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Reinshard: An optimally sharded dual-blockchain for concurrency resolution

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Decentralized control, low-complexity, flexible and efficient communications are the requirements of an architecture that aims to scale blockchains beyond the current state. Such properties are attainable by reducing ledger size and providing parallel operations in the blockchain. Sharding is one of the approaches that lower the burden of the nodes and enhance performance. However, the current solutions lack the features for resolving concurrency during cross-shard communications. With multiple participants belonging to different shards, handling concurrent operations is essential for optimal sharding. This issue becomes prominent due to the lack of architectural support and requires additional consensus for cross-shard communications. Relying on the advantages of hybrid Proof-of-Work/Proof-of-Stake (PoW/PoS), like Ethereum, hybrid consensus and 2-hop blockchain, we propose Reinshard, a new blockchain that inherits the properties of hybrid consensus for optimal sharding. Reinshard uses PoW and PoS chain-pairs with PoS sub-chains for all the valid chain-pairs where the hybrid consensus is attained through Verifiable Delay Function (VDF). Our architecture provides a secure method of arranging nodes in shards and resolves concurrency conflicts using the delay factor of VDF. The applicability of Reinshard is demonstrated through security and experimental evaluations. A practical concurrency problem is considered to show the efficacy of Reinshard in providing optimal sharding.

Additional Key Words and Phrases: Blockchain; Hybrid Consensus; Sharding; Concurrency Control.

1 INTRODUCTION

Blockchain through its decentralized and authenticated append-only ledgers provides transparent, easily available, and accessible digital content sharing with censorship resistance [25, 32, 47]. The use of blockchain is dominated by the cryptocurrencies in the financial market and major efforts are made to make them efficient, scalable, and flexible [15, 44]. However, the market trends are changing and the applications of blockchains are seen beyond cryptocurrencies [33]. The maintenance of low-latency, flexible, secure and scalable architecture is the key requirement of blockchain applications [13, 27]. There exist a plethora of approaches to the formation of provably secure and scalable blockchains by using different consensus like PoW, PoS, etc. Dominantly, PoS has been a promising paradigm for future blockchain implementations as it provides multiple benefits over PoW-based systems, which involve a highly difficult puzzle-solving increasing with the network size. In general, PoS can be divided into four main categories [45], namely, chain-based PoS (Ppcoin [22], Nxt [4]), committee-based PoS (Ouroboros [21], Ouroboros Praos [7], Snow White [6]), Byzantine Fault Tolerance (BFT)-based PoS (Tendermint [24], Algorand [16]), and delegation-based PoS (Lisk [30], EOS.IO [12]). However, despite clear benefits, PoS-blockchains need to counter with issues affecting the consensus,
which include influential assets, identity revealing, unwanted centralization, non-flexible and non-adaptive chaining, and community-frauds [45]. Scaling blockchains beyond the current state require decentralized control, low-complexity, flexible and efficient communications, which can be attained by reducing ledger size and providing parallel operations in the blockchain, such as Sharding[46].

In the sharded-blockchains, the communications are severely affected by concurrent requests between the shards, which includes the split infrastructure of the blockchain. Concurrency-resolution requires enough delay to initiate a waiting mechanism between the involved parties to complete their transactions. A solution in the form of new architecture is required that can add certain delay during the cross-shard communications without compromising the security as a higher delay value can risk the security. Such architecture should be supported by an efficient consensus scheme that should not affect the general workflow as well as maintain the security properties of the sharded-blockchain that involves chain-growth, chain-quality, common-prefix, and unbiased sharding. The main contributions of our work are:

• A dual-blockchain architecture, based on hybrid consensus [11, 36, 38], is presented with provision of auto-sharding. A unique auto-sharding feature is proposed, which helps to lower the burden in terms of ledger maintenance and reduce the synchronization problem with application to both PoS-sub-chain and the main chain-pairs.
• The new architecture resolves the fundamental issue of concurrency conflicts during cross-shard communications. A simulated VDF is used for resolving concurrency issues and chain-extensions via a delay-factor.
• An exemplary concurrency problem, Train-and-Hotel booking system [41], is used for demonstrating the effectiveness of the proposed model.

2 RELATED WORKS

Security and decentralization are two main factors to maintain in large scale and permissionless systems [37, 45]. The existing mechanisms use a central entity or checkpoints for attack mitigation. However, this leads to unwanted centralization and affects performance, which can be handled through optimal sharding. It involves both intra- and inter-(cross) shard communications. Several sharding mechanisms have been developed for either scalability, security, or both. Most prominent includes, Zilliqa’s model [39, 42], Omniledger [23], RapidChain [48], Elastico [31], and Harmony [42]. However, there exists a practical issue of concurrency when cross-shard operations are involved, and there are no evident demonstrations on how concurrency is handled in these sharded blockchains. Such issues cause deadlocks which prohibits the use of blockchain for a wide range of network-based applications. The lack of architectural-support by the existing blockchain-solutions in resolving concurrency conflicts while performing inter-shard communications motivated us to design a new blockchain without compromising the security.

The properties of the user selection process effectively dominate the security of the blockchain [26]. To understand the working of blockchain architecture, specific platforms, like [19] on blockchain analysis, can help in understanding the evaluations of applications related to cryptocurrencies. Crain et al.[5] introduced that the shared verification to control the number of signature verification with an impact on improved performance of the blockchain concerning the transactions without compromising the security. Storage auditing can have a severe effect on the performance of the blockchain. In this direction, Du et al.[9] identified a critical security problem that impacts the integrity of storage auditing solutions in the blockchain. In a blockchain, worker’s fairness is vital and can be affected by the usage of third parties in performing computations. Lin et al.[29] developed an optimised blockchain-based fair payment method for
the outsourcing of computations. The authors proved security analysis while utilising their approach for scalability and concurrency resolutions. Concurrency can also be handled via smart contracts. Smart contracts can be used to implement parallel solutions, which can improve the performance in permissioned blockchain as studied in Jin et al. [40]. Chen et al. [3] proposed a scalable blockchain by exploiting intra- and inter-block concurrency. The authors used three phases for multiple organisations to form a network allowing improved gains for handling concurrency.

Hybrid consensus allows better support for integrating, securing and improving different blockchains by using the strength of one consensus mechanism to resolve the shortcomings of another [2, 36, 38]. One of the examples of a hybrid blockchain is 2-hop blockchain [11], which is a provably secure and scalable public blockchain. It uses PoW and PoS chain-pair as its operational principles. The key principle is two-way security which prevents an attacker from controlling the PoW-chain even if it owns the majority of the mining power. The use of PoS along with PoW allows the construction of a secure chain which is extended as TwinsCoin by Duong et al. [10]. The primary advantage of 2-hop blockchain and TwinsCoin is the prevention of adversaries that tend to control more than 50% of the mining power [10, 11]. Fig. 1 shows the PoW-block generation in TwinsCoin by following the concept of a modified 2-hop blockchain.

The difference between the 2-hop blockchain [11] and TwinsCoin [10] is the variation in the difficulty adjustments. The former uses an equal number of blocks for PoW and PoS chain, which makes difficulty-adjustment tedious and high complex; whereas the latter uses a ratio mechanism to decide on the number of PoW and PoS blocks, as shown in Table 1. This makes difficulty-adjustment possible, however at an expense of additional resources which are not yielding to performance apart from security, in the case of hybrid consensus. The 2-hop blockchain uses a PoW-PoS chain-pair, in which an extension to PoW chain is carried using a hash of the previous PoW block, a hash of the head of the PoS block and then solving it to find a suitable solution until a value lesser than the target value is not attained [11]. The PoS-chain is extended by finding a verification key to satisfy the new block under the given PoS target. This mechanism is used to generate a long-chain in one direction and then select the best valid chain-pair. In 2-hop blockchain, a PoW-block must be accompanied by a PoS-block for its possible inclusion in the blockchain, whereas in TwinsCoin, PoW-blocks without PoS-blocks are referred to as attempting blocks. The actual length of the blockchain is only based on the successful blocks.

3 PROPOSED MODEL: REINSHARD
The proposed blockchain is a combination of the PoW-PoS chain-pair and PoS sub-chain which allows an effective way of including blocks, especially targeted towards the resolution of the concurrency issues, as shown in Fig. 2. In
Table 1. Comparison of chain extensions and difficulty adjustments of existing blockchain models. \( h_\rho \in \{0, 1\}^\lambda \) is the hash of the previous PoW block, \( \lambda \) is the security parameter, \( \rho \) is the suitable solution, \( X \) is the block record, \( T \) is the current PoW target, \( h_s \in \{0, 1\}^\lambda \) is the hash of the head of the PoS chain, \( B_{PoW} \) is the PoW block, \( v_k \) is the verification key, \( \tilde{T} \) is the current PoS target, \( h_a \in \{0, 1\}^\lambda \) is hash of the attempting PoW block for the local view, \( r \) is the epoch, \( t \) is the expected time of an epoch, \( t_r \) is the actual time of an epoch, \( n \) is the number of coins with the stakeholder, \( E \) is the expectation of probability of successful PoW to stakeholder mapping, \( \mu_r \) are the PoW blocks in \( r \)th epoch and \( \mu \) is the number of blocks after which the difficulty has to be adjusted. (NA: Not Applicable because of principle difference)

| Blockchain          | Extensions (PoW) | Extensions (PoS) | Difficulty (PoW) | Difficulty (PoS) |
|---------------------|------------------|------------------|------------------|------------------|
| Nakamoto blockchain [35] | \( H(h_\rho, \rho, X) < T \) | NA | \( T_{r+1} = \frac{t_{r+1}}{t_r} T_r \) | NA |
| 2-hop blockchain[11] | \( H(h_\rho, h_s, \rho) < T \) | \( \tilde{H}(B_{PoW}, v_k) < \tilde{T} \) | NA | NA |
| TwinsCoin [10]      | \( H(h_\rho, h_s, h_a, \rho) < T \) | \( \tilde{H}(B_{PoW}, v_k) < n\tilde{T} \) | \( T_{r+1} = \frac{\mu_{r+1}}{\mu_r} T_{r+1} \) | \( \tilde{T}_{r+1} = \frac{\mu_{r+1}}{\mu_r} \tilde{T}_{r+1} \) |

Fig. 2. An overview of the proposed blockchain structure with growth in two directions.

Reinshard, the initial blocks of the chain-pairs are generated using the principles of PoW in 2-hop blockchain [11], which on lateral functioning are joined by many sub-PoS blocks. Thus, growing the chain in two directions. In general, the proposed blockchain structure can be expressed as follows:

**Definition 3.1.** The dual-blockchain structure can be defined as a variant of the 2-hop chain-pair denoted by \( B_G = (C_W, C_S) \), where \( C_W \) and \( C_S \) are the set of PoW blocks (for miners) and PoS blocks (for stakeholders) with \( M \) and \( N \) blocks, respectively, and \( B_G \) is the global blockchain. Here, each pair (by definition of 2-hop blockchain [11]) will be considered valid if every PoW block is possessing at least one PoS block.

**Definition 3.2.** Each PoW-PoS chain-pair can further have pseudo blocks which are denoted by a set \( C_W^{(P)} \), such that \( C_W^{(P)} \subseteq C_W \) and \( |C_W^{(P)}| < |C_W| \). As stated in Definition 3.1, \( M \) also involves the pseudo blocks. The pseudo blocks are used to include additional PoS blocks under the same PoW-PoS chain-pairs respecting the limits of maximum PoS blocks in each sub-chain.
In the proposed model, $N = \sum_{i=1}^{M} K_i$, where $K_i$ denotes the number of sub-blocks with the $i$th PoW block including the one associated before the attachment of the incoming blocks. Hence, the minimum number of PoS blocks in the entire chain is given as $N_{\text{min}} = M - M'$, where $M' = |C_{\text{w}}|$ is the number of pseudo blocks. The key factor in the formation of this initial blockchain is the identification of the maximum permissible value of $K$ so that the performance, as well as the security, can be realized simultaneously.

How many PoS blocks can be appended to a valid PoW-PoS chain-pair? This deals with the optimization aspect and should be adjusted dynamically, which means that the chain structure should be able to grow as well as shrink. This adds to the complexity of guessing the difficulty adjustment for an adversary and it cannot identify the leader amongst the valid chain-pairs; alongside, it fails to track the nodes’ locations in the shards. The key factor to account for the chain length is the stake-ownership for the PoS-chain by the nodes with the added blocks. If $S_{\text{max}}$ and $S_{\text{min}}$ are the maximum and the minimum number of stakes, then the length of the PoS chain under each PoW block must satisfy the earned stakes, as $S_{\text{min}} \leq S_i \leq S_{\text{max}}$. However, an attacker may show high stakes and can affect the chain limits by controlling the chain length leading to a single-shard takeover attack. This can be prevented by optimal calculation of upper bounds of $K$, and even if an attacker controls the operations, it cannot guarantee the growth of the same PoS chain beyond a certain range. Such a mechanism will prevent false block generation as well as help other nodes to identify the faulty operations. The value of $K$ can be calculated either through equal bounds, random or reward-based allocations. Equal bounds affect the sharding procedures by causing long-range attacks as well as a limited-stake attack (controlling at least $x$ number of stakes instead of showcasing majority). Such attacks, otherwise, can be prevented if bounds on $K$ are unpredictable. Random allocation can reduce the overheads associated with the predictability of blocks based on the difficulty adjustments, but it increases the complexity of shard formations and communications. In contrast, reward-based can help in unpredictable as well as low-complex fixing of the bounds.

### 3.1 Reinforcement Learning (RL) based-bound

RL-based bound is an important strategy to be used in the case of uncertain environments, and can be used for automated attack analyses [18]. RL helps to accumulate decisions based on certain rewards that are observed when the environment transits from its current state to the desired state. In Reinshard, PoW-PoS chain-pairs (part of $B_G$) are the environments which are in a state possessing a certain number of PoS blocks and the next state refers to the inclusion of an incoming PoS block. In the proposed approach, the attachment through RL is based on metrics of the nodes owning a valid PoW-PoS chain-pair. The properties involve a list of metrics that are to be considered for deciding the rewards on transitions which help to fix the upper bounds on $K_i$. These metrics include, the number of permissible pseudo IDs ($\eta_i$), available storage ($G_i$), expected required storage ($G_e$), available stakes ($S_a$), Computation-power reward ($\omega$), and chain-growth rate reward ($\theta$). The computational power and block operations (chain growth rate) are presented as a value where the physical meaning is mapped to parameters, $\omega$ and $\theta$, respectively. All these metrics are operated over RL-model to help decide the rewards, which are translated into the upper limits of the number of blocks that must be present or allowed as a part of a sub-PoS chain. The use of RL-rewards helps to ensure that actual details on the configurations of nodes are never revealed to its peers, which prevents attackers to know the possibilities of incoming blocks. Moreover, it also prohibits the attacker to generate more PoS blocks to prevent general PoW-PoS operations. Such provisioning prohibits the long-range attacks as well as prevents an excessive number of untraced pseudo-IDs which may otherwise increase the performance overheads. Considering this, the additional number of blocks that can
be accommodated under one pseudo ID of a valid chain-pair is given by:

\[ K_{i,t}^{(A)} = \frac{G_\omega}{\eta_i G_e} \]  

(1)

provided that \( G_e \eta_s \leq G_\omega \). If this condition is unsatisfied, the new blocks cannot be included under the valid chain-pair. Consequently, the permissible range of \( K_i \) at \( t+1 \) becomes \( K_{i,t} + K_{i,t}^{(A)} \). On observing this value, each pseudo ID group of the valid PoW-PoS chain-pair is evaluated for their chain length, and the one with available slot (position for the block) and being a leader can accommodate the incoming block. In case the available space is split between the two or more pseudo chains, the attachment is unaffected as one block is appended at a time. In case the blocks are in batches, the First Come First Serve (FCFS) is considered, and in the case of the parallel instances, the blocks are assigned in order of their memory utilization (decreasing order). There are certain cases where the number of pseudo IDs possesses similar properties (especially when the blockchain is initiated or additional nodes join), then the selection of pseudo chain is done using \( S_\omega, \omega \) and \( \theta \). As a solution, the pseudo chain with the corresponding users having \( \max(S_\omega) \) is selected to accommodate the new PoS block. Scenarios, where the stakes cannot be distinguished, account for reward values of \( \omega \) and \( \theta \) to select a sub-chain with the maximum reward-value. The reward-value based on \( \omega \) and \( \theta \) is calculated as:

\[ R(\omega, \theta)_{i,t} = \theta_{i,t}^{-1} + \gamma_{i,t} \omega_{i,t}^{-1}, \]

(2)

where \( \gamma \) is the controlling parameter which shows the association and is depicted as the probability of successful identification of a valid chain-pair. For most of the cases, \( \gamma = 1 \), as the ledgers are always aware of the associated blocks. Here, \( \omega \) is evaluated as the maximum likelihood estimate for the mining-rewards earned (upon validation), for the duration \( t \), considering that the block operations follow a single parameter beta distribution [17], such that

\[ \omega_{i,t} = K_{i,t} \left( \sum_{j=1}^{K_{i,t}} \log \left( \frac{1}{1 - \left( \frac{O_\alpha(t)}{O_\epsilon(t)} \right)_j} \right) \right)^{-1}, \]

(3)

where \( O_\alpha \) and \( O_\epsilon \) are the actual earning rate and expected earning rate (these metrics are affected by the difference in the hash rate and the difficulty of mining), respectively. This helps to prevent the dominance effect\(^1\). However, in non-available situations, the reward is calculated based on \( \theta \), which is calculated as:

\[ \theta_{i,t} = \left( \theta_{i,t-1} + \delta_{i,t-1} \right)^{1}, \]

(4)

where \( \delta \) is the chain growth rate, which is calculated as the ratio of the actual number of blocks appended to the PoS-sub-chain to the expected number of appends. In a fully-aware scenario, this ratio is taken to the total PoS-blocks in all the valid chain-pairs. It is to be noted in (2) that the chain with subsequent lower values for the observation rates defined for incoming rewards and the chain growth is given preference in selection. This prevents long-waits as well as increases participation. In the scenarios, where the above designing does not account for the inclusion of a new PoS block, a valid (winner) PoW-PoS chain-pair may delegate the incoming PoS block to another valid PoW-PoS chain-pairs. The procedures for handling incoming PoS block by the winning chain-pair are given in Algorithm 1. To model delegation, the model uses Q-learning RL, such that \( B_C \) forms the environment considering a given chain-pair, \( (C_W, C_S)^x \), where \( V_x \) denotes the valid pair. Now the set of actions are denoted as \( (C_W, C_S)^x \), which includes two possible values, allow (delegate) and disallow. Using these, a timely Q-learning table is generated to understand the

\(^1\)Consider an application process, where a server keeps on earning mining-rewards and manipulates users. In such a case, the server imbalances the PoW-PoS chain-pairs and leads to a dominance effect. This will lead to several attacks that are bounded to occur in an uncontrolled PoS chain.
Algorithm 1: PoS block allocations with RL.

Result: PoS block allocation

\[ V = (C_W, C_S)^V \]

obtain (at \( t \)) \( \eta, G_a, G_e, S_a, \omega, \theta \);

\( f_v = \text{check_validity}(V, \text{bool}) \);

if approach == reinforced then

while pos_decision \( \neq \) True do

select \( i = \text{valid}(f_v) \)

\( \eta_x = \text{count}(\text{pseudo_ids} \leftarrow \text{valid}(f_v)) \);

\( K_{i}^{(A)} = \frac{C_a}{\text{pseudo}} \)

\( K_{\text{max}} = K_{i}^{(A)} + \text{strength}(i) \)

if \( \eta_x \leq \eta_s \) then

if \( K_{i}^{(A)} > 1 \) \&\& \( \eta_x > 1 \) then

while \( j \leq \eta_x \) do

if \( K_{i}^{(A)} + \text{strength}(j) \leq K_{\text{max}} \) then

\( X = (f_v, j) \);

end

\( j = j + 1 \)

end

if count(\( X \)) == 1 then

allocate_unobject_reinforced(\( X \))

else

while \( q > \text{count}(X) \) do

\( S_a, q = \text{stakes}(X_q) \);

\( q = q + 1 \);

end

if Equal(\( S_a \)) == True then

\( Z = \text{count}(\text{Equal}(S_a)) \)

while \( r \leq Z \) do

\( R(\omega, \theta) = \theta^{-1} + \gamma \theta^{-1} \)

\( r = r + 1 \)

end

\( Y = \text{max}(R(\omega, \theta)) \)

allocate_unobject_reinforced(\( Y \))

else

\( Y = \text{max}(S_a) \)

allocate_unobject_reinforced(\( Y \))

end

end

else if \( K_{i}^{(A)} = 1 \) \&\& \( \eta_x = 1 \) then

allocate_unobject_reinforced(i);

else

wait_or_delegate();

end

else

wait_or_delegate();

end

Logs()
around the non-inverse maximization of (2), which means that the choice of next PoW-PoS chain-pair, by definition [34], is based on:

$$\max(Q((C_W, C_S)^{V_x}_{t+1}, (C_W, C_S)^A)), \quad (5)$$

such that

$$Q((C_W, C_S)^{V_x}_{t+1}, (C_W, C_S)^A) = Q((C_W, C_S)^{V_x}_{t-1}, (C_W, C_S)^A) + \delta(t-1).$$

$$\left(R'(\omega, \theta) + P_x \cdot \max(Q((C_W, C_S)^{V_x}_{t+1}, (C_W, C_S)^A)))\right),$$

where

$$R'(\omega, \theta)_{i(t)} = \theta_{i(t)} + p(t) \omega_{i(t)}.$$ \quad (6)

Here, \(\delta \neq 0, Q((C_W, C_S)^{V_x}_{0}, (C_W, C_S)^A) = 0,\) and \(P_x\) is the probability of reserving a future slot for the incoming blocks. As it is difficult to predict such reservations, we model this probability around controlling parameter, such that \(P_x = \gamma\).

The physical meaning of the maximization means that the delegated PoS block must not over consume the resources of the PoW-PoS chain-pair to which it is delegated leaving no space for its own PoS blocks. Thus, the chain-pairs which show sufficient intake possibilities are selected for delegation.

3.2 Chain-growth and difficulty adjustments

The chain-growth in the proposed blockchain is observed in two directions, one for the PoW-PoS chain-pair and another for PoS-sub-chain.

–PoW-PoS chain-pair: The operations of the PoW-PoS chain-pair in the proposed model are inspired by 2-hop blockchain [11]. However, the PoW blocks which are ignored from chain inclusion have to re-approve their mechanism and convert itself to a valid pair by first joining through a PoS sub-chain. The block format in the chain-pair is similar to 2-hop blockchain (Fig. 2) as \(H(h_p, h_s, \rho) < T\). However, the expansion of the PoW-PoS chain-pair is controlled by the current pseudo-pair generation rate of the entire blockchain. This means, if \(\alpha_m\) is the pseudo-pair generation rate, then the new chain-pair can be accommodated according to,

$$H (\alpha_m, Z(h_p, h_s), \rho) < T,$$ \quad (7)

where \(H(.)\) and \(Z(.)\) are the respective cryptographic hash functions. The proposed model uses pseudo-blocks’ generation rate as it focuses on improved applications along with sharding. The function uses parts of the blocks to which the newly added chain-pair must be appended to provide reliable as well as sustainable growth of the chain. This chain pairing helps to prevent the major of the chain-controlling attacks, as well as it increases the participation by allowing the blockchain nodes to control the pseudo generation rates. Additionally, it prevents multiple forks and single node control over the incoming PoS blocks. The block generation can be further enhanced to accommodate direct inclusion of VDF in the PoW-PoS chain-pair as well as include other types of consensus mechanisms in the place of PoS-sub-chain. However, this will affect the complexity of storage depending on the type of the hashing operations.

–PoS sub-chain: This chain operates in three parts. At first, a list of valid chain-pairs is selected, who can compete to be the leader, and is selected using the concept of a VDF (construction provided in Appendix A), and finally, the PoS block is ready to be allocated to a chain-pair. VDF prevents PoS blocks from attempting to attach to additional chain-pairs at the same instance because of its core ideology of sequential work with deterministic functions. From the application’s perspective, VDF helps to delegate in situations of unavailable miners or stakeholders as well as model the
wait algorithms.

- **List of validators.** This list includes the valid chain-pairs who can compete to be the leader for extending the PoS sub chain under their pre-attached PoS block. The validators are selected based on the original rewards earned as a part of the RL mechanism, such that all the chain-pairs, which hold $R'(\omega, \theta)_t \geq \text{mean}(R'(\omega, \theta)_{t-1})$ are marked as valid. Additionally, the valid chair pairs must satisfy the requirements in (1). Furthermore, the valid chain-pair must hold $\eta_s \leq \eta_d$ and a valid $a_m$ with a consideration that each pair must be complete and no PoW-PoS chain-pair with a pending status can be included in the list of the validators.

- **Selection of a leader.** A VDF is defined as a function $'W=\text{Setup, Eval, Verify}'$, considering that the operations of Verify take much lesser time than the Eval [1]. This means that the node with a valid PoW-PoS chain-pair must possess sufficient computational ability than the nodes of the corresponding sub-chain, which will prevent an adversary from taking control by solving the evaluation puzzle in extremely lesser time than the verification puzzle. The solution is modeled around the time ($\tau$), which is taken to evaluate a valid pseudo-chain-pair. In the given model, out of the validators, the one with a valid $(E_k, v_k)$ is selected as a leader.

1. **Setup:** The proposed model operates with the basic assumption of a VDF for generating the PoS block, i.e, the public parameters, $(E_k, v_k)$, are available for evaluating and verifying the blocks within the polynomial limits (sub-exponential time as stated in Boneh et al. [1]). With such public parameters, the validator, which solves

   \[ \overline{H}(B_{PoW}, v_k) < R'(\omega, \theta) \overline{T}, \]  

   (8)

   is elected as the leader. Accordingly, the public parameters are obtained through the randomized Setup algorithm which uses $(\lambda, \zeta)$ as its parameters with $\zeta \neq f(\tau, \overline{T})$.

2. **Evaluation:** The leader performs the evaluation function by considering the allocation mechanism which will be used for placing the block under the required chain-pair. For this, the leader uses the hash of the parent chain-pair’s PoS block ($h_q$) and the hash of the previous PoS block ($h_g$). The Eval algorithm takes $E_k$ and $I = H(h_q, h_g)$, where $I \in \{0, 1\}^L$ operates with $\tau$ which is the current time consumption as per $a_m$, to generate an output $O \in \{0, 1\}^L$ as an image of $I$ along with a proof $\pi$.

3. **Verify:** Once the Eval is executed, the PoS block is generated using $B_{PoW}, v_k, I, O$, and $\pi$. The Verify function is evaluated with $(v_k, I, O, \pi)$ and a Boolean is recorded as an observation. Upon success, the PoS block is appended to the intended location which was used by the leader during the evaluation procedure. Any adversary, which poses to be a valid PoW-PoS chain-pair, needs to solve the Eval function in a shorter time than that of Verify. As the allocation is decided by the winning pair, an adversary needs to acquire all the possible locations as well as run the Eval for all the cases under time extremely lower than $\tau$, which is computationally expensive even with influential hardware. Thus, the security of the PoS block is supported by the choice of allocation procedure (known locally only to the leader) and the time-difficulty of the VDF.

- **Difficulty adjustments:** The primary target of the proposed model is to develop a generic system that can be widely adopted for the major of the applications listed for the blockchain. The difficulty adjustment is required to control the extreme growth as a valid chain-pair that may show excessive storage to keep increasing its pseudo pairs or sub-chains. Thus, in the main PoW-PoS chain-pair, the difficulty is adjusted as:

   \[ T_{r+1} = \left( \frac{\max(\eta_k, (C_W, C_S)V_k)}{\sum_{i \neq j} (\eta_k)_j} \cdot \frac{R'(\omega, \theta)_{i, (C_W, C_S)V_k}}{\sum_{i \neq j} R'(\omega, \theta)_{j, (C_W, C_S)V_k}} \right) T_r, \]  

   (9)
where $T_{r+1}$ is the next difficulty level w.r.t. time $t$, and (9) controls the winning pair and prevents reducing the participation and control over the blockchain. Although the PoW-PoS chain-pair difficulty and time delay from VDF are enough to control the global blockchain, to manage the deadlocks/concurrent operations and to control the pseudo-pair competition, difficulty adjustment is also modeled for sub-chain, such that, for $K(R)$ number of incoming PoS blocks,

$$
\overline{T}_{r+1} = \begin{cases} 
\frac{K(\text{A})}{\sum_{i \in j} (K_{i}^{(\text{A})})_{ij}} \cdot \frac{S_{i,j}(\text{CW},\text{CS})}{\sum_{i,j} (K_{i}^{(\text{A})})_{ij}} \overline{T}_{r}, & \sum_{i,j} (K_{i}^{(\text{A})})_{ij} \geq K(R) , \\
-1 & \text{otherwise.}
\end{cases}
$$

**Sharding (Storage and Processing):** A fully-scaled ledger may lead to several overheads in terms of storage, synchronization, and sharing, whereas the partial-ledgers are better in terms of performance but require additional protocols for communications. Using external methods for sharding in a pre-formed blockchain leads to several overheads. This is overcome in the proposed model as the node allocations across the valid chain-pairs provide a unique auto-sharding feature which helps to lower the burden in terms of ledger maintenance as well as reduce the synchronization problem with application to both PoS-sub-chain as well as the main chain-pairs. The newly formed blockchain helps to attain sharding by architecture. An illustration of sharding can be observed in Fig. 3 with procedures in Algorithm 2. Here, function `node_ability()` calculates the ability of the node to have 1 or more PoS blocks. Function `extern_node_value(Pos_block_allocation)` obtains the external node value for the allocated PoS block, function `strength_real()` calculates allocated sub-PoS blocks, function `store_chain()` stores the formed chain to shards, function `store_advertise_reward()` rewards for the shard formation, function `count()` calculates the number of nodes, function `external_block_alloc()` expresses the block location and function `valid_chain_pairs` validates the chain pairs. As shown in Fig. 3, Reinshard can be operated in two ways, the first one involves a dedicated application-specific
Algorithm 2: Auto-sharding with Reinshard.

**Result:** Sharding and ledger division

Input: PoS_block_allocation()

set inst=node_ability() ➞ 1 or more PoS blocks
set i=0, j=0, q=0, d=0;

obtain N=extern_node_value(PoS_block_allocation);

if inst=1 then

while i ≤ M && sum(j) ≤ N do

c=strength_real(i) ➞ Allocated Sub-PoS blocks

while j ≤ c do

    shard[i]=store_chain(Kj,i,c);j=j+1;

end

j=j+1;

end

store_advertise_reward(shard) ➞ shard and reward

else

while q ≤ count(external_nodes) do

    ex_loc=external_block_alloc() ➞ block location

    while d ≤ count(ex_loc) do

        z=valid_chain_pairs(d,ex_loc);
        shard[q]=store_chain(Kz,q,z);
        d=d+1;

    end

    q=q+1;

end

store_advertise_reward(shard) ➞ shard and reward

end

sharding in which each external node is entitled to generate a single PoS block (e.g. use for login) and the shards are formed based on the attachments of PoW-PoS chain-pairs. The second involves multiple PoS blocks from external nodes, which are allocated as per the decision of the valid PoW-PoS chain-pairs. In such a scenario, the shards are formed following the external node contents and the location of their PoS blocks. In the first case, each external node is entitled to a single stake each time a new PoS block is appended to their sub-chain and it is convenient to manage and control such a blockchain. However, unlike this, in the second case, the stakes are rewarded every time a new PoS block is appended as well as these are given stakes out of the rewards earned by the valid PoW-PoS chain-pair on their selection as a leader. Furthermore, the arrangement of nodes in shards also earns them more stakes which are shared by the nodes which fall in their shards and have earned stakes from their respective chain-pair. This allows effective incentives in the blockchain and helps to acquire the further operations of communications and node transitions.

- **Concurrency resolutions:** Concurrency is a correct measure of efficiency for sharded blockchains. In the proposed approach, at first, priority $\psi$ is defined to select the receiver, as shown in Fig. 4. This priority helps to control the concurrent operations as well as prevent any deadlocks during transactions. $\psi$ is calculated based on the rewards/stakes earned by a generator (external node). It is similar to the booking of the receiver node to share some information. However, with unlimited control over the receiver, the entire blockchain can undergo certain attacks (single-shard takeover) as it will prevent any sort of updates across the chain. Thus, to prevent this, a VDF mechanism is adopted and a sender with priority $\psi$ can only hold the receiver for $(\tau', D + \Gamma)$ duration, ($\tau' < \tau$), where $D$ is the number of involved valid chain-pairs which are used to trace the receiver and $\Gamma$ is the network latency. Note that each node may not have an average time greater than $\tau$ as it may compute $Eval$ faster than $Verify$. This allows simultaneous control
over the intended receivers during concurrent operations. Once these controls are available, the transaction can be processed, and ledgers can be updated based on the sharded blockchain.

**Intra and Inter-shard communications:** The intra- and inter-shard communications are bounded by the concerns of participation, which is easier when operating in a single shard and becomes complex when multiple shards, as well as multiple receivers, are involved. The two Algorithms 3 and 4 facilitate the required mode of transactions. The choice of P2P or P2MP depends on the number of participants as receivers and the selection of the protocol for communication depends on the underlying network architecture. The inter-shard communications proposed in this article uses the hold time which is derived based on the delay factor of the VDF, and it provides an effective strategy to resolve concurrency issues. One of the examples can be the Train-and-Hotel booking problem [41], where two transactions are involved and synchronous mode may lead to the non-availability of one of the two requirements (hotel or a train). To control this, the proposed algorithm initiates the hold procedures for the time which is enough to prevent an adversary from performing the Eval function and try to manipulate the block before it is verified. The hold procedures bound the receivers until the connection (tunnel) is not formed between the receivers. With such facilitation, receivers of the different shards can be accommodated to wait for a duration, which is enough to bring participants to wait until the completion of one full transaction (booking of train and hotel). However, network latency plays a crucial role and its derivation and conceptualization are beyond the scope of this article.

**Algorithm 3: Intra-shard communications.**

**Result:** Intra-shard communications

**Input:** shards, sender, receivers

if `valid(sender, receiver())` == true then
    `fetch_info(shards)`  ➔ sender’s call to proceed
    `set P2P or P2MP`  ➔ communication modes
    `initiate protocol`  ➔ network layer operations
    `initiate transactions`  ➔ Begin communication
else
    `exit(-1)`  ➔ invoke control procedures
end

`update ledgers()`  ➔ ledger update and rewarding

---

Fig. 4. An overview of states for inter-shard communications.
Algorithm 4: Inter-shard communications (Fig. 4).

Result: Inter-shard communications
Input: shards, sender, receivers
Set timer;

if valid(sender, receiver()) == true then
    prove_priority(ψ)
    fetch_info(shards)
    rec_info(cp_lookup(receivers))
    init_receiver_hold(r.f + H)
    if valid(timer.r.f + H) == true then
        set P2F or P2MP
        initiate protocol
    else
        timeout(-1);
        initiate transactions
    end
else
    exit(-1)
end
update_ledgers()

4 SECURITY EVALUATIONS

The Reinshard chains are analyzed for security properties, such as chain growth, chain quality, and common prefix similar to [7, 10, 11, 21, 38]. To understand the security evaluations, a block’s position in the chain is referred to as its height. Furthermore, in each round, at least one block will be appended to the global chain or sub-chain using (7) or (8). In Reinshard, the entire blockchain is divided into two distinct chains, one is the subsidiary (sub-chain) chain (i.e., PoS-consensus), another is the global chain (i.e., hybrid (PoW + PoS) consensus) that contains PoW and PoS blocks. Notably, the global chain is similar to the 2-hop chain [11] (or TwinsCoin [10]).

Security analysis of Reinshard-global Chain. A chain-pair of Reinshard-global chain, ⟨CW, CS⟩, is considered for evaluations. In order to extend the pair of Reinshard-global blockchain, a PoW-miner needs to generate a PoW-block first, and then corresponding PoS-holders (or leader) will sign this block and generate a new PoS-block. Notably, both PoW-miners and PoS-stakeholders can be honest or malicious. Thus, the three properties are guaranteed by the following cases:

• The ideal case is both PoW-miners and PoS-stakeholders are honest which can guarantee the property of chain growth. The main reason is that malicious players cannot prevent the operations of the ideal case. Such types of situation is difficult to attain and cannot be guaranteed.

• The common case contains two distinct types. In the common case, the PoW block mined by the PoW-miner is corresponding to the PoS block and mapped to the PoS-stakeholder. The first type is that PoW-miner is malicious and PoS-holder is honest, and the honest PoS-holder will either sign the block mined by the malicious PoW-miner or discard it. Another type is that the PoW-miner is honest but the PoS-holder is malicious, here, the malicious PoS-holder will either sign the block mined by the honest PoW-miner or discard it. Notably, if the probability of the common case is smaller than the ideal case, then malicious players cannot generate more PoS-blocks than honest players. Even if they win all the competitions, there are still some blocks remaining from honest players. Apparently, the chain quality can be guaranteed by the common case.

• The worst case is both PoW-miners and PoS-stakeholders are malicious. It is assumed that the probability to find a
new PoW-block by all the PoW-miners in one round is very small. Following this, if all of the honest players do not receive the new block from some rounds, they would obtain the same best chain-pair \((C_W, C_S)\). The reason is that, in the worst case, all the honest players have the same view of the global chain-pair. The common prefix property can be guaranteed due to the reason that malicious players do not have enough resources to corrupt and diverge the view of the honest players by sending new blocks regularly. The actual architecture itself is able to secure the entire chain against known attacks as the direct inclusion of the blocks is not possible and has to be earned based on sufficient storage and computational powers, which prohibits an adversary to be a part of the global chain. However, PoS sub-chains are not aloof from such conditions as an intermittent chain-pair holder (node) may go rogue and create multiple forks by generating as many false blocks to the sub-chains, which may complete the limits on the blocks and result in a deadlock. Thus, the security of the sub-chain is required to prevent such attacks.

**Security analysis of Reinshard sub-chain.** In essence, this sub-chain is similar to the conventional PoS chain. The key point is that the sub-chain is realized via a VDF with a time delay parameter \(\tau\). To obtain a secure sub-chain, Reinshard needs to achieve the property of, in particular, persistence and liveness. In fact, persistence follows from the properties of a common prefix (or chain consistency) and chain growth, and liveness follows from the properties of chain quality and chain growth. Intuitively, the chain growth property states that the chains of honest players should grow linearly to the number of rounds. Meanwhile, because of the use of VDF, it is required that the verification time \(t_V\) is less than the evaluation time \(t_E\) (= \(\tau\)), where \(t_V < t < t_E\), which implies that the existing participants will be verifying the signed blocks in time lesser than that required by an intruder to generate the new block, which is equivalent to or greater than the evaluation time. The following properties from the existing approaches \([10, 11, 14, 21]\) help to formally understand the correct functioning of the proposed blockchain.

**Definition 4.1 (Chain Growth).** For all shards, each honest player finalizes chain-pairs at the end of their round \(R_d\) and has length \(L \geq L - K\) for the growth parameter \(K\), such that \(L \leq K_{\text{max}}\). Following this, each honest chain-pair must have a synchronized value of \(N\).

**Lemma 4.1 (Chain Growth Lemma [14]).** If an honest party has a chain-pairs with length \(L\) at the round \(R_d\), then every honest party has adopted chain-pairs of length at least \(L + \sum_{i=R_d}^{N-1} K_i\) \((\leq K_{\text{max}})\) by the round \(N \geq R_d\) and \(N\) for all parties must be same when observed from the last appended block.

**Proof.** By induction on \(N - R_d \geq 0\), and assuming the basis \((N = R_d)\), if an honest party has a chain \(C\) with length \(L\) at the round \(R_d\), then the party broadcasts \(C\) at a round earlier than \(R_d\). It follows that every honest party will receive \(C\) by the round \(R_d\). For the inductive step, according to the inductive hypothesis, every honest party has received a chain of length at least \(L' = L + \sum_{i=R_d}^{N-1} K_i\) by the round \(N - 1\). Obviously, in this setting, if \(K_{R_d-1} = 0\) the statement follows directly, so assume \(K_{R_d-1} = 1\). Notably, \(K_i\) implies that the expectation of the block number mined by an honest player after \(i\) rounds. Furthermore, it is to be noted that every honest party can query the valid chain-pair with a chain of length at least \(L'\) and \(N'\) at the round \(N - 1\). It follows that all honest parties successful at the round \(N - 1\) broadcast a chain of length at least \(L' + 1\) and sum \(N\). Since \(L' + 1 = \sum_{i=R_d}^{N-1} K_i\), and \(N'\) is the same for all, it completes the proof. \(\square\)

The chain quality property guarantees that there will eventually be a block in the finalized chain-pair that was proposed by an honest player subject to the limits imposed by \(K_{\text{max}}\). In other words, the property of chain quality aims at expressing the number of honest blocks’ contributions that are contained in a sufficiently long and continuous part
of an honest chain. Here, $\gamma$ is used to define the stakes ratio of the adversaries, $\varrho$ is used to define the stakes ratio of the honest holds and $\epsilon$ acts as the system parameter, and $\epsilon \in (0, 1)$.

**Definition 4.2 (Chain Quality $C_q$ [14])**. The chain quality $C_q$ with parameters $\varrho \in R$ and $L \in N$ state that for any honest party $P$ with chain $C$, it holds that for any $L$ consecutive blocks of $C$ the ratio of honest blocks is at least $\varrho$.

**Theorem 4.1 (Chain Quality [14]).** Let $\gamma - \epsilon$ be the adversarial stake ratio. The protocol satisfies the chain quality property with parameters $\varrho \cdot (\gamma - \epsilon) = \gamma/(1 - \gamma)$ and $L \in N$ through an epoch of $R$ slots with probability at least

$$1 - \exp(-f(e^2 \cdot (\gamma \cdot L)) + \ln R),$$

s.t.

$$K_i^{(A)} \leq K_{\text{max}} - L.$$  

**Proof.** From the proof of chain growth, it is known that with high probability a segment of $L$ will involve at least $(1 - \gamma) \cdot L$ slots with honest leaders; hence the resulting chain must advance by at least $(1 - \gamma) \cdot L$ blocks, which is $\leq K_i^{(A)}$. Similarly, the adversarial parties are associated with no more than $\gamma \cdot L$ slots, and thus can contribute no more than $\gamma \cdot L$ blocks to any particular chain over this period. It follows that the associated chain possessed by any honest party contains a fraction $\gamma/(1 - \gamma)$ of adversarial blocks with probability $1 - \exp(-f(e^2 \cdot (\gamma \cdot L)) + \ln R)$. $\square$

**Definition 4.3 (Common Prefix [14, 21]).** The common prefix (or chain consistency) implies that if $C$ and $C'$ are the finalized chains of two honest players, then $C$ is a prefix of $C'$ or vice versa at any point of time.

**Lemma 4.2 (Common Prefix Lemma [14, 21]).** If $C_1$ is adopted by an honest party at round $R_1$, and $C_2$ is either adopted or diffused (broadcast) by an honest party at round $R_2$ and has $\text{len}(C_2) \leq \text{len}(C_1)$, then $C_1$ is a prefix of $C_2$ or vice versa at any point of time for consecutive rounds.

**Proof.** In the sharded blockchain, if the honest players receive different chains for different intervals, both the chains, i.e., $C_1$ and $C_2$ are the prefix of a common chain that proves the Lemma. Additionally, the validation of PoS sub-chain can be guaranteed in any $R_d$ following the honesty of the valid chain-pair, which ensures the correctness of the sub-chains. $\square$

**Definition 4.4 (Chain Wait).** For the sharded blockchain, this property ensures that only valid chain-pair generates the blocks (equal opportunity to all participants) for the inter-shard communications, and minimum wait for the concurrent operations has been followed. This is guaranteed by the fact that each valid party must advertise $t_V$ and $\forall R_d, t_V < t_E$, which is known to all the chain-pairs.

**Lemma 4.3 (Chain Wait Lemma).** For a given inter-shard communications, if two different $t_1$ and $t_2$ are observed from valid chain-pair and the intended receiver by the sender (initiator), both $t_1$ and $t_2$ are equal in a valid blockchain and $t_V < (t_1 \equiv t_2) < t_E$.

**Proof.** Consider a scenario where a sender has initiated a request for two different nodes having locations in either the same or different shards. Now, the wait request for each query is a time $t_1$, which can be either decided by the sender or its corresponding chain-pair (depending on the mode of deployment and configurations). Now, a wait time $t_2$ corresponds to the intended receivers, and then a P2P or P2MP connection is initiated. The block signing is accompanied by advertising the $t_2$. For a valid chain, both $t$ and $t'$ are same and must be following $t_V < (t_1 \equiv t_2) < t_E$. This ensures equal waiting for all the involved nodes and prevents intentional termination of connections when inter-shard communications are involved. $\square$
**Definition 4.5 (Unbiased Sharding).** We say this is an Unbiased Sharding in the sharded blockchain, if it satisfying the following requirements: 1) the process of generating the shards should be unpredictable and must not be controlled (or manipulated) by any single node, 2) the knowledge of nodes in the shards should not be predicted.

**Lemma 4.4 (Unbiased-Sharding Lemma).** If an adversary $\mathcal{A}$ becomes part of the chain as a chain-pair, $\langle C_W, C_S \rangle$, or sub-chain $\langle C_S \rangle$, then no adversary can decide the shard-participants with an overwhelming probability.

**Proof.** In the sharded blockchain, the architecture is built such that it may grow or shrink for sub-chain based on the dynamic difficulty adjustment, which is unpredictable as stated in the chain-extension. The bounds on $K$ are governed by the RL-rewards and must be validated by the stakeholders. Thus, no chain-pair can extend it without validation. Once these are made, the state of the blockchain can be known to every participant. Now, the sharding is carried based on the location of the PoS block generated by a node. The node can generate any blocks, but the attachment is controlled by the winning chain-pair and verified by the valid chain-pairs. This means to bias the sharding, the adversary ($\mathcal{A}$) must be able to affect the verification and control the decision on sharding which is against the working of the VDF as the sub-node cannot present the computational requirement of being a part of the PoW-PoS chain pair. Even if it manages to show the same level of computational power, it has to solve the VDF puzzle under the verification time ($t_V$), which is practically impossible due to sequential steps in evaluation (governed by $t_E$) which have to be unique and need to be publicly verified. Thus, unbiasedness is guaranteed through the procedures of VDF used for extending the PoW and the PoS chains.

**Remark 4.1 (Chain Availability).** In the case of Reinshard, chain availability refers to the all-time accessibility of the node information despite the occurrence of failures in the targeted applications. It also includes the possession of information of sub-chain of the chain-pairs which have failed or inaccessible in any round.

**Remark 4.2 (Non-cascading failures).** For general failures, the inclusion of the pointer to the PoS sub-block of the failed chain-pair can help to recover the entire sub-chain. However, in practical situations, a single server is the chain-pair generator, thus, the recovery is based on the condition that sharding information is available to all the neighboring servers. Additionally, in Reinshard, the sharding helps to maintain the recovery of non-cascading failures by allowing sharded nodes to provide the information for the lost or unavailable nodes or even chain-pairs. Scenarios, where external nodes generate more blocks and lead to different shards, have better accessibility in the case of failures than the scenarios with only one block per node.

**Remark 4.3 (Cascading failures).** In the case of cascading failures, even the nodes with a different number of blocks may fall short of recovering as consecutive failures affect the recovery. However, with Reinshard, the scenario with multiple blocks is sharded as per the external nodes, which helps to retain maximum information and allow better recovery. At present, Reinshard is able to detect failures with pseudo-chain-pairs and the major of other operations are evaluated by assuming that the generators of the chain-pairs are always available and accessible.

5 PERFORMANCE EVALUATION AND COMPARISONS

Reinshard was evaluated on Intel® Core™ i7-8750H CPU @ 2.20 GHz on a Dell G7 series workstations using instances from [20] with concurrent clients coded in Node.js® which allows visualization through Chrome’s JavaScript engine. The evaluations are presented in two parts, the first part helps to understand the run time operations of the proposed blockchain especially for sharding. The second part discusses the importance of using VDF by considering an exemplary
concurrency problem (Train-and-Hotel booking problem [41]). The time to shard and allocation decisions account for latency for which each node must wait before processing/generating new blocks in the blockchain. In the proposed Reinshard, the sharding is performed optimally by its architecture, which causes very few overheads that do not show a major impact on the performance. The result in Fig. 5(a) suggests that an application-specific scenario (Scenario-1), where a node can be a part of only one shard, is efficient as sharding is done at the chain-pair, whereas for a scenario where a node can belong to multiple shards (Scenario-2 and Scenario-2') sharding may cause additional overheads, but these are well in the limits and do not affect the functioning of the entire blockchain. The increment of 20% in the total blocks per node can increase the overheads by 46.6%. However, the maximum range of latency is quite low at 89.32 ms. Furthermore, belonging to multiple shards enhances the types of applications for which Reinshard can be used as well as help in maintaining high availability and accessibility in case of failures. These results suggest that the number of blocks per node impacts the performance as more overheads are observed in deciding the members of the shards. More the number of involved shards more is the participation, and higher are the overheads. However, these overheads grow at a rate of 4.1% only when the number of shard occurrences is doubled for each node. With more valid chain-pairs, the number of verification and signing increases that increase the overall appending time of the PoS block, as shown in Fig. 5(b). However, during evaluations, it was found that the number of blocks per external node does not impact the average generation time. Rather, the number of validators has more impact on it. Alongside, the signature size also causes some overheads, but results vary only by 6.2% between SHA-256 and SHA-512 at ± 2 (ms) error for 100 runs.

Concurrency Resolution: In Reinshard, concurrency is resolved by using VDF as a delay factor that helps to maintain a lock (hold) on nodes. Such observations are presented by using the Train-and-Hotel booking problem [41] with and without the use of VDF. To understand this, nodes acting as train and hotel booking servers are attached to the global blockchain by generating their respective PoS blocks and 50 concurrent requests are generated for each ticket. Both the servers belong to different shards. A simulated VDF is considered with a fixed value for the delay factor and is determined by the involved chain-pairs. At first, the number of available train and hotel tickets are deliberately kept at

![Fig. 5. (a) Operational latency per client (shard identification) vs. the number of external nodes. (b) PoS block inclusion time vs. the number of valid chain-pairs.](image-url)
5 each. It means that for efficiently resolving deadlocks in concurrent operations, the nodes with train tickets must be able to book the hotel as well. However, during run-time, it was observed that without the utilization of VDF, the nodes were able to generate random requests to either of the two ticketing servers resulting in some of the participants having one ticket only, as shown in Fig. 6(a). In contrast, the VDF models hold on the servers allowing nodes to establish connections with the train and hotel ticketing servers with the success of booking both the tickets, as shown in Fig. 6(b).

The proposed model was also evaluated in the presence of an adversary under the Train-Hotel booking problem, as shown in Fig. 8. For this, the adversaries were modeled with and without VDF capabilities and their possessions were varied between 30-50% of the computational power and stakes (controlling the chain-pairs). The simulations were carried under the same settings. Despite such favorable conditions for an adversary (which is practically difficult to
Table 2. A comparison between the proposed solution and the related works (Computing Power (P), Stake (S)). (*the platform reserves 51% of the balance to prevent attacks).

| Blockchain          | Block proposal | Type        | Attack Resilience | Cross-platform integration | Sharding by architecture | Concurrency resolutions |
|---------------------|----------------|-------------|-------------------|----------------------------|--------------------------|-------------------------|
| 2-hop blockchain    | PoW-PoS Hybrid| >50% (P)    | ✗                 | ✗                          | ✗                        | ✗                      |
| TwinsCoin           | PoW-PoS Hybrid| >50% (P)    | ✗                 | ✗                          | ✗                        | ✗                      |
| Hcash               | PoW-PoS Hybrid| >50% (S)*   | ✓                 | ✓                          | ✗                        | ✗                      |
| PeerCensus          | PoW-BFT Hybrid| 33% (P)     | ✗                 | ✗                          | ✗                        | ✗                      |
| Nxt [4]             | PoS Hybrid    | >50% (S)    | ✗                 | ✗                          | ✗                        | ✗                      |
| Proposed (Reinshard)| PoW-PoS Hybrid| >50% (P), (S)| ✓               | ✓                          | ✓                        | ✓                      |

Fig. 8. An illustration of concurrency problem in the blockchain.

Taint because of sequential and unique features of the VDF function, it could only lead to DoS attack but cannot affect the concurrent operations as no users were stranded with a single ticket. The key observations were the inability of an adversary to hinder concurrent operations even at the maximum capacity. This means under ideal assumptions; the adversary was able to prohibit the booking, but it could not cause serialization where one user could book only one ticket.
ticket. The concurrency was not affected because of the presence of the validators (manages hold), which are the part of PoW-PoS chain-pair and follows similar VDF puzzle-solving even in the shards. These observations can be visualized in Fig. 9. However, to fully control the entire blockchain, an adversary needs to be at the communicating chain-pairs as well as control more than 51% of the PoS sub-chain, which is practically difficult as it involves solving an exponential time puzzle under the limits when other operations are being handled in a deterministic polynomial duration.

Table 3. A qualitative comparison for attack prevention without centralization and third party evaluations (requires- † central entity/checkpoints, ‡ identity provider).

| Blockchain       | Nothing-at-stake | Long-range attack | No Unwanted Centralization/ Non-TEE executions | System level block generation (Block Size: Time) (KB: ms) |
|------------------|------------------|------------------|-----------------------------------------------|------------------------------------------------------|
| Ppcoin [22, 28]  | ✗                | ✓                | ✗                                             | -                                                   |
| Blackcoin [28, 43]| ✗                | ✓                | ✗                                             | -                                                   |
| Snow White [6, 28]| ✗                | ✓                | ✗                                             | -                                                   |
| TEE-based PoS [28]| ✓                | ✓                | ✗                                             | 1: 1000 ~1.70                                       |
| NXT [4, 28]      | ✓                | ✓                | ✗                                             | 1: 1000 ~0.42                                       |
| Proposed         | ✓                | ✓                | ✓                                             | 1: 1000 ~0.39                                       |

To further understand the handling capacity of the Reinshard in the real-time, a delay factor is set around 2.5 s, which is the time to book one ticket, the evaluation time and verification time are ranged between 3 and 9 s, and 1 and 3 s, respectively. Where no concurrent control operations are used in Reinshard, the allocation time is around 39 s for a short evaluation duration. However, as stated previously, such a scenario resulted in certain failures where a node is able to book only one ticket. Theoretically, a complete operation including unavailability messages must take 32.5 to 92.5 s with a varying evaluation time. This serves as our baseline as anything below this value means incorrect operations. The proposed Reinshard, with VDF (sequences in booking a train first), performs accurately with only successful participants getting both the tickets and the entire process with unavailability messages was completed in the time between 66 and 188 s with varying evaluation time, as shown in Fig. 7(a). The actual time to book the tickets, irrespective of the competing ones, is between 34 and 35 s. As per the architecture as well as the security analysis, no ticket should be booked when the verification time and the delay factor are the same. Such observations can be noticed in Fig. 7(b). These traces show that at the same verification time and delay factor, the system goes into deadlocks and generates error messages without booking any ticket. However, as the significant difference between both increases, users can book all the available tickets in a competitive time.

Comparison with state-of-the-art: Some related works, as discussed in Table 2, help to understand the key differences between the proposed (Reinshard) and the existing consensus mechanisms at the architectural and property levels. It is clear that none of the existing solutions provide any direct resolution to shard the nodes especially for using blockchain beyond cryptocurrencies. Recently, it has been determined that the architectures that aim at scaling through sharding must be able to resolve concurrency issues amongst shards, which is neither provided nor resolved by any of the existing approaches such as 2-hop blockchain [11], TwinsCoin [10], Heash [38], PeerCensus [8], Nxt [4] or Ppcoin [22]. Apart from the Heash and the proposed solution, no other blockchain even talks about cross-platform integration, which is the actual future of the blockchain systems. Even for 51% attack resilience, Reinshard covers both the computational power as well as stake owner-ships, whereas other hybrid mechanisms only rely on the computational power for attack
resilience. For the block generation, the delay from the VDF only accounts when cross-shard and concurrent requests are involved in the blockchain, otherwise, there is no delay imposed on the nodes which prevent any overheads on the operations of the entire chain. Apart from these, Reinshard can prevent nothing-at-stake and long-range attacks that too without the use of checkpoints or trusted hardware. The existing solutions, [4, 6, 22, 28, 43], partially resolve the long-range attacks as their key functionality is dependent on a central entity.

At the system-level, the block generation rate of Reinshard was compared with the Nxt [4] and Trusted Execution Environment (TEE)-based PoS [28], as the latter improves the former for preventing the nothing-at-stake and long-range attacks, however, at the cost of unwanted centralization and dependence on an external identity provider. Results were compared at two block sizes of 1 KB and 1000 KB using SHA-256 where Reinshard was simulated with 100 to 1000 validators. The evaluations (Table 3) suggest that Reinshard can generate 1 KB block in 0.39 ms and 1000 KB block in 69.22 ms with a maximum of 1000 validators, which is far better than the Nxt and TEE-based PoS as these reported a block generation of 0.42 and 1.72 ms for 1 KB, respectively, and around 100 ms (approx.) for 1000 KB block size. Reinshard, with its dual-chain architecture, the unpredictability of block allocation, and VDF puzzle, is efficient and secure. If an attacker tries to stick for a duration and be a leader at a particular height, it has to become one of the PoW-PoS chain-pairs, whose difficulty is affected by RL-reward mechanisms and the non-probabilistic adjustments reduce any chances for becoming a leader if the node does not show consistent participation. Furthermore, counterfeiting the PoS sub-chain requires solving of VDF exponential puzzle in polynomial time that should be lesser than the verification time, which is practically beyond the limits of the current infrastructure. Thus, protecting Reinshard, without requiring any third-party solutions, checkpoints or identity providers.

The proposed Reinshard can provide a way forward to bring architectural level changes to the blockchain, which requires a unique and common solution to the problem of handling concurrent and dependent requests from the same source. The broad applicability of the proposed model can be utilised not only for the given architecture but can be adapted to improve coordination in the blockchain relying on sharding. The practical demonstration of the architecture with a Train-Hotel Problem highlights the applications that are attainable with Reinshard.

6 CONCLUSION

A dual blockchain, Reinshard, via hybrid consensus is proposed, utilising 2-hop blockchain, for optimal sharding with a high capacity of resolving concurrency issues in cross-shard communications. The proposed blockchain can provide a low complex and non-probabilistic difficulty adjustment in a non-flat model, which is far more suitable for practical applications than the probabilistic adjustments. The use of VDF helped to resolve concurrency issues as well as control the growth of the PoS sub-chain under the PoW-PoS chain-pair. The security proofs helped to validate the resilience of the proposed blockchain against known attacks as well as establish general blockchain properties. The experimental study helped to understand the practical aspect where the Reinshard is used for handling concurrent operations. In the future, the key target would be to scale the proposed Reinshard as an independent platform, which can provide a unique feature of combining different PoS-blockchains as sub-chains of the PoW-PoS chain pairs. Furthermore, a rigorous mechanism would be developed to provide a secure and efficient way of generating VDF for PoS-leader selection.

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This paper follows the definition of VDF proposed by Boneh et al. [1] and we introduce a relaxation version of VDF (a simulated (weak) VDF). Notably, the algorithm VDF outputs a proof \( \pi \) corresponding to \( y \) by executing the sub-algorithm \( \pi \leftarrow \text{Prove}(sk, x) \). The algorithm produces a proof \( \pi \) such that \( y \) is consistent with the verification key \( vk \).

\[ \text{VDF} = \langle \text{Gen, Eval, Vrfy} \rangle \]

The rigorous definition of simulated-VDF is as follows:

- \( (sk, vk) \leftarrow \text{VDF.Gen}(\lambda, t_G) \). The setup algorithm takes as an input a security parameter \( \lambda \) and time delay parameter \( t_G(T < t_G) \), then outputs a secret key \( sk \) and public verification key \( vk \in \{0, 1^k\} \).
- \( (\pi, y) \leftarrow \text{VDF.Eval}(sk, x) \). The algorithm takes as input the secret key \( sk \) and a message \( x \) and outputs a string \( y \in \{0, 1^m\} \). Notably, the algorithm VDF.Eval\((sk, x)\) will obtains the proof \( \pi \) corresponding to \( y \) by executing the sub-algorithm \( \pi \leftarrow \text{Prove}(sk, x) \). The algorithm produces a proof \( \pi \) such that \( y \) is consistent with the verification key \( vk \).
• VDF.Vrfy(vk, π, x, y). The verification algorithm takes as input the verification vk, a message x, a string y and a proof π. It outputs 1 if the proof verifies and 0 otherwise.

The important three properties are: 1) the execution time of Gen is in \(\text{poly}(\lambda)\); 2) the execution time of Eval is in time \(t_E\); 3) the verification algorithm runs in time \(t_V = \text{poly}(\lambda, \log T) < T < t_E\). Meanwhile, the VDF also has the following properties:

(1) **Completeness.** Informally, it states that given any input x, if y is generated by running the honest evaluation algorithm and π is generated by running the honest prove algorithm, the verification algorithm would always given an output 1. Formally, if \(y, π = \text{Prove}(sk, x)\), then \(\text{Vrfy}(vk, x, y, π) = 1\).

(2) **Uniqueness.** Informally, it states that for any input x and any verification vk, there exists at most a single y for which there is an accepting proof π. Formally, no values \((vk, x, (y, π), (y', π'))\) can satisfy both \(\text{Prove}(vk, x, y, π) = 1\) and \(\text{Prove}(vk, x, y', π') = 1\), unless \(y = y'\).

(3) **Sequentiality.** We say the honest parties can compute in \(T\) sequential steps, while no parallel-machine adversary with a polynomial number of processors can distinguish the output y from random in significantly fewer steps. Formally, the VDF is sequential if for all \(\lambda \in \mathbb{N}\) and for all pairs of PPT adversaries \(A = (A_0, A_1)\), where \(A_0\) runs in time \((\lambda, t)\) and \(A_1\) runs in time \(t := \text{poly}(\lambda, t_E, t_V)\) (the parallel running time of \(A_1\) with any polynomial amount of processors in \(t_E\) less than \(t_E\)). Then we have

\[
\Pr \left[ \begin{array}{c}
(t_E) \leftarrow A_0(\lambda) \\
(sk, vk) \leftarrow \text{VDF.Gen}(\lambda, t_E) \\
x \xleftarrow{\mathrm{R}} \mathcal{X} \\
y, A \leftarrow A_1(sk, x, t_E)
\end{array} \right] \quad \text{y, A} = y = (\lambda).
\]

Here, the adversary \(A_0\) and \(A_1\) can be viewed as a “pre-processing” algorithm and the “online” adversarial evaluation algorithm.