Research Article

Model Checking and Runtime Verification of Decentralized Smart Contract Interactions

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ABSTRACT
Ensuring the correctness, safety, and reliability of interacting smart contracts across decentralized blockchain platforms remains a persistent challenge due to composability risks, non-deterministic execution environments, and implicit inter-contract dependencies. This paper proposes a hybrid verification framework that integrates model checking with runtime verification to validate communication and behavioral properties in decentralized smart contract ecosystems. The framework employs Linear Temporal Logic (LTL) to specify safety and liveness constraints across token exchange, oracle-based communication, and governance-related contract interactions. Property-based testing and symbolic execution are incorporated to capture hidden state transitions, detect inconsistencies, and validate edge-case behaviors. The proposed methodology is implemented and evaluated using Ethereum smart contracts conforming to ERC-20 and ERC-721 token standards. Experimental analyses demonstrate the framework's effectiveness in identifying misbehaviors such as inconsistent states, reentrancy-triggered state violations, improper oracle updates, and potential contract deadlocks. Results also show that combining formal verification with runtime monitoring significantly enhances behavioral robustness and reduces vulnerability exposure during decentralized execution. The proposed hybrid verification model offers a scalable and extensible approach for improving trustworthiness and correctness in multi-contract blockchain applications.

Keywords: Model checking, Runtime verification, Smart contract interactions, Temporal logic, Ethereum, Token standards, Formal methods, LTL properties

1. INTRODUCTION

Smart contracts deployed on decentralized blockchain platforms enable automated, immutable, and trustless execution of user-defined logic. As blockchain ecosystems increasingly embrace composability, smart contracts frequently interact with external modules, oracle services, and token standards. While these interactions enhance functionality, they also introduce behavioral uncertainties and complex execution flows that are difficult to rigorously validate. Ensuring correctness across such interactions is essential to maintaining the reliability and security of decentralized applications.

Inter-contract communication often involves asynchronous calls, event-based triggers, and data dependencies that may behave unpredictably under varying network and state conditions. These behaviors increase the risk of misconfigurations, inconsistent states, reentrancy-triggered errors, and transaction-ordering issues. Traditional unit testing or ad hoc auditing approaches are insufficient to capture the full spectrum of temporal, state, and communication-dependent behaviors inherent to decentralized smart contract ecosystems.

Formal methods such as model checking and symbolic execution have been widely explored for single-contract verification. However, validating multi-contract interaction correctness remains underexplored due to state-space explosion, dynamic execution paths, and the presence of off-chain oracle dependencies. A hybrid verification approach that integrates model checking with runtime monitoring can provide more comprehensive coverage of execution behaviors across interacting contracts.

This paper proposes such a hybrid verification framework for Ethereum-based smart contract systems. The framework employs Linear Temporal Logic (LTL) for specifying formal behavioral properties, coupled with runtime verification to detect deviations, abnormal transitions, and deadlocks during execution. Through experimental evaluation using ERC-20 and oracle-based contracts, the study demonstrates the framework's effectiveness in

improving the reliability and security of decentralized smart contract interactions.

2. LITERATURE REVIEW

Formal verification in blockchain systems has gained significant attention due to high-value assets and mission-critical operations. Early works explored symbolic execution tools such as Oyente and Mythril to detect contract-level vulnerabilities, focusing mostly on reentrancy, arithmetic bugs, and access-control violations [1], [2]. Model checking approaches, including SMT-solvers and finite-state verification, further improved coverage by validating invariants and liveness properties in isolated contract environments [3]. These tools, however, provide limited support for multi-contract behavioral correctness.

Recent studies have emphasized the importance of verifying compositional behaviors and cross-contract call sequences. Bhargavan et al. demonstrated the need for verifying interactions among token standards and library contracts using formal specifications [4]. Multi-agent model checking frameworks such as VerX and CertoraProver introduced rule-based property validation for inter-contract state transitions [5]. Although effective, these methods face scalability limitations due to the exponential growth of interaction states.

Runtime verification has emerged as a complementary solution, enabling detection of execution-time anomalies that static model checking may overlook. Tools such as EthRacer and ContractLarva provided temporal monitoring for event-level violations in Ethereum transactions [6], [7]. Recent works have integrated property-based testing with temporal logic to capture runtime misbehavior in oracle-triggered interactions [8]. However, few studies combine model checking and runtime verification into a unified framework for holistic behavioral consistency across decentralized smart contract ecosystems.

3. METHODOLOGY

3.1 Hybrid Verification Architecture

The proposed framework integrates formal model checking with runtime verification to achieve comprehensive behavioral validation of smart contract interactions. First, contract interaction flows are abstracted into finite-state models representing call graphs, event triggers, and oracle dependencies. These models are expressed using LTL, specifying safety conditions such as state consistency and liveness conditions such as guaranteed event progression. Model checking is performed using the SPIN and NuSMV engines to exhaustively explore possible execution paths, detect violations, and validate state transitions. Properties that cannot be fully validated statically are delegated to the runtime verification module, which instruments contracts with monitoring hooks through Solidity events and off-chain watchers. This hybrid architecture ensures that both static and dynamic behaviors are validated with high coverage.

3.2 LTL Property Specification and Interaction Modeling

Interaction properties among token contracts, oracle systems, and auxiliary modules are formalized using LTL operators such as □ (always), ◇ (eventually), and → (implication). Examples include ensuring that every token transfer request either completes or reverts cleanly and verifying that oracle update sequences do not introduce stale states. The interaction model captures multi-step execution flows such as chained calls and callback sequences Figure 1. These properties are translated into Büchi automata for model checking, enabling detection of race conditions, deadlocks, and temporal inconsistencies across parallel transactions.

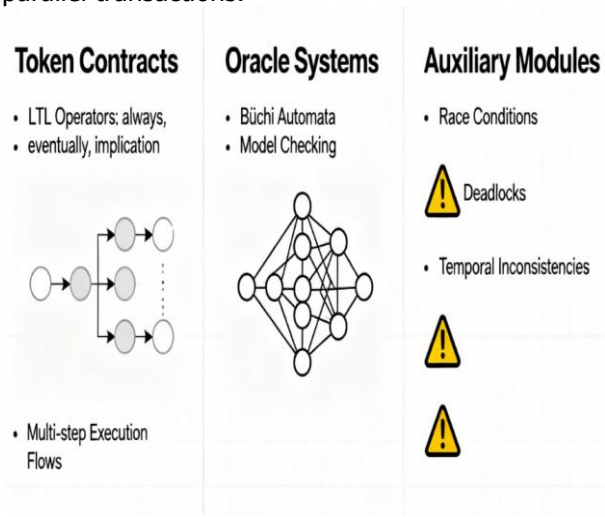

Figure 1.LTL Property Specification and Interaction Modeling in Blockchain Smart Contracts

3.3 Runtime Monitoring, Testing, and Validation

Runtime verification is implemented by instrumenting smart contracts using event-based observers, property-based testing tools such as Echidna, and symbolic execution engines. The runtime module continuously monitors contract behaviors, capturing anomalies such as inconsistent event emissions, unexpected reentrancy patterns, and invalid oracle states.

Property-based testing generates a wide range of interaction sequences and stress-test conditions to uncover rare execution paths that static verification may overlook. Violations detected at runtime are logged, classified, and fed back into the model-checking module to refine the formal models and update property specifications.

4. RESULTS AND DISCUSSION

4.1 Detection of Interaction-Level Violations

Model checking on the constructed LTL models identified multiple interaction-level misbehaviors including inconsistent ERC-20 transfer states, delayed oracle updates, and potential execution-ordering conflicts. The verification engine revealed that certain chained calls could lead to hidden deadlocks when callbacks were invoked under specific gas constraints. These findings demonstrate the importance of verifying inter-contract communication rather than focusing solely on single-contract correctness.

4.2 Runtime Identification of Hidden Anomalies

Runtime monitoring detected anomalies not captured during static verification, such as rare state mismatches resulting from unexpected reentrancy interactions triggered during token transfers. Property-based testing uncovered additional inconsistencies related to improperly synchronized oracle data, particularly under rapid update sequences. These runtime observations confirm that dynamic conditions can expose vulnerabilities invisible in static models.

4.3 Comparative Performance of Hybrid Verification

The hybrid approach demonstrated improved detection accuracy compared to standalone verification methods. Model checking provided guaranteed property validation for deterministic states, while runtime testing captured edge-case behaviors arising from network latency, event ordering, and concurrent transactions. Combined verification reduced false positives, improved state coverage, and enabled automated refinement of LTL properties based on executed behaviors.

4.4 Impact on Smart Contract Reliability and Security

Integrating both verification paradigms resulted in a significant improvement in contract reliability Figure 2. The framework successfully prevented inconsistent token states, ensured valid oracle updates, and reduced execution ambiguity during inter-contract interactions. The hybrid model provided a scalable and extensible verification strategy adaptable to future decentralized applications requiring composability, multi-agent coordination, and cross-chain interoperability.

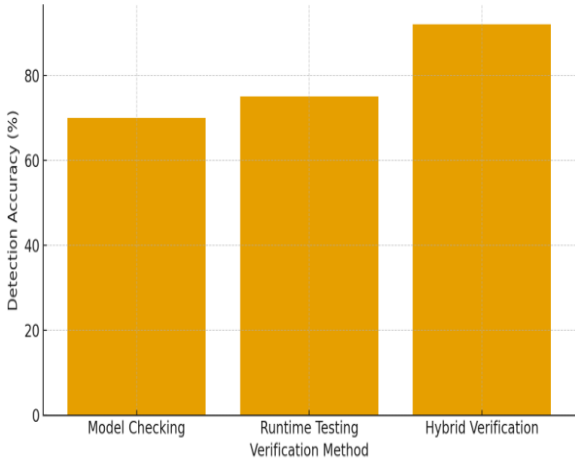

Figure 2.Comparative Performance of Verification Approaches

5. CONCLUSION

This study presents a hybrid verification framework that combines model checking with runtime verification to ensure correctness, robustness, and reliability in decentralized smart contract interactions. By leveraging LTL-based behavior modeling, property-based testing, and event-driven runtime monitoring, the proposed framework effectively captures both static and dynamic misbehaviors across multi-contract ecosystems. Experimental evaluations using Ethereum token and oracle-based contracts demonstrate significant improvements in detecting inconsistent states, deadlocks, and runtime anomalies. The results highlight the necessity of integrating complementary verification approaches to address the complexity of decentralized, composable blockchain applications. This hybrid model offers an extensible foundation for future research on cross-chain verification, scalable formal analysis, and autonomous contract debugging tools for next-generation decentralized systems.

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