AMERICAN JOURNAL OF AI CYBER COMPUTING MANAGEMENT
PEER REVIEWED, REFERRED & INDEXED JOURNAL
E-ISSN:3069-0102
VOL.5, NO. 3(2025)

Secure Escrow and Settlement Architecture for High-Value Web3 Marketing Campaigns: Multi-Sig, Role Segregation, and Formal State Transition Controls

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Abstract

Escrow trust is a foundational requirement for high-value campaign execution in Web3 marketing marketplaces. When campaign budgets exceed USD 50,000 and settlement is enforced on-chain, the security properties of the escrow contract and its surrounding settlement architecture determine whether the platform can be trusted by enterprise brands. Naive escrow designs — single-key deployment, monolithic contract logic, and implicit state transitions — expose platforms to fund loss through key compromise, smart contract exploit, and fraudulent dispute resolution. This paper presents SESA (Secure Escrow and Settlement Architecture), a formal engineering framework for Web3 campaign escrow that integrates multi-signature approval policies, strict role segregation between campaign management and fund release authority, control-plane and data-plane separation with hardware-backed signing, and explicit finite-state machine governance of all escrow lifecycle transitions including dispute resolution. SESA is grounded in a formal threat model that enumerates eleven attack vectors specific to Web3 escrow systems and maps each to a corresponding architectural control. A formal verification of the escrow state machine using the TLA+ specification language demonstrates the absence of deadlock, fund loss, and unauthorised release under all reachable states. A gas cost analysis of the reference Solidity implementation demonstrates that SESA's security controls add a mean overhead of 23% in gas cost relative to a naive single-key escrow — a trade-off that enterprise buyers consistently accept in exchange for verifiable security assurances. SESA enables campaign budgets that would be commercially unviable under insecure escrow designs to flow safely through the platform, directly expanding the addressable market for high-value brand partnerships.

Keywords: smart contract escrow, multi-signature, role segregation, state machine verification, TLA+, dispute resolution, Web3 settlement, campaign finance, control plane separation, formal verification

1. Introduction

Smart contract escrow in Web3 marketing platforms occupies a uniquely high-stakes position in the stack: it is simultaneously a financial control (holding campaign budgets of tens to hundreds of thousands of dollars), a trust mechanism (providing brands with assurance that funds will only release on verified campaign completion), and a fraud prevention tool (blocking premature or unauthorised disbursement to low-quality or fraudulent KOL participants). When escrow fails, the consequences are immediate, irreversible, and visible on-chain. Unlike a database record that can be rolled back or a payment that can be charged back, a misdirected on-chain fund release cannot be recalled.

Despite this criticality, first-generation Web3 escrow designs are often engineered for simplicity rather than security. A single platform-controlled private key authorises fund releases; contract logic combines campaign state management with fund custody in a monolithic implementation; and dispute resolution is handled through an ad-hoc process without formal state machine guarantees. These design choices are rational in early-stage development where velocity is prioritised, but they become critical liabilities as campaign budgets scale into enterprise territory and as sophisticated adversaries specifically target the escrow layer as the highest-value attack surface.

This paper presents SESA (Secure Escrow and Settlement Architecture), a formal engineering framework that treats escrow trust as a first-class design requirement. SESA's contributions are:

- A formal threat model enumerating eleven attack vectors specific to Web3 campaign escrow systems, grounded in documented smart contract exploit post-mortems and DeFi bridge incident reports.
- An architectural framework integrating multi-signature approval policies, cryptographic role segregation, control-plane and data-plane separation with hardware security module (HSM) signing, and explicit finite-state machine (FSM) governance of all escrow lifecycle transitions.
- A formal verification of the SESA escrow FSM using the TLA+ specification language, demonstrating the absence of deadlock, fund loss, and unauthorised release under all reachable states and under Byzantine fault assumptions for individual signers.
- A reference Solidity implementation with gas cost analysis demonstrating that SESA's security overhead is commercially acceptable at 23% mean gas cost increase relative to a naive single-key escrow.
- A deployment model for enterprise brand buyers that maps SESA's technical controls to due-diligence requirements, demonstrating how escrow architecture directly reduces enterprise sales friction.

2. Background and Related Work

2.1 Smart Contract Security and Escrow Exploits

Smart contract vulnerabilities have resulted in cumulative losses exceeding USD 3.8 billion across documented incidents through 2024 [1]. Atzei et al. [2] provided the first systematic taxonomy of Solidity vulnerability classes, identifying reentrancy, arithmetic overflow, and access control failure as the three highest-impact categories. Wood et al. [3] extended this taxonomy to DeFi-specific patterns including flash loan manipulation, oracle price manipulation, and governance attack vectors. For escrow-specific systems, the most relevant vulnerability classes are access control failures (enabling unauthorised fund release), state confusion attacks (exploiting inconsistencies between contract state and expected execution sequence), and logic errors in multi-party approval conditions (enabling threshold bypass).

2.2 Multi-Signature Schemes in Blockchain Systems

Multi-signature (multi-sig) approval requires M-of-N designated signers to co-authorise a transaction before execution, distributing the key-compromise risk across N parties and ensuring that no single compromised key enables fund loss. Gnosis Safe [4] is the dominant multi-sig framework in the Ethereum ecosystem, managing over USD 100 billion in assets across 20 million transactions as of 2024. Bonneau et al. [5] analysed the security properties of threshold signature schemes relative to naive multi-sig, demonstrating that threshold ECDSA [6] eliminates the on-chain visibility of individual signer participation, providing privacy advantages for institutional deployments. SESA supports both Gnosis Safe-compatible multi-sig and threshold ECDSA, with the choice driven by institutional signer requirements.

2.3 Formal Verification of Smart Contracts

Formal verification applies mathematical proof techniques to smart contract specifications to demonstrate the absence of specified error conditions under all reachable states. Bhargavan et al. [7] demonstrated formal verification of ERC-20 token contracts using the F* proof assistant. The K Framework [8] has been applied to verify EVM bytecode semantics. For state machine-governed systems, TLA+ [9] provides a particularly appropriate specification language: its temporal logic operators directly express safety properties ("the fund balance never decreases without an authorised release") and liveness properties ("every approved release eventually executes") over infinite execution traces. Bernstein et al. [10] applied TLA+ to verify the Cosmos Inter-Blockchain Communication (IBC) protocol state machine, establishing a precedent for formal specification of distributed blockchain protocols that SESA extends to campaign escrow.

2.4 Role-Based Access Control in Smart Contracts

OpenZeppelin's AccessControl library [11] provides a standard Solidity implementation of RBAC for smart contracts, enabling fine-grained role assignment and role-gated function execution. Perez and Livshits [12] conducted an empirical study of access control failures in deployed contracts, finding that 21% of high-value contract incidents involved improper access control — the most frequent vulnerability class by incident count. For escrow systems, the critical design principle is the separation of the role that controls campaign state (advancing the campaign through lifecycle stages) from the role that controls fund custody (authorising releases from the escrow vault). SESA formalises this as a control-plane and data-plane separation, ensuring that an adversary who compromises the campaign management system cannot autonomously authorise fund releases without co-signing from the separate signing policy layer.

3. Formal Threat Model

3.1 Adversarial Assumptions

The SESA threat model assumes an adversary who may: (i) compromise a single platform private key or HSM module through credential theft, insider attack, or supply-chain compromise; (ii) control up to M-1 of N multi-sig signers, where M is the approval threshold; (iii) deploy malicious contracts that interact with the SESA escrow via re-entrant calls; (iv) manipulate on-chain oracle data feeds used in milestone verification; and (v) submit fraudulent campaign completion evidence through the platform's off-chain evidence API. The adversary may not break elliptic curve cryptography, corrupt the underlying EVM, or simultaneously compromise more than M-1 signers within a single signing epoch.

3.2 Attack Vector Taxonomy

ID	Attack Vector	Impact	SESA Control
A1	Single-key compromise: platform release key exfiltrated, enabling full escrow drain.	CRITICAL — all locked funds at risk	Multi-sig M-of-N; HSM-backed signing; no single-key release path
A2	Reentrancy attack: malicious KOL contract re-enters release function before balance update.	HIGH — fund duplication	Checks-Effects-Interactions pattern enforced; ReentrancyGuard applied to all state-modifying functions
A3	State confusion: adversary calls release function during DISPUTED state when funds should be locked.	HIGH — premature fund release	FSM guards on all state-modifying functions; explicit state precondition assertions
A4	Milestone oracle manipulation: adversary manipulates off-chain data feed used to confirm campaign completion.	HIGH — fraudulent completion signal	Multi-source oracle aggregation; platform co-signature required alongside oracle result
A5	Fraudulent dispute initiation: adversary initiates spurious dispute to freeze funds and extort settlement.	MEDIUM — fund lock, operational disruption	Dispute bond requirement; dispute timelock (maximum 21 days); arbitrator role segregated from fund custody
A6	Role privilege escalation: attacker exploits RBAC misconfiguration to self-grant fund-release role.	CRITICAL — full escrow drain	Two-phase role grant: proposal + 48-hour timelock + M-of-N confirmation; role change events monitored
A7	Flash loan governance attack: adversary borrows governance tokens to pass malicious upgrade proposal.	HIGH — contract logic replacement	Upgradeable proxy with 7-day timelock; upgrade requires 4-of-6 multi-sig; no flash-loan-minted tokens counted in quorum
A8	Replay attack across chains: signed release approval submitted on alternative chain after bridge.	HIGH — fund double-release	Chain ID included in all signed message digests (EIP-712); signatures chain-scoped
A9	Insider campaign manager fraud: platform employee creates fraudulent campaign and self-approves release.	HIGH — fund theft	Campaign creation role separated from release role; all releases require KOL-side co-signature
A10	Dust and griefing attacks: adversary sends micro-transactions to bloat escrow state and increase gas costs.	LOW — operational disruption	Minimum campaign deposit enforced; state storage optimised for fixed-size entries

A11	Key rotation race: adversary submits release transaction in the window between key revocation and new key activation.	MEDIUM — unauthorised release during key rotation	Atomic key rotation with no validity gap; pending transactions invalidated on key change

Table 1. SESA Threat Model: Eleven Attack Vectors and Corresponding Controls

4. SESA Architecture

4.1 Architectural Principles

SESA is organised around four architectural principles that derive directly from the threat model. First, no single point of authorisation: every fund release requires co-authorisation from at least two roles held by organisationally segregated parties. Second, explicit state machine governance: the escrow contract may only transition between states via pre-defined, guarded transitions; no state is reachable by an unguarded external call. Third, control-plane and data-plane separation: the system that tracks campaign milestones and collects evidence (control plane) is architecturally and cryptographically separated from the system that holds private keys and signs fund releases (data plane). Fourth, defence in depth with formal verification: each control layer is independently defensible and the FSM controlling escrow transitions is formally verified to be free of unsafe reachable states.

4.2 Escrow Finite-State Machine

The SESA escrow FSM defines eight states and fifteen transitions. Table 2 defines the states; Figure 1 (Table 3) defines the legal transitions, their guard conditions, and the actor roles that may trigger each.

State	Description	Fund Status	Who May Transition Out
UNINITIALISED	Escrow contract deployed but not yet funded.	No funds held	CAMPAIGN_MANAGER (via FUND)
FUNDED	Brand deposit received; campaign not yet started.	Funds held, locked	CAMPAIGN_MANAGER (via ACTIVATE) or BRAND (via CANCEL)
ACTIVE	Campaign execution underway; milestones being tracked.	Funds held, locked	CAMPAIGN_MANAGER (via COMPLETE) or BRAND (via DISPUTE)
PENDING_RELEASE	Campaign completion asserted; awaiting multi-sig release approval.	Funds held, locked	SIGNING_POLICY (via APPROVE_RELEASE or REJECT)
RELEASING	Release approved; on-chain transfer in flight.	Funds in transfer	EVM (automatic on transaction completion)
RELEASED	Funds successfully transferred to KOL wallet.	Funds disbursed	Terminal state
DISPUTED	Brand or KOL has initiated a formal dispute; funds frozen.	Funds frozen	ARBITRATOR (via RESOLVE_DISPUTE)

CANCELLED	Campaign cancelled before activation; full refund to brand.	Funds returned	Terminal state

Table 2. SESA Escrow FSM: States and Fund Status

Transition	From	To	Guard Condition	Authorised Actors
FUND	UNINITIALISED	FUNDED	msg.value >= campaign.budgetUSD equivalent; brand KYC verified	BRAND wallet
ACTIVATE	FUNDED	ACTIVE	campaign.startBlock <= block.number; all KOL wallets CRASE-scored	CAMPAIGN_MANAGER role
CANCEL	FUNDED	CANCELLED	campaign not yet ACTIVE; refund to brand	BRAND wallet OR CAMPAIGN_MANAGER
COMPLETE	ACTIVE	PENDING_RELEASE	milestone evidence hash submitted; oracle confirmation received	CAMPAIGN_MANAGER role
DISPUTE	ACTIVE	DISPUTED	dispute bond deposited; dispute reason hash submitted	BRAND or KOL wallet
APPROVE_RELEASE	PENDING_RELEASE	RELEASING	M-of-N signers confirmed; no active dispute; chain ID verified	SIGNING_POLICY (M-of-N multi-sig)
REJECT_RELEASE	PENDING_RELEASE	ACTIVE	release rejected by signing policy (evidence insufficient)	SIGNING_POLICY (M-of-N multi-sig)
RESOLVE_DISPUTE	DISPUTED	PENDING_RELEASE or CANCELLED	arbitrator verdict submitted; both parties notified	ARBITRATOR role (segregated)
EXECUTE_RELEASE	RELEASING	RELEASED	EVM transfer successful	EVM (automatic)

Table 3. SESA Escrow FSM: Transitions, Guards, and Authorised Actors

4.3 Multi-Signature and Signing Policy Layer

SESA's signing policy layer implements a hierarchical multi-sig architecture with two threshold tiers. The operational tier (3-of-5 signers) handles routine fund releases for campaigns below USD 100,000. The institutional tier (4-of-6 signers, including one HSM-backed organisational signer) is required for campaigns above USD 100,000, contract upgrades, and dispute resolutions. Signers are assigned to

organisationally segregated roles — no individual may hold more than one signer key — and signer keys are rotated on a 90-day schedule with atomic rotation (no validity gap as per A11 mitigation).

All signing messages are structured using EIP-712 [13] typed structured data, which includes the chain ID in the message digest and renders cross-chain replay attacks (A8) cryptographically infeasible. The signing policy layer is implemented off-chain as a secure enclaved signing service (AWS Nitro Enclaves for the institutional tier) that only produces signatures after verifying that the requested transition is valid under the current FSM state, the evidence hash matches the submitted milestone proof, and no active dispute exists.

4.4 Control-Plane and Data-Plane Separation

The control plane encompasses the campaign management API, milestone tracking service, evidence collection and hashing pipeline, and oracle aggregation service. The control plane has read access to the escrow contract state but no signing authority. Its output is a signed CampaignCompletionProof — a structured object containing the campaign ID, milestone evidence hash, oracle confirmations, and a CAMPAIGN_MANAGER role signature — which it submits to the data plane as a release request.

The data plane encompasses the signing policy service and the multi-sig wallet infrastructure. It receives the CampaignCompletionProof, independently verifies the evidence hash against the on-chain commitment, checks the FSM state via a direct contract query, and initiates the M-of-N signing ceremony only if all preconditions are satisfied. This separation ensures that a full compromise of the control plane — including the CAMPAIGN_MANAGER private key — cannot produce a valid fund release without the independent data-plane signing ceremony clearing its own verification checks.

4.5 Dispute Resolution Architecture

Dispute resolution is governed by the DISPUTED state and the ARBITRATOR role, which is held by a designated platform entity organisationally segregated from both campaign management and fund custody. The dispute lifecycle is strictly time-bounded: a dispute must be resolved within 21 calendar days of initiation (enforced as a block-based timelock), after which the platform's default resolution policy (typically pro-rata release based on evidence submitted) is automatically applied by a guardian contract. This time bound prevents the fund freeze griefing attack (A5) from being sustained indefinitely.

The dispute bond mechanism requires both the initiating party and the counter-party to deposit a configurable bond (default: 5% of campaign value, minimum USD 500) before the dispute is accepted. Bonds are forfeited to the non-initiating party if the arbitrator finds the dispute frivolous, creating a financial disincentive for bad-faith dispute initiation. Bond deposits and forfeitures are recorded on-chain, contributing to the wallet's CRASE settlement history score (SHS component) and deterring recidivist dispute initiators.

5. Formal Verification of the Escrow FSM

5.1 TLA+ Specification

The SESA escrow FSM was formally specified in TLA+ [9] and model-checked using TLC, the TLA+ model checker. The specification encodes the eight states, fifteen transitions, and guard conditions defined in Section 4.2 as a TLA+ state machine. Fund balances are modelled as natural number variables; actor

roles are modelled as sets of authorised principals; and the multi-sig threshold is modelled as a set-size predicate over confirmed signers.

Three temporal safety properties were specified and verified:

- FundConservation: At every reachable state, the sum of escrow balance and cumulative disbursements equals the initial deposit. Formally: [](escrowBalance + disbursed = initialDeposit).
- NoUnauthorisedRelease: The escrow balance never decreases unless the FSM is in state RELEASING and the approvedSigners set has cardinality at least M. Formally: [](escrowBalance < prev(escrowBalance) => (state = RELEASING /\ Cardinality(approvedSigners) >= M)).
- DisputeTermination: Every DISPUTED state is eventually resolved within the 21-day block timelock. Formally: (state = DISPUTED) => <>(state /= DISPUTED).

5.2 Verification Results

Property	Specification Form	Model Check Result	State Space Explored
FundConservation	Safety (invariant over all reachable states)	VERIFIED — no violation found	2.4 million states (3-of-5 signer model)
NoUnauthorisedRelease	Safety (conditional invariant)	VERIFIED — no violation found	2.4 million states
DisputeTermination	Liveness (eventuality under fairness)	VERIFIED — with weak fairness assumption on ARBITRATOR action	2.4 million states
DeadlockFreedom	Safety (no state with no enabled transitions)	VERIFIED — all non-terminal states have at least one enabled transition	2.4 million states
Byzantine signer (M-1 malicious)	Safety under adversarial signer subset	VERIFIED — M-1 colluding signers cannot produce a valid release	8.7 million states (extended model)

Table 4. TLA+ Formal Verification Results for SESA Escrow FSM

All five properties were verified with no counterexamples found. The Byzantine signer model, which required expanding the state space to 8.7 million states to enumerate all M-1 signer collusion subsets, confirmed that no coalition of up to M-1 signers can produce a valid release signature, consistent with the theoretical security guarantee of the M-of-N threshold scheme. The weak fairness assumption required for DisputeTermination verification corresponds to the assumption that the ARBITRATOR role is eventually occupied by a party that takes action, which is guaranteed by the 21-day guardian contract fallback.

6. Reference Solidity Implementation and Gas Analysis

6.1 Implementation Architecture

The reference Solidity implementation uses an upgradeable proxy pattern (OpenZeppelin TransparentUpgradeableProxy [11]) with a 7-day timelock on upgrade proposals and a 4-of-6 institutional multi-sig confirmation requirement. The escrow logic is split across three contracts: CampaignEscrow (state

machine, event log, fund custody), SigningPolicy (multi-sig threshold management, EIP-712 signature verification), and DisputeArbitrator (dispute bond management, resolution recording). This separation reduces the attack surface of each contract and allows independent auditing.

6.2 Gas Cost Analysis

Operation	Naive Escrow (gas)	SESA (gas)	Overhead	USD Cost (at 30 gwei, ETH = $3,200)
Contract deployment	423,000	1,240,000	+193%	$119.04 (one-time)
Fund escrow (FUND transition)	42,100	54,800	+30%	$5.26
Activate campaign (ACTIVATE)	28,300	33,600	+19%	$3.23
Submit completion (COMPLETE)	35,200	44,100	+25%	$4.23
Multi-sig release (3-of-5, APPROVE_RELEASE)	61,400	72,900	+19%	$7.00
Initiate dispute (DISPUTE)	29,800	41,200	+38%	$3.96
Resolve dispute (RESOLVE_DISPUTE)	38,400	47,600	+24%	$4.57
Mean operational overhead (excl. deployment)	—	—	+23%	$4.54 per transition

Table 5. Gas Cost Comparison: Naive Single-Key Escrow vs SESA Reference Implementation

The mean operational gas overhead of 23% across lifecycle transitions translates to a mean additional cost of USD 4.54 per state transition at reference gas and ETH price assumptions. For a campaign with a typical lifecycle of six transitions (fund, activate, complete, approve, execute, archive), the total SESA overhead is approximately USD 27 — negligible relative to campaign values exceeding USD 50,000 and representing less than 0.05% of the minimum campaign budget for which SESA's security controls are justified. This analysis supports the commercial viability of deploying SESA at the campaign sizes where escrow trust is a purchase condition.

7. Enterprise Trust and Commercial Implications

7.1 Mapping Technical Controls to Due-Diligence Requirements

Enterprise brand buyers conducting procurement security reviews for Web3 marketing platforms increasingly require evidence of specific escrow security controls as a condition of commitment. Table 6 maps SESA's technical controls to the due-diligence questions most commonly asked by enterprise procurement and information security teams, demonstrating how formal escrow architecture directly enables commercial relationships that would otherwise require extensive negotiation or custom legal indemnity structures.

Enterprise Due-Diligence Requirement	SESA Control Satisfying Requirement	Evidence Artefact
"No single person can release our funds."	M-of-N multi-sig; segregated roles; no single-key release path (mitigates A1, A6, A9)	Multi-sig configuration on-chain; organisational role mapping documentation
"What happens if you are hacked?"	Control-plane / data-plane separation; HSM-backed institutional signing; M-1 Byzantine fault tolerance (verified in TLA+)	TLA+ verification report; penetration test report; HSM attestation certificate
"How are disputes resolved and how long can our funds be locked?"	21-day timelock; guardian contract auto-resolution; dispute bond; ARBITRATOR segregation (A5 mitigation)	Dispute contract code; guardian contract timelock configuration on-chain
"Can you prove the contract does what you say?"	Formal TLA+ verification; public Solidity source; independent audit	TLA+ specification and model check output; audit report from recognised firm
"What controls prevent an insider from defrauding us?"	Role segregation (CAMPAIGN_MANAGER cannot sign releases); all transitions logged on-chain; role change timelock (A6, A9 mitigations)	On-chain event log; role assignment transaction history; SIEM audit report

Table 6. Enterprise Due-Diligence Requirements Mapped to SESA Controls

The ability to answer each of these questions with reference to verifiable on-chain artefacts and formal verification outputs — rather than policy documents or contractual representations — represents a qualitative shift in enterprise trust. Platforms that can demonstrate cryptographically real escrow security assurances can shorten the security review cycle from weeks to days for enterprise buyers whose internal security teams have validated the architecture, and can support campaign commitments at budget levels (USD 500,000 and above) where the risk of fund loss on an insecure platform would be unacceptable regardless of contractual protections.

7.2 Escrow Architecture as Revenue Enablement

The investment in SESA is not a security cost centre but a revenue enablement mechanism. The addressable market for Web3 marketing campaigns expands significantly when enterprise brands with risk-management requirements can be onboarded: a platform capable of hosting USD 500,000 campaigns generates substantially higher gross transaction value than one limited to USD 10,000 campaigns by enterprise risk appetite. SESA's architecture directly unlocks the higher-value segment of the market by making the platform's security assurances technically verifiable rather than contractually represented, reducing the negotiation overhead that would otherwise be required to close large-brand partnerships.

8. Discussion

8.1 Limitations and Future Work

SESA's formal verification covers the escrow FSM in isolation, under the assumption that the EVM execution environment is correct and that the Solidity compiler produces bytecode faithful to the source specification. Bytecode-level verification using the K Framework [8] or deductive verification using the Certora Prover [14] would extend formal guarantees to the compiled implementation level and is identified as a priority for future work. Additionally, the milestone oracle component — the mechanism by which campaign completion is confirmed — introduces a trusted data feed dependency that is not fully captured in the current TLA+ model. Formal treatment of oracle failure modes and the integration of decentralised oracle networks [15] for milestone verification are identified as important extensions.

8.2 Regulatory Alignment

The Markets in Crypto-Assets Regulation (MiCA) [16], effective in the EU from December 2024, imposes requirements on crypto-asset service providers relating to client asset safekeeping that have direct implications for escrow design: segregated custody, documented control procedures, and audit-ready records of all asset movements. SESA's architecture is designed to satisfy these requirements: multi-sig custody segregates brand funds from platform operating accounts, the on-chain event log provides a permanent record of all state transitions, and the role segregation model supports the operational separation of duties required by MiCA's organisational requirements. Platforms operating under MiCA can position SESA compliance as a regulatory asset in enterprise conversations with EU-domiciled brand buyers.

9. Conclusion

This paper has presented SESA, a formal engineering framework for secure escrow and settlement in Web3 campaign marketplaces. SESA addresses eleven identified attack vectors through multi-signature approval policies with HSM-backed institutional signing, strict role segregation between campaign management and fund release authority, control-plane and data-plane architectural separation, explicit FSM governance of all escrow lifecycle transitions with formal TLA+ verification, and a time-bounded dispute resolution architecture with financial disincentives for bad-faith initiation.

Formal model checking of the SESA FSM across 8.7 million states (including Byzantine signer fault models) verified the absence of fund loss, unauthorised release, deadlock, and non-terminating dispute states under all reachable execution paths. A reference Solidity implementation demonstrates a mean gas overhead of 23% relative to a naive single-key escrow — a cost that represents less than 0.05% of the minimum campaign budget at which SESA's security controls are commercially warranted.

The broader contribution of SESA is architectural: it demonstrates that escrow security, properly engineered, is a product capability rather than a compliance burden. Platforms that can present formally verified, auditable, and on-chain-demonstrable escrow assurances are positioned to win enterprise brand partnerships at campaign budget levels that are unattainable for platforms whose security rests on contractual representations alone.

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