messages for $B$.

- **Pre-commit rules:**
  1. (line 11) $u$ pre-commits $B$ if the following two conditions hold: 1), $u$ receives $2f + 1$ prepare messages of $B$ in one view with no pre-commit messages for a conflicting block $B' \perp B$ on the canonical chain; 2) $u$ is not pre-committing for any block.
  2. (line 13) $u$ pre-commits $B$ if the following four conditions hold: 1), $u$ sees a pre-commit message for $B$ received with new view messages for $B' \succ B$ in the canonical chain; 2), $u$ receives another chain $C, B \in C$ with $2f + 1$ new view messages and $2f + 1$ prepare messages for $B$; 3), $u$ is not pre-committing for a block $B'' \succeq B$; 4), $B$ comes later than any other block that also satisfies the previous three conditions.

- **Prepare rules:** (line 16-22) If $u$ receives $2f + 1$ new views with no pre-commit message for a conflicting block $B' \perp B$ on the canonical chain, then $u$ prepares $B$ if one of the two following conditions holds
  1. $u$ has not pre-committed for any block.
  2. $u$ has pre-committed for a block $B'$ in chain $C$ latest at view $B^*$, and $B \succ B^*$.

  - **Unlock the pre-committed block** (line 24) if there exists a block that is prepared in a higher view than the pre-committed block and conflicts the pre-committed block.

- **New view rules:**
  1. (line 27) $u$ changes the view to the view of the previous block $B$ if $u$ is at a view of $B' \prec B$.
  2. (line 29) $u$ changes the view to the current block $B$ if the view of the previous block $B''$ is older than and conflict with his current view $B'$, i.e., $B'' \preceq B', B'' \perp B'$.

  - **Unlock the prepared block** (line 34) if the prepared block conflicts the new view block.

### 3.7 Role determination

The leader and the committee members are selected by using a hash function and a VRF, respectively, on the random beacon of the epoch and the round number.

#### 3.7.1 Random beacon

A random beacon of epoch $e$, denoted by $b_e$, is determined in the epoch $e - 1$. We find the $C_{End}$ contained in the last finalized block before round $r_{e-1} - \tau_0 - \tau_1$, where $r_{e-1}$ is the last round of epoch $e$, $\tau_0$ is a parameter set according to the estimated maximum latency of block propagation, and $\tau_1$ is an estimated maximum latency of finality. We then compute $b_e$ by $b_e = H(C_{End})$.

#### 3.7.2 Role determination function

We then use the `RoleDetermine` function to determine the roles of nodes in round $r$, which determines the leader of each round by a hash function and determines the committee by comparing a random number generated by a VRF function to a predetermined threshold $\epsilon$. 


Algorithm 3 Updating the finality vector $\text{Finality}(B(u, r), C(u, r), F(u, r - 1))$

1: Denote the last block in $C(u, r)$ by $B$.

2: $B_{nv}(u, r) \leftarrow B_{nc}(u, r - 1), B_{pre}(u, r) \leftarrow B_{pre}(u, r - 1), B_{pcmt}(u, r) \leftarrow B_{pcmt}(u, r - 1), B_{cm}(u, r) \leftarrow B_{cm}(u, r - 1), B_{final}(u, r) \leftarrow B_{final}(u, r - 1)$

3: \# First, update the commit block.

4: if $\exists B, B' \in C(u, r) : N_{pcmt}(B, C(u, r), B') \geq 2 + 1 + N_{nv}(B', C(u, r), B) = 0 \forall B' \in B(u, r), B' \perp B_{pre}(u, r - 1)$ then

5: $B_{cm}(u, r) \leftarrow B, B_{pcmt} \leftarrow b_0$

6: else if $\exists C' \in B(u, r), B' \in C' : N_{cm}(B', C', B) > 0 \land N_{nv}(B', C', B) \geq 2 + 1 \land N_{pre}(B', C', B') \geq 2 + 1 \land (B_{cm}(u, r - 1) = b_0 \land B_{cm}(u, r - 1) \perp B)$ then

7: $B_{cm}(u, r) \leftarrow B'$

8: if $B_{final}(u, r - 1) \perp B_{cm}(u, r)$ then

9: $B_{final}(u, r) \leftarrow B_{cm}(u, r)$

10: \# Second, update the pre-committed block.

11: if $\exists B \in C(u, r) : N_{pre}(B_{pre}(u, r - 1), C(u, r), B) \geq 2 + 1 \land N_{pcmt}(B', C(u, r), B) = 0 \forall B' \in B(u, r), B' \perp B_{pre}(u, r - 1)$ then

12: $B_{pcmt}(u, r) \leftarrow B_{pre}(u, r - 1)$

13: else if $\exists C' \in B(u, r), B' \in C' : N_{pcmt}(B', C(u, r), B) > 0 \land N_{nv}(B', C', B) \geq 2 + 1 \land N_{pre}(B', C', B') \geq 2 + 1 \land (B_{cm}(u, r - 1) = b_0 \lor B_{cm}(u, r - 1) \perp B)$ then

14: $B_{pcmt}(u, r) \leftarrow B'_{max}$ where $B'_{max}$ is the block with the largest round number if there are multiple $B'$ satisfying the condition.

15: \# Third, update the prepared block.

16: if $\exists B \in C(u, r) : N_{nv}(B_{nv}(u, r - 1), C(u, r), B) \geq 2 + 1 \land N_{pcmt}(B', C(u, r), B) = 0, \forall B' \in B(u, r), B' \perp B_{nv}(u, r - 1)$ then

17: if $B_{pcmt}(u, r - 1) = b_0$ then

18: $B_{pre}(u, r) \leftarrow B_{nv}(u, r - 1)$

19: else if $B_{pcmt}(u, r - 1) = B'$ then

20: $B^* \leftarrow B_{nv}(u, r^*), r^* = \max_{B_{pcmt}(u, r') = B'_{max}(r')}$

21: if $B_{nv}(u, r - 1) \succ B^*$ then

22: $B_{pre}(u, r) \leftarrow B_{nv}(u, r)$

23: \## Unlock the pre-committed block if there is a prepared block in a higher view.

24: if $B_{pcmt}(u, r) \neq b_0 \land \exists C' \in B(u, r), B' \in C' : B' \succ B_{pcmt}(u, r), N_{pre}(B', C') > 0, N_{nv}(B', C') \geq 2 + 1, B_{pcmt}(u, r) \perp B'$ then

25: $B_{pcmt}(u, r) \leftarrow b_0$

26: \# At last, we update $B_{nv}$ according to $C(u, r)$.

27: if $B_{nv}(B) \succ B_{nv}(u, r - 1)$ then

28: $B_{nv}(u, r) \leftarrow B_{nv}(B)$

29: else if $B_{nv}(B) \preceq B_{nv}(u, r - 1), B_{nv}(B) \perp B_{nv}(u, r - 1) \lor B_{nv} = b_0$ then

30: $B_{nv}(u, r) \leftarrow B$

31: else

32: $B_{nv}(u, r) \leftarrow B_{nv}(u, r - 1)$

33: \## Unlock the prepared block if it conflicts the current view.

34: if $B_{pre}(u, r) \perp B_{nv}(u, r)$ then

35: $B_{pre}(u, r) \leftarrow b_0$

36: return $H(B_{nv}(u, r)), H(B_{pre}(u, r)), H(B_{pcmt}(u, r)), H(B_{cm}(u, r)), H(B_{final}(u, r))$
Here, we use the ECDSA-based VRF scheme proposed in [24], where the VRF could be abstracted as the following. Node \( u \) could use his private key \( sk_u \) to compute a random number \( \beta_u \) with an arbitrary input \( \alpha \) by:

\[
\beta_u = f_{\text{VRF}}(\alpha, sk_u)
\] (2)

Then, node \( u \) could provide a proof:

\[
\pi_u = \Pi_{\text{VRF}}(\alpha, sk_u).
\] (3)

Any node could use the public key of \( u \), denoted by \( pk_u \) and \( \Pi_u \) to verify that \( \beta_u \) is collision free defined similarly to a cryptographic hash function, pseudorandom in the sense that it is indistinguishable from a random number created by another node, and unique in the sense that each \( \alpha \) corresponds to a unique \( \beta_u \). Moreover, the ECDSA-based VRF scheme proposed in [24], we also have

\[
\beta_u = H(\pi_u).
\] (4)

Further, we define a mapping function \( M(x) = u \) that will map an arbitrary input \( x \) to a node \( u \) with uniform probability.

3.8 Committee member's procedure

If node \( u \) is a committee member in round \( r \), in the time interval of \([\Delta, 2\Delta]\) in round \( r \), he will wait for the block summary as well as the transaction set sent by the leader of the round. Then, he calls the \( \text{ValBlockSum}(s', \text{sig}', \mathcal{T}, C(u, r)) \) to validate the block summary. If the result is 'valid', it endorses this block summary and broadcasts its endorsement.

3.8.1 Validation of the block summary

The block summary is validated with \( \text{ValBlockSum}(s', \text{Sig}', \mathcal{T}, C(u, r)) \).

Algorithm 5 Validate Block Summary \( \text{ValBlockSum}(s', \text{Sig}', \mathcal{T}, C(u, r)) \)

\( s' \) is a summary in the form of \( H(h(B'))|r'|MR(\mathcal{T}')|F' \);
\( B \) ← the last block on \( C(u, r) \);
if \( B' == B \land r' == r \land F(u, r) == F' \land \text{Sig}' \) is \( s' \) signed with the correct key of the leader of round \( r \) then
return 'valid'

3.8.2 Endorsement

If the result of the validation of the block summary is 'valid', node \( u \) endorses it by broadcast \( \text{End}_u(s') = \text{Endorsement}(s', u) \).

Algorithm 6 Endorsement algorithm \( \text{Endorsement}(s', u) \)

\( \pi_u \leftarrow \Pi_u(b_e| r, sk_u) \)
return \((\pi_u, \text{Sig}_u(s'))\)

Here, \( \pi_u \) should be broadcast with the endorsement so that the role of \( u \) can be verified. The block summary has to be broadcast again in order to prevent the malicious leader sending different block summaries to different nodes.
3.9 Mode switch

There are two modes in the consensus algorithm: normal and abnormal. Note that by our assumption, the modes observed by nodes are not necessarily aligned with the situation of the network, but with some fault probability. Moreover, nodes are self-motivated to use any on-chain or off-chain information to detect the change of the situation, e.g., they could periodically ping some random peers in the network to check if there are network partitions. Here, we give a simple situation detecting scheme using merely on-chain information. It has a low false positive probability for situation changes from normal to abnormal and a low false negative probability for situation changes from abnormal to normal.

Algorithm 7 Determine the mode according to the network \( \text{SwitchMode}(u, r) \)

```plaintext
if There are more than \( k_0 \) empty rounds in the most recent \( R_0 \) rounds then
    mode = 'abnormal'
else if There exists a fork of \( C(u, r) \) of depth \( k_1 \) in \( B(u, r) \) then
    mode = 'abnormal'
else
    mode = 'normal'
return mode
```

Algorithm 7 suggests that nodes should consider the network in abnormal situation whenever a \( k_1 \)-depth fork is detected or \( k_0 \) empty rounds occur in recent \( R_0 \) rounds. Here, \( k_0, k_1 < \min(k, \frac{2f+1}{d+1}) \), \( k \) is the confirmation threshold.

4 Mechanisms in SURFACE

In this section, we explain the reason behind the designs introduced in Section 3 with context. We decompose the algorithm into several mechanisms and compare them to their counterparts in existing works, and clarify the similarities and differences, as well as our reason of choice.

4.1 Round based leader selection

With the practical asynchronous network assumption, we use a round based leader selection mechanism which has been widely used in existing works, in particular, proof-of-stake (POS) algorithms like [10, 27, 23, 26]. These algorithms are different in three aspects:

- **Sole leader vs. Committee:** The single leader approach is a straightforward extension of Bitcoin. It is followed by POW based algorithms like [19] as well as POS based algorithms like [10, 27, 15]. These algorithms achieve Nakamoto-like consensus that require several rounds to probabilistically confirm with no finality. In POW based algorithms like [38, 28] and POS based algorithms like [23, 26], a random selected committee is used to achieve immediate finality with negligible fault probability. However, it introduces a higher message complexity due to the communication in the committee. Moreover, the fault tolerance ratio (the ratio of allowed adversaries in the total population) should be calculated carefully in order to guarantee that less than 1/3 of the committee are adversarial.

- **The choice of random function:** Hash function is one of the most straightforward choice as a random oracle, which is used by [10, 27]. However, it suffers the disadvantage of predictability, which can be exploit by the adversaries. Then, VRF is used by [23, 15] so that the role of a node is not known until himself revealing it with a proof. However, the number of leader or committee members is not definitive. In [26], the BLS threshold signature is used for it is both deterministic and unpredictable.

- **Random beacon:** A random beacon is required to generate a pseudo-random number, which must have reached consensus and could not be manipulated by the adversaries. An epoch based random beacon is used by most algorithms, where an epoch is a period that is sufficiently long for nodes to reach consensus on the beacon. Then, in order to prevent manipulation, [10] uses the concatenation of randomness from many nodes so that adversaries could not manipulate all of them and in [27, 23], the randomnesses are proposed with a commitment scheme to further prevent manipulation. Then, the beacon is used for an epoch so that it is impossible to successfully bias the selection of the whole period.

In SURFACE, we aim at a consensus algorithm that “almost forlk-free” under normal situation in practical so that the bandwidth will not be wasted on transmitting blocks that are eventually discarded. Hence, we choose a leader plus committee approach, which is similar to [23]. The main difference in here is that in [23] the size of the committee
should be chosen sufficiently large so that the super majority (more than 2/3 of the population) of the committee are honest. However, in SURFACE, this is not a hard requirement as we only aim for “almost fork-free” but not absolute fork free. As a result, SURFACE could be seen as a generalization of leader based approach and committee based approach. It can achieve fast confirmation or even immediate finality if the committee size is large, and has a less message complexity but longer confirmation time if the committee size is small.

Second, for the random function, we use the straightforward hash mapping to select the leader and uses VRF to select the committee. The VRF committee selection will limit the capability of adversarial leaders to collude with the committee. Then, the hash mapping will guarantee that each round having exactly one leader, which will not result in empty rounds or inconsistency caused by multiple leaders in one round like in [15]. However, it does result in predictability of the leaders of the next epoch, which gives a chance of corruption attack. In our assumption, we assume the “one-epoch ahead” predictability is acceptable.

Third, we also uses the randomness from many nodes of the previous epoch to determine the random beacon. In particular, the random beacon is determined by the randomness created by VRF in the last finalized and received block in the previous epoch. It is guaranteed to be consistent for all nodes as it is finalized. Then, it could be manipulated with a non-negligible probability, which is the main different of SURFACE and [23]. However, we will later show that we could still achieve probabilistic consistency even if the adversaries could manipulate the random seed.

4.2 Optimizing throughput

In SURFACE, many schemes are used to achieve an optimized throughput in practical use cases, especially in a industrial oriented consortium blockchain where the nodes are considered trusted in a certain degree.

4.2.1 One round, one block

The idea of “one round, one block” is the most straightforward approach of making a “blockchain”. However, if we consider reaching consensus on messages rather than “blocks”, then we have alternations like BFT algorithms and directed acyclic graphs (DAGs).

Classical BFT algorithms [11, 9, 13] has $O(N^2)$ message complexity per consensus, where $n$ is the number of nodes in the network. Some more recent BFT algorithms could reduce the message complexity to $O(N)$ [30, 28, 25, 36, 48]. The finality mechanism of SURFACE is inspired by HotStuff BFT [48], which also organizes the consensus into a chain of blocks. We will later clarify the similarities and differences between our algorithm and HotStuff BFT.

DAG based consensus algorithms allow multiple nodes to propose blocks simultaneously and eventually reach consensus on a graph instead of a chain [41, 49, 44, 33, 43, 38]. However, these algorithms are in general more complicated, especially to order transactions, and there are no clear evidence that they achieve higher throughput, lower latency, and/or have better bandwidth efficiency than the chain based approaches.

Another alternation is scale-out consensus algorithms like sharding approaches [29, 6, 42] or off-chain approaches like [40, 39]. However, all these algorithms compromise in security, decentralization, or functionality, which are not suitable for our case.

Hence, we use a one-round one-block approach for our blockchain, which is also in line with many state-of-the-art consensus algorithms like [27, 23, 5, 26].

4.2.2 Decomposition of the blocks

In our algorithm, the block is decomposed into multiple parts and the actual block is never broadcast together. The purpose of this design is to reduce communication redundancy. In particular, the transactions will only be broadcast once by the leader, instead of twice, i.e., first sent to the committee for validation, then broadcast with the complete block to the whole network.

There are other works that partially address this problem. In [23, 17], the redundancy of the “the transactions is broadcast twice, once before the block and once in the block” is mitigated by only sending the hash indices of the transactions in the block.

Note that these algorithms are different in many aspects with the only similarity of organizing data in the form of DAG.
4.2.3 Delayed validation

In our algorithm, the transaction set included in the block of round $r$ is actually not validated by the committee members of round $r$. It is validated by the leader and the committee members of round $r + 1$ to decide whether to append blocks to it.

The reason behind this choice is to reduce the latency and wasted bandwidth caused by the validation of the transactions. If the committee validates the transaction of this round, then, the leader has to wait for the committee to validate the transactions and response with the endorsements, during which the bandwidth is wasted. The delayed validation design will allow the leader to fully utilize the bandwidth of a round for block transmission, while the validation could be done by the committee in the next round, while they are receiving the block of the next round. This is essentially optimistically trading the bandwidth wasted on waiting for the validation results for the possible bandwidth wasted on receiving invalid blocks, which will improve throughput in general as we assume that the network is mostly in normal situation and it is almost fork-free.

Similar approaches have also appeared in [50][5], however, in different forms and for different purposes.

4.3 Finality

The idea of our finality mechanism is inspired by HotStuff BFT, where a 3-phase commit approach including new view phase, prepare phase, pre-commit phase is used before a node is committed to a block. It always takes a quorum consensus (QC), i.e., $2f + 1$ consistent votes in a higher view, to proceed to the next phase. Whenever a block is committed by one honest nodes, it will eventually be finalized by all honest nodes. The normal procedure of finalizing block is shown in Figure[1]

A node will prepare a block $B$ when he sees $2f + 1$ new view votes for a block $B$. A node that has prepared for a block will unlock from their prepared block if they change to a conflicting view as seen in Figure[2]

Then, to guarantee liveness, we allow a node to always change view to a newer block as shown in Figure[3].
Figure 3: Nodes will always change to a newer view on the canonical chain.

Figure 4: Node $u$ changes view when he has already prepared and pre-committed a conflicting block. Note that in here, node $u$ and $v$ will still consider the chain of $B'$ is the canonical chain until they commit $B$. Then, they will discard the chain of $B'$ and change to $B$.

Then, the consistency is guaranteed by the second pre-commit rule: If there are $2f+1$ new view messages received with at least one pre-commit message for a conflicting block, then it could be that the block has already been committed. Hence, honest node should pre-commit for that block, as shown in Figure 4.

Note that one of the major difference between the finality mechanism of SURFACE and HotStuff BFT is that in SURFACE, the consensus will only proceed to the next phase if a QC is received on its chain. For example, if an honest node receives $f$ pre-commits of $B$ in a chain $C$ and receives $f+1$ pre-commits of $B$ from different nodes in a chain $C'$, he will wait for $2f+1$ pre-commits appearing on the same chain to commit $B$ instead of committing $B$ directly. As a result, all consensuses are self-contained with its chain so that if an honest node newly joins the network or recovers from asynchrony, he could catch up with the consensus result by only receiving the current canonical chain.

5 Performance Analysis

5.1 Probabilistic confirmation in normal situation

In Nakamoto consensus [37][22], the consensus of a block is probabilistic, which grows stronger as the number trailing blocks grows. This is due to the “longest chain rule” and the fact that the honest nodes are the majority. A block created
As discussed previously, a fork is defined as two chains $C_1$ and $C_2$ that are returned from \texttt{CanonicalChain}(\texttt{Block}(u,r),\texttt{Block}(u,r-1)) and \texttt{CanonicalChain}(\texttt{Block}(u_1,r),\texttt{Block}(u_1,r-1)) respectively. Here, $C_2$ is a predetermined parameter, where $C_2 \bot C_1$ is defined as there exists a block set $B_1 \subseteq C_1, B_1 \cap C_2 = \emptyset$ and $B_2 \subseteq C_2, B_2 \cap C_1 = \emptyset$. Similarly, we use the notation $B_2 \bot B_1$ if they are not on the same chain and $B_2 \sim B_1$ if they are on the same chain. Then, we define the depth of the fork as $\max(|B_1|,|B_2|)$. We concern about the possibility of existing a fork with depth $k$, where $k$ is a predetermined parameter for confirmation. Clearly, a fork of depth $k$ is able to be exploit to perform a double spending attack.

5.1.1 Forks

A fork is defined as two chains $C_1$ and $C_2$ that are returned from \texttt{CanonicalChain}(\texttt{Block}(u, r), \texttt{Block}(u, r-1)) and \texttt{CanonicalChain}(\texttt{Block}(u_1, r), \texttt{Block}(u_1, r-1)) respectively. Here, $C_2 \bot C_1$ is defined as there exists a block set $B_1 \subseteq C_1, B_1 \cap C_2 = \emptyset$ and $B_2 \subseteq C_2, B_2 \cap C_1 = \emptyset$. Similarly, we use the notation $B_2 \bot B_1$ if they are not on the same chain and $B_2 \sim B_1$ if they are on the same chain. Then, we define the depth of the fork as $\max(|B_1|,|B_2|)$. We concern about the possibility of existing a fork with depth $k$, where $k$ is a predetermined parameter for confirmation. Clearly, a fork of depth $k$ is able to be exploit to perform a double spending attack.

5.1.2 Forks with colliding blocks

In this case, as the leader and committee are deterministic and fixed for each round given the random beacon is consistent, the leader of round $r$ must be adversarial to create $B_1$ and $B_2$. Then, in order to create inconsistency, he sends these two blocks, in particular, the last part of the block, in the very end of round $r$. However, by our endorsement rule, the committee members will only endorse for a block summary after a period of $\Delta$ in round $r+1$. Then, by the gossip communication model in normal situation, both blocks will be received and be considered as suspicious by honest nodes and discarded. Hence, a $k$-depth fork with colliding block must be caused by $k$ consecutive adversarial leaders and committee members in synchronous scenario.

5.1.3 Forks without colliding blocks

There is another scenario in which the fork could be created and extended without colliding blocks. Let consider the following case:

At round $r+1$, the adversarial leader $l_{r+1}$ creates a block $B_{r+1}$ appending to the block in round $r$, denoted by $B_r$. He follows the normal procedure to broadcast the block summary, collect the endorsements, except for that he “fraudulently delays” the broadcast of the collected endorsements. As a result, $B_{r+1}$ is not actually broadcast, and thus not acquired by the rest of the network. Then, the adversarial leader of round $r+2$, $l_{r+2}$, creates a block appending to $B_r$. It will be endorsed by the honest committee as $B_r$ is the latest block that they observed. However, $l_{r+2}$ again “fraudulently delays” the broadcast of $B_{r+2}$. At the meantime, $l_{r+1}$ broadcasts $B_{r+1}$. Then, the adversarial leader of round $r+3$ will perform the same strategy to extend the chain of $B_{r+1}$. Further, the leader of round $r+4$ could also use the same strategy to extend $B_{r+2}$. Note that although the chain of $B_{r+2}$ has the same length as the chain of $B_{r+1}$, however, by our chain selection rule, $B_{r+2}$ is the latest and should be selected. So on and so forth, adversaries could create a $k$-depth fork with $2k$ adversarial leaders with honest committees.

However, this type of forks are addressed by our rules of honest blocks. In normal mode, the blocks which are received outside of its round will be considered as suspicious and will not be taken into account for canonical chain selection.

5.1.4 Numerical analysis

As discussed previously, a $k$-depth fork requires at least $k$ consecutive malicious leaders and committees in the normal situation. However, we need to consider the possibility of biasness, i.e., if the beacon happens to be created by a malicious leader, then, he could exhaust approximately $C(c, d)$ times to try to create a scenario of $k$ consecutive adversarial leaders and committees. Hence, we show the probabilities of successful double spending attack in the worst case, i.e., allow corruption and accurate prediction of the random beacon creator.

The probability of a malicious committee, i.e., at least $d$ committees are malicious is the cumulative distribution function of binomial distribution:

$$\Pr(\text{MC}) = \sum_{d'=d}^{\infty} \binom{f}{d'} \left( \frac{c}{n} \right)^{d'} \left( 1 - \frac{c}{n} \right)^{f-d'}$$
First of all, we need to set \( k < \tau \) so that it is guaranteed that honest nodes will not confirm any transaction in asynchronous situation. Then, the round duration should be set accordingly to the capacity of the network. Assume that we could set the round duration to 10 seconds. Then, if \( \tau = 6 \), by Table 1 we could choose \( k = 5, c = 15, \) and \( d = 11 \). Then a transactions \( tx \) will be confirmed in at most 60 seconds after it is proposed in a valid block. Once it is confirmed, a double spending attack on this transaction, i.e., an attack on the consistency, is exactly the case that there exists a \( k \)-depth fork. Then, by Table 1 the probability of attack is \( 1.51 \times 10^{-8} \).

### 5.2 Finality

Besides a generalization of the Nakamoto-like consensus, SURFACE is also a generalization of BFT algorithms like \([23,48]\) with a flexible committee size. As a result, SURFACE could also achieve finality, i.e., the consistency condition in BFT consensus, in a similar fashion as \([48]\).

Firstly, we prove the following lemma:

**Lemma 1** (Forward consistency). If an honest node \( u \) has \( B_{\text{cmt}}(u, r) = B \), then, there could not be another honest node \( u' \) that pre-commits a newer but conflicting block \( B' \), i.e., \( B' \preceq B, B' \perp B \) and \( B_{\text{cmt}}(u', r') = B' \).

**Proof.**

By our algorithm, if \( B \) is committed, then there must exist a chain \( C, B \in C \) that has \( 2f + 1 \) prepare messages in a view \( B_1 \) and \( 2f + 1 \) pre-commit messages for \( B \) in a view \( B_2 \). W.l.o.g. we assume that \( C \) is the chain that \( B \) is pre-committed for the first time, i.e., the does not exist another chain \( C' \) that has \( 2f + 1 \) pre-commit messages for \( B \) in a view \( B_2, B_2 \prec B_2 \). Then, since \( B' \) is pre-committed, there is another chain \( C' \) that has \( 2f + 1 \) new view messages and \( 2f + 1 \) pre-commit messages for \( B' \) in a view \( B_2' \). Then, there must exist an honest node \( v \) that sends both the pre-commit message for \( B \) in the chain \( C' \) in view \( B_2' \) and the prepare message for \( B' \) in the chain \( C' \) in view \( B_2' \) and an honest node \( v' \) that sends both the pre-commit message for \( B \) in the chain \( C' \) in view \( B' \) and the new view message for \( B' \) in the chain \( C' \) in view \( B' \). \( v \) and \( v' \) could be the same node.

Firstly we consider node \( v \). By the prepare rule, if he first pre-commits \( B \) then prepares \( B' \), then \( B' \succ B_2 \) should hold. Then we focus on \( v' \). It must hold that node \( v' \) first pre-commits \( B \) in view \( B_2 \) then send new view message for \( B' \), otherwise he cannot send pre-commit message for \( B \) in view \( B_2' \) by the new view rule. Then, he will send a pre-commit message for \( B \) along with the new view message for \( B' \). Then, by the first prepare rule, \( B' \) cannot be prepared, which contradicts our assumption.

Hence, \( v \) must have first prepared \( B' \) in view \( B_2' \) then pre-commits \( B \) in view \( B_2 \). Note that by our assumption that \( B \) is first pre-committed in chain \( C' \), the second pre-commit rule does not apply. Then, by the first pre-commit rule (in line 11), he must have first prepared \( B' \prec B \), then pre-commits \( B \), which is not possible as the rule of unlock pre-commit blocks (in line 24) comes after the pre-commit rule and will unlock the pre-committed block.

Then, with Lemma 1 we straightforwardly have our theorem for finality (consistency).

**Theorem 1** (Finality). In SURFACE, if an honest node \( u \) has \( B_{\text{cmt}}(u, r) = B \), then, there could not be another honest node \( u' \) that considers a conflicting chain is final, i.e., there cannot be another node \( u' \) and a round \( r' \) that has \( B_{\text{cmt}}(u', r') = B' \) and \( B \perp B' \).

### 5.3 Synchronous liveness and high responsiveness

Firstly, we prove the following lemma showing that blocks will be prepared in “normal” situations.

**Lemma 2.** In the normal situation, new blocks can be prepared regardless of the finality vectors of the nodes.
Proof. By our assumption, it is straightforward that blocks will be prepared if the network is always in normal situation. We focus on the scenario that nodes start with different finality vectors, in particular, locked with different pre-commit blocks. We show that there will eventually be a large group of nodes having consistent finality vectors if they have the same $B(u, r)$. Hence, in each round, blocks could be generated with a non-zero probability. Let us assume that honest nodes are pre-committed to a set of blocks $B^*$ at round $r$, in which $B^*_1$ is the latest one.

Firstly, for all nodes that are pre-committed to a block $B^*_0 \neq B^*_1$, they will unlock from their pre-committed block as $B^*_1$ is prepared and $B^*_1 \succ B^*_0$ according to the unlock rule of the pre-committed block.

Then, if there exists a block $B^*$ that is prepared after $B^*_1$ being pre-committed, then by the rule of unlocking pre-committed blocks, nodes will not pre-commit $B^*_1$ as well as any other block. Then, all nodes will have a consistent finality vector to make new blocks.

If there does not exist a block that is prepared after $B^*_1$ and there is a pre-commit message of $B^*_1$ appearing on the canonical chain. By our pre-commit rule, all honest nodes will pre-commit $B^*_1$ and then prepare for new blocks.

At last, if there does not exist a block that is prepared after $B^*_1$ being pre-committed and there is no pre-commit message of $B^*_1$ appearing on the canonical chain. Then, assume that there are $m$ honest nodes that have pre-committed $B^*_1$ and $2f + 1 - m$ honest nodes that have not pre-committed $B^*_1$. Then, in normal situation, approximately, with a probability of $\frac{C^{m+f}_{f+m}}{2^{m+f}}$ that a new block with no pre-commit message for $B^*_1$ will be made and with a non-zero probability of $\frac{C^{n-m}_{n-f}}{2^{n-m}}$ that a new block with pre-commit messages for $B^*_1$ will be made. In the former case, if $m \geq f + 1$, a new block will eventually be prepared and all nodes will unlock $B^*_1$. In the latter case, all honest nodes will pre-commit $B^*_1$. Hence, for any $m$, we guarantee that blocks could be in normal situation.

With Lemma 2, we have the following theorem.

**Theorem 2** (Liveness). *In normal network situation, new blocks could be committed.*

**Proof.** By Lemma 2, all node will eventually prepare for a new block. Then, in the normal situation, all node should be able to have a consistent canonical chain. Hence, by our algorithm, the prepared block would be able to collect $2f + 1$ prepare messages, $2f + 1$ pre-commit messages, and eventually be committed.

Note that an attack can be made by colluded a leader and committee to propose a block $B$ with a commit message for arbitrary $B'$ in a view to delay the process. However, the liveness is still guaranteed if we choose the committee size deliberately such that the probability of a collude leader and committee happens in a view is low. Hence, we guarantee that new blocks will eventually be finalized in the normal situation.

6 Comparison to other algorithms

In general, one of the major difference between SURFACE and all other algorithms are the design of two modes, which distinguishes SURFACE from most blockchain consensus algorithms. The most similar ones are the Nakamoto consensus algorithms with finality, like Casper [12] and GRANDPA-BABE [47, 5]. Besides, we will also compare SURFACE to BFT algorithms like Algorand, HotStuff BFT, Tendermint, and Nakamoto consensus algorithms like Ouroboros.

6.1 Casper and GRANDPA-BABE

Casper [12] is a consensus algorithm that is designed to promote public blockchains like Ethereum with finality. Polkadots [47] uses a consensus scheme called GRANDPA-BABE [5], which uses the finality arguments of Casper in a permissioned blockchain. Firstly, BABE is an algorithm that is similar to Ouroboros-Praos [15] that uses a VRF based approach to determine the block proposer of each round. Then, GRANDPA is used to allow nodes to spontaneously vote for the blocks and uses BFT arguments to reach finality.

As far as we know, GRANDPA-BABE is independently developed and is the most similar consensus algorithm to SURFACE in sense that it also uses a VRF based approach to guarantee an ever-growing chain and achieve finality upon that with BFT arguments. However, SURFACE and GRANDPA-BABE are different in the following aspects:

- In a certain sense, the voting mechanism of GRANDPA is equivalent to a dynamic-size committee for each block. Hence, the performance of GRANDPA-BABE will differ from SURFACE depending on the network situation. In general, SURFACE will give a more stable confirmation time and a lower fork rate, while the
performance of GRANDPA-BABE will depend on how motivated nodes are for voting. On the other hand, GRANDPA-BABE has not yet introduce an incentive scheme for the voters.

- GRANDPA does not have optimal responsiveness as stated in [48]. In other words, in extreme scenario, honest nodes will have to wait for the maximum delay $\delta$ to make progress, which is not the case in SURFACE.

6.2 HotStuff BFT

The “abnormal” mode in SURFACE uses a similar but not identical approach as HotStuff BFT [48] to achieve consensus. One of the major differences is that in SURFACE, we make a chain self-contained in terms of new view, prepare, pre-commit, and commit messages, i.e., a node that later joins the network or recovers from disconnection can determine whether a block has reached finality by checking its chain but not other forks, which is not the case if we let nodes simply follow HotStuff BFT and send these messages as transactions. In that case, all these messages, regardless what chains they are on, should all be received and recorded to achieve consensus.

Another difference is that SURFACE functions in the practical asynchronous network and HotStuff BFT functions in partial synchronous network. However, although these two network assumptions are different, both algorithms could in fact be easily modified to function in the other network assumption as well.

The main advantage of SURFACE over HotStuff BFT is the random sample of committee allows a faster probabilistic confirmation speed in large networks in the “normal” mode. In HotStuff BFT, the block interval needs to be sufficient for $2f + 1$ nodes to respond. However, in SURFACE, the block interval could be set smaller as the leader only needs to wait for the committee to respond.

6.3 Algorand

Algorand [23] is similar to the “normal” mode of SURFACE in many aspects. However, Algorand achieves provable BFT with the leader and committee selected in each round, while SURFACE aims to only reduce the probability of forks. Note that there is a trade-off between the committee size and the fault tolerance in Algorand: in order to guarantee that the number of the adversaries in each committee is less than 1/3 by the law of the large number, the size of the committee and the ratio of adversaries in the network should be set accordingly. In SURFACE, this is not a concern as we allow the committee to be malicious and to create forks.

6.4 Tendermint

Tendermint [31] achieves BFT in synchronous network, which is a stronger assumption than practical asynchronous network model in SURFACE. Hence, in Tendermint, the consistency still replies on the synchrony, which is sometimes not a sufficient security guarantee for industrial uses.

7 Conclusion

In this paper, we present SURFACE, a blockchain consensus algorithm that is especially designed and optimized for large real-world blockchains. The main reason behind the proposal of blockchain is the observation that in real-world, we tend to use double standards on the consensus algorithms used in blockchains. On one hand, it is commonly believed that synchronous consensus algorithms are not sufficient and suitable for blockchains. On the other hand, most blockchains function in highly synchronous networks and Bitcoin’s POW actually has a very high requirement of synchrony. As a result, the proposed blockchain consensus algorithms are either theoretically sound for asynchronous case but not optimized in practice, or achieve sky-high performance in laboratory environments but vulnerable in extreme situations. Hence, we take both perspectives into account and put forth the practical asynchronous network model. We then propose SURFACE, which will give a near-optimal performance in the normal situation but still be able to reach definitive consistency in the extreme situations. Certainly, the drawback of SURFACE is that it will have sub-optimal performance if the network is different from our assumptions, e.g., the network shifts between multiple situations or partitions or attacks in network becomes a new “normal” situation for various reasons. However, we believe SURFACE does fit the scenarios of most real-world blockchains and could provide a reasonably good performance for general cases.

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