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# IOTASDN: IOTA 2.0 Smart Contracts for Securing Software-Defined Networking Ecosystem

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**Abstract:** Software-Defined Networking (SDN) has revolutionized network management by providing unprecedented flexibility, control, and efficiency. However, its centralized architecture introduces critical security vulnerabilities. This paper introduces a novel approach to securing SDN environments using IOTA 2.0 smart contracts. The proposed system utilizes the IOTA Tangle, a directed acyclic graph (DAG) structure, to improve scalability and efficiency while eliminating transaction fees and reducing energy consumption. We introduce three smart contracts: Authority, Access Control, and DoS Detector, to ensure trusted and secure network operations, prevent unauthorized access, maintain the integrity of control data, and mitigate denial-of-service attacks. Through comprehensive simulations using Mininet and the ShimmerEVM IOTA Test Network, we demonstrate the efficacy of our approach in enhancing SDN security. Our findings highlight the potential of IOTA 2.0 smart contracts to provide a robust, decentralized solution for securing SDN environments, paving the way for the further integration of blockchain technologies in network management.

**Keywords:** Blockchain (BC); integrity; IOTA 2.0; security; smart contracts; software-defined networking; trust

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## 1. Introduction

SDN is driving transformative changes in network management and operations by decoupling the control plane from the data plane. This approach introduces new levels of flexibility, control, and efficiency that were previously unattainable in the rapidly evolving digital landscape. This paradigm shift in networking not only redefines the traditional network architecture but also aligns seamlessly with the dynamic requirements of contemporary digital ecosystems [1,2]. While SDN provides significant advantages in network management and efficiency, it also introduces new security challenges that are essential to address. The centralized architecture of SDN controllers poses a potential single point of failure, rendering the network vulnerable to targeted attacks that could compromise the entire infrastructure.

The dynamic and programmable nature of SDN, while contributing to enhanced network flexibility, also introduces heightened vulnerability to potential attacks from malicious actors. They can use flaws in the software layers to launch attacks like DoS, man-in-the-middle, and data theft. These challenges necessitate robust security mechanisms and policies to ensure the integrity, confidentiality, and availability of network resources in an SDN environment [3,4].

In tackling the security challenges inherent in SDN, machine learning and BC emerge as pivotal solutions [5–7]. ML algorithms aim to enhance the SDN network's capability to intelligently detect, predict, and respond to cyber threats. By analyzing network data, identifying patterns, and learning from past incidents, ML algorithms provide a dynamic and proactive approach to network security, significantly improving the ability of SDN environments to safeguard against a wide range of cyber threats. The integration of BC technology into SDN architectures aims to achieve several key objectives: enhancing operational transparency, fortifying network security, and ensuring control data integrity.

BC technology is a decentralized and distributed digital ledger system characterized by its immutability, transparency, security, smart contracts, tokenization, interoperability, efficiency, anonymity, privacy, and programmability [8,9]. These features make BC a promising technology for various applications in addition to cryptocurrencies (e.g., Bitcoin and Ethereum), including agricultural product traceability [10], healthcare [11,12], renewable energy management [13], education [14,15], Internet of Things (IoT) cybersecurity [16–18], and more.

In recent years, BC technology has emerged as a promising solution to security concerns, including those in SDN environments. BC's decentralized and immutable nature offers a new paradigm for securing network environments [19,20]. By decentralizing the control plane, BC can mitigate the risks associated with SDN's centralized nature, providing a more resilient infrastructure. BC also introduces transparency and accountability into network operations [21,22], making it more difficult for malicious actors to compromise the system.

However, traditional BC-based applications like Bitcoin [23,24] and Ethereum [25,26] are not without their limitations, particularly when applied to high-speed and high-volume environments like SDN [27,28]. These challenges include scalability, energy consumption, throughput time, and transaction fees [29,30].

While BC technology was originally designed to secure and verify human transactions, another type of DLT, IOTA Tangle, was designed for the IoT ecosystem. IOTA Tangle is optimized for machine-to-machine communication and supporting microtransactions. The emergence of the IOTA Tangle represents a revolutionary shift in DLT. In contrast to traditional BCs, which rely on a linear chain of blocks, the IOTA Tangle employs a directed acyclic graph structure to address the scalability and efficiency issues associated with conventional BCs. The IOTA enables the parallel processing of multiple transactions, eliminating the need for miners and significantly reducing transaction fees and energy consumption [31,32]. The distinct features of the IOTA Tangle include high scalability, feeless transactions, fast transaction speeds, and low energy consumption. These features make it a promising technology for a diverse range of applications, e.g., IoT [33,34], healthcare [35], industrial sectors [36,37], and federated learning [38]. The introduction of IOTA 2.0 and its smart contract capabilities further extends its applicability, making it a suitable candidate for enhancing SDN security.

This paper primarily focuses on enhancing the scalability of Access Control systems in SDN environments through the innovative use of IOTA 2.0 smart contracts. While security and energy efficiency are also critical aspects of our approach, the central objective is to demonstrate how IOTA's unique architecture can significantly improve the scalability of Access Control mechanisms, enabling SDN environments to efficiently handle larger and more complex networks. The original contributions presented in this research are as follows:

- **Overcoming BC challenges**: By employing IOTA 2.0 Tangle, we overcome the scalability, energy consumption, throughput time, and transaction fee challenges inherent in traditional BC-based solutions for securing SDN environments.

- **Automating SDN management**: We use IOTA smart contracts to automate and secure the management and operation of the SDN network.
- **Strengthening Access Control**: We use an authority smart contract as a CA to define and verify trusted entities, and we implement SC-based Access Control to manage interactions between controllers and switches within the SDN, ensuring secure and authorized communication.
- **Ensuring control data integrity**: Our approach leverages IOTA 2.0's Tangle architecture, decentralized consensus, and the immutability of transactions to guarantee the integrity of control data in SDN, protecting it from unauthorized modifications, and ensuring reliable operations.

We structure the remainder of this paper as follows: Section 2 gives an overview of recent studies on the use of BC technology to enhance SDN security. Section 3 gives the necessary background, providing an overview of SDN security challenges and IOTA 2.0 smart contracts. Section 4 presents the IOTA 2.0 smart contracts-based system for fortifying the security of SDN. Section 5 focuses on the practical implementation of IOTA 2.0 SCs within SDN environments and presents a comprehensive analysis of the results obtained. Section 6 concludes the paper by summarizing the key findings and contributions of the research.

## 2. Related Work

This section provides a comprehensive review of recent research focusing on the application of distributed ledger technologies (DLTs), e.g., BC, to enhance the security of SDN.

Weng et al. [39] proposed a BC-based monolithic secure mechanism to enhance SDN security by decentralizing the control plane, ensuring the authenticity and accountability of application flows, implementing Access Control mechanisms, and integrating secure protocols with smart contracts on the BC. By recording network events on the BC, the mechanism enables the traceability and auditing of network behaviors, addressing single-point failures and improving scalability in SDN environments. The paper concludes that this innovative approach offers a comprehensive solution to SDN security challenges, leveraging BC technology to provide a secure, decentralized, and accountable framework for network management and control.

Pourvahab and Ekbatanifard [40] presented a novel forensic SDN–IoT architecture that utilizes BC technology to enhance security and efficiency in digital forensics processes within IoT environments. The proposed architecture demonstrates a superior performance in terms of delay, throughput, accuracy, response time, processing time, and security compared to previous works. The study emphasizes the importance of BC in ensuring data integrity by preventing tampering, and establishing a secure chain of custody for digital evidence. Future validation plans include testing the architecture in a large-scale network environment and implementing additional authentication and load-balancing mechanisms.

Yazdinejad et al. [41] presented a novel approach to enhancing security in SDN through the BC-enabled packet parser (BPP) architecture. By leveraging BC technology and FPGA hardware, the BPP architecture demonstrates efficient attack detection capabilities with a low false-positive rate and a high detection rate. The study emphasizes the importance of integrating security measures into both the control and data planes of SDN networks, as well as BPP's potential to improve network security by detecting and communicating attacks to the SDN controller.

Aujla et al. [42] explored the integration of BC technology with SDN to address the challenges faced by smart cities, such as channel congestion and limited scalability. By proposing BlockSDN as a solution, the study aimed to enhance data transmission efficiency and security in smart city environments. It emphasizes the role of SDN in providing improved bandwidth capabilities and flexibility for dynamic data transmission requirements. Additionally, the paper highlights the security concerns associated with SDN architectures, particularly the vulnerability of the centralized controller to attacks.

Shashidhara et al. [43] introduced SDN-chain, a BC-based privacy-preserving protocol for software-defined networks, aiming to address the vulnerabilities in existing security protocols such as ARP poisoning and DDoS attacks. By integrating BC technology, SDN-chain enhances network reliability, safety, and decentralization, mitigating the risks associated with centralized SDN controllers. The Ethereum BC implements a delegated proof of stake algorithm to support the initialization, registration, and authentication phases of the proposed security model. Through informal security analysis and simulations, SDN-chain demonstrates an improved network efficiency with reduced delay and bandwidth.

Algarni et al. [44] introduced BCNBI, a BC-based security framework for the northbound interface in SDN, aiming to enhance security by addressing the confidentiality, integrity, and availability concerns. BCNBI utilizes a light-weight BC architecture to authenticate applications and the SDN controller, enforce Access Control policies, and monitor the application behavior. Compared with existing solutions and demonstrating its superior performance in handling transactions, BCNBI showcases its efficiency in securing the SDN environment.

Kovacs et al. [7] investigated a range of critical topics concerning network optimization and security within the realm of BC-enabled SDN controllers and IoT deployments. The research delved into secure storage and access for task-scheduling schemes on consortium BC and the Interplanetary File System, as well as the development of proof-of-authentication mechanisms for scalable BC in resource-constrained distributed systems. Furthermore, the paper explored cooperative traffic control schemes among ISPs using bargaining game approaches, analyzed the impact of zero-rating content on the Internet's quality of service, introduced machine learning-based action recommenders for network operation centers, and discussed enhancements in SDN security for IoT deployments through BC integration.

The aim of this paper is to enhance the security of SDN environments by leveraging IOTA 2.0 smart contracts. Our proposed system introduces three separate smart contracts, namely Authority, Access Control, and DoS Detector, to provide robust security mechanisms that ensure secure network operations, prevent unauthorized access, and mitigate DoS attacks. By utilizing the IOTA Tangle's directed acyclic graph structure, our approach aims to enhance scalability, efficiency, and energy consumption while eliminating transaction fees. To validate the efficacy of IOTA 2.0 smart contracts in providing a decentralized and efficient solution for securing SDN environments, we conducted comprehensive simulations using Mininet and the ShimmerEVM IOTA test network.

Table 1 presents a comparative analysis of our proposed IOTA 2.0 smart-contract-based system compared to existing systems using DLTs to improve SDN security.

**Table 1.** Comparison of the proposed system with other existing systems based on DLTs.

| Ref. | Focus Area | Key Contributions | DLT | SC | Limitations |
|---|---|---|---|---|---|
| [39] | BC-based monolithic secure mechanism for SDN. | Decentralizing control planes, ensuring authenticity and accountability of application flows, Access Control mechanisms, and integrating secure protocols with SCs. | HLF V 1.0 | ✔ | Potential scalability challenges, performance overhead, SC complexity, and interoperability issues. The type of SCs used is not specified. |
| [40] | Forensic SDN–IoT architecture with BC. | Enhancing security and efficiency in digital forensics, ensuring data integrity, preventing tampering, and securing the chain of custody for digital evidence. | BC | ✕ | Potential scalability challenges and overhead of BC integration in large-scale SDN environments. |

**Table 1.** *Cont.*

| Ref. | Focus Area | Key Contributions | DLT | SC | Limitations |
|---|---|---|---|---|---|
| [41] | BC-enabled packet parser architecture. | Enhancing security in SDN through FPGA hardware, efficient attack detection, a low false positive rate, and a high detection rate. | BC | ✗ | Scalability challenges inherent in BC implementation at the data plane level of SDN networks. |
| [42] | Integration of BC with SDN for smart cities. | Addressing challenges in smart cities, enhancing data transmission efficiency and security, and improving bandwidth capabilities and flexibility. | BC | ✗ | Complexity and potential overhead introduced by integrating BC technology into SDN infrastructures. |
| [43] | BC-based privacy-preserving protocol for SDN. | Addressing ARP poisoning and DDoS attacks, enhancing network reliability, safety, and decentralization, and reducing delay and bandwidth. | Ethereum | ✓ | Potential scalability and performance challenges for real-world network operations. |
| [44] | BC-based security framework for northbound interface in SDN. | Enhancing security by addressing confidentiality, integrity, and availability, authenticating applications and SDN controllers, and enforcing Access Control policies. | BC | ✗ | Potential challenges related to scalability, performance overhead, and the computational resources required for BC operations. |
| [7] | Network optimization and security in BC-enabled SDN and IoT. | Secure storage and access for task scheduling, the development of proof-of-authentication mechanisms, cooperative traffic control, and ML-based action recommenders. | Ethereum | ✗ | Challenge of scalability and performance issues for large-scale infrastructure networks. |
| Our system | IOTA 2.0 SCs for securing SDN. | Introducing a novel approach to secure SDN environments using IOTA Tangle and leveraging smart contracts for Authority, Access Control, and DoS Detection. | IOTA 2.0 | ✓ | Potential reduction in quality of service, increased latency, and impact on data traffic due to the integration of the DoS Detector smart contract. |

## 3. Background

This section explores the key research areas, focusing on the security challenges in SDN and presenting IOTA 2.0 SCs as an innovative solution to address these issues.

### *3.1. Comprehensive Analysis of SDN Security Challenges*

SDN provides a significant advancement in network management by decoupling the control plane from the data plane, and thus enhancing the programmability and flexibility. However, it also introduces security challenges due to its unique structural design [4,45,46], presenting various threats and vulnerabilities across different network layers and interfaces, as shown in Figure 1.

1. **The SDN switch**, a hardware and software device, is susceptible to threats like flow table modification, topology spoofing, and DDoS attacks, which can insert malicious nodes or modify flow rules.
2. **With regard to the link between switches,** the SDN architecture's lack of encryption on the links between SDN switches allows hackers to intercept information, thereby compromising network security.

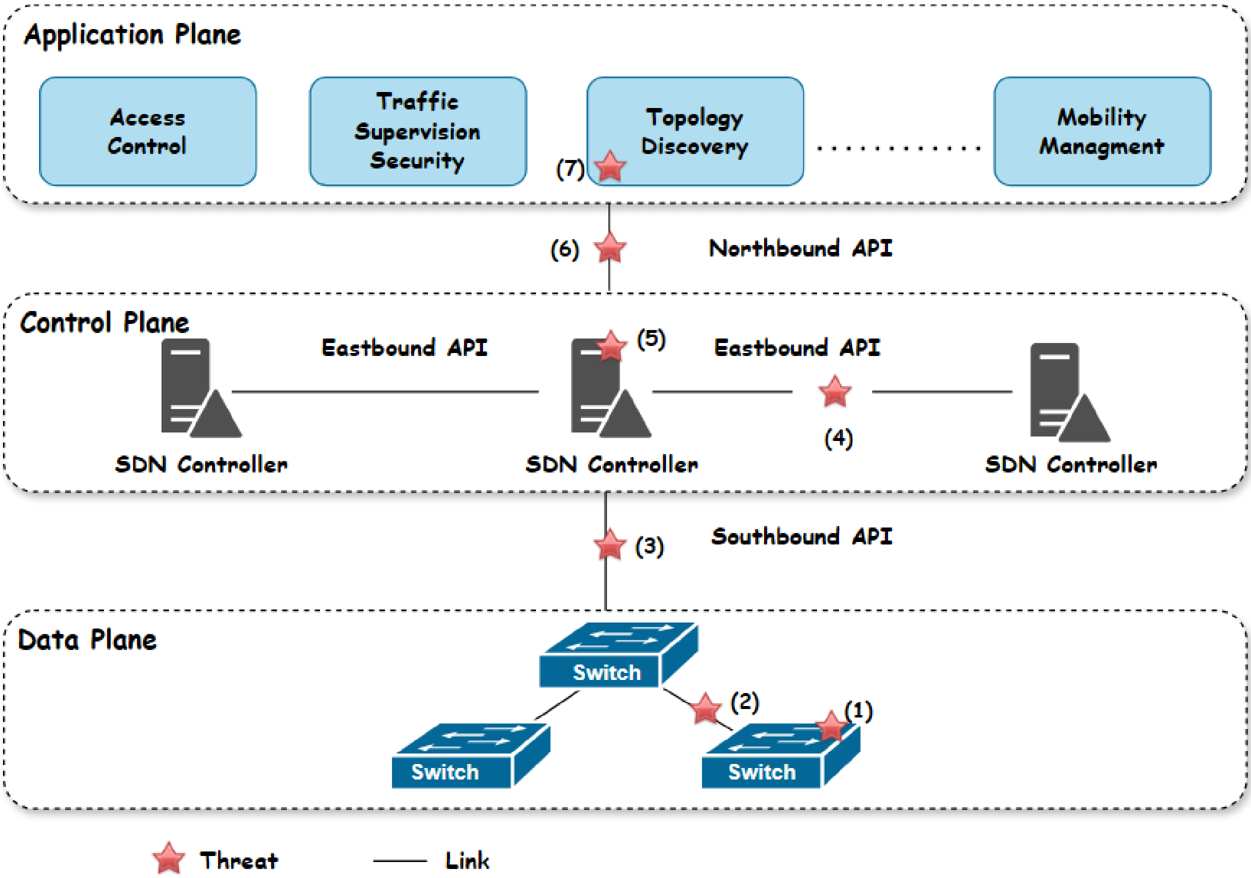


**Figure 1.** Security threat and vulnerability analysis in SDN by layer.

1. **The eastbound interfaces** are vulnerable to security threats due to the lack of encryption on the links connecting controllers. This vulnerability compromises the integrity of inter-controller communications, allowing hackers to manipulate network behavior and share false information.
2. **SDN controllers** face security challenges like DDoS attacks, unauthorized access, and interception risks due to their centralized architecture. The lack of standardized protocols exacerbates these vulnerabilities, allowing attackers to alter network topology and hack switches.
3. **The northbound interface**—a communication link between applications and controllers—is susceptible to security breaches due to weak authentication and inappropriate authorization. This can enable identity theft and unauthorized access, leading to flow modifications and processor overload.
4. **The applications plane** faces security challenges due to its role in managing network behaviors and policies, lack of robust authentication and Access Control mechanisms, direct interaction with SDN controllers, and standardized security protocols.

### *3.2. Overview of IOTA 2.0 Smart Contracts*

BC technology offers benefits like decentralization, security, and transparency, but also faces challenges like scalability, high energy consumption, transaction fees, throughput time, and network latency [47,48] in IoT devices. The IOTA Tangle [49], an alternative DLT for the IoT ecosystem, implements a directed acyclic graph structure for parallel transaction processing and scalability.

The IOTA 2.0 Tangle [50] has undergone significant improvements to address scalability, security, and decentralization challenges. Its architecture, consensus mechanisms, and functionality have been redesigned to address the limitations of previous releases [51,52]. Tangle, a novel DAG data structure for IoT, offers immutable data, fee-less microtransactions, low resource consumption, and security based on PoW consensus. IOTA 1.5 (Chrysalis) [53] improves the security and usability of IOTA 1.0 by introducing improvements like better tip selection, autopeering, atomic transactions, adoption of the UTXO model [54], increased throughput, and faster confirmations.

IOTA 2.0 [55] is the first fully decentralized version of the network, incorporating SCs and a decentralized consensus mechanism, and allowing network nodes to independently validate transactions and achieve consensus without a central authority [56].

Coordicide has numerous features, including the following:

- **Tangle technology**: Coordicide employs a Tangle-directed acyclic graph for parallel transaction processing, enhancing scalability and TPS compared to traditional BCs' linear chain of blocks.
- **Decentralization and scalability**: IOTA 2.0 eliminates the Coordinator, a special node for transaction validation. Moving towards a fully decentralized system enhances the network's scalability and security.
- **Energy efficiency**: Tangle's design simplifies the transaction validation, reduces computational power, and makes IOTA more energy-efficient compared to traditional proof-of-work BC systems by eliminating the need for miners.
- **No transaction fees**: IOTA 2.0 maintains its no-fee transaction feature. This feature makes microtransactions viable and opens up a range of applications, particularly in the Internet of Things domain.
- **Interoperability**: IOTA Tangle 2.0 facilitates the transfer of value between different BC networks due to its interoperability with other BC platforms.
- **Smart contract capabilities:** IOTA 2.0 enhances its platform's competitiveness in DLTS by enabling developers to create complex decentralized applications using SCs.

IOTA 2.0 SCs constitute a decentralized network designed for IoT applications, offering enhanced security, scalability, and suitability. They operate on a distributed network with multiple validators, going through four phases: creation, deployment, execution, and completion. The protocol (ISCP) uses programming languages like Solidity and subchains linked to the main Tangle, reducing the reliance on the main network. This setup supports parallel execution, inter-chain communication, and an Ethereum virtual machine.

Figure 2 illustrates ISCP chains that manage state and contract execution, with validator nodes validating state changes and publishing them to Layer 1. This setup reduces the transaction costs, minimizes the network strain, and supports Solidity-based contracts. IOTA SCs enhance scalability and support complex contracts, operating on Layer 2 within the IOTA multi-asset ledger.

IOTA Tangle has created new opportunities for various application domains due to its unique smart contracts, feeless transactions, and fully decentralized nature. These domains include healthcare [35,57], Industry 4.0 [37,58], the Internet of Things (IoT) [59], and autonomous IoT systems [60].

Table 2 concludes the subsection with a comprehensive comparative study between IOTA 2.0 and well-known BC-based cryptocurrencies, specifically Bitcoin [61], Ethereum [62,63], and Hyperledger [63]. Table 2 provides a comparative study of IOTA 2.0 and other BC-based cryptocurrencies.

**Table 2.** Comparative study between IOTA 2.0 and various BC platforms with SCs and parallel transactions.

| Feature/Criterion | IOTA 2.0 | Bitcoin | Ethereum | Hyperledger | SEI | Monad | Solana |
|---|---|---|---|---|---|---|---|
| **Transaction Speed** | Up to 1000 TPS | 3–7 TPS | 15–30 TPS | 1000–10,000 TPS (varies by implementation) | 20,000+ TPS | High TPS (specifics TBD) | 65,000 TPS |
| **Scalability** | High | Low | Low | Low | High | High | High |
| **Energy Consumption** | Very low | High | Medium-high | Low to medium | Low | Low | Low |
| **Consensus Mechanism** | FPC binary voting protocol | PoW | PoW, transitioning to PoS | PBFT variants, Raft, etc. | Tendermint BFT | Proof of Stake | Proof of History + PoS |
| **Security Protocols** | EdDSA | ECDSA | ECDSA | ECDSA | EdDSA | EdDSA | EdDSA |
| **Decentralization** | Fully decentralized | Fully decentralized | Fully decentralized | Permissioned (partially decentralized) | Fully decentralized | Fully decentralized | Fully decentralized |
| **SC support** | ✔ | ✗ | ✔ | ✔ | ✔ | ✔ | ✔ |
| **SC speed** | Fast execution (parallel transactions) | - | Slower execution | Slower execution | Fast execution (parallel transactions) | Fast execution (parallel transactions) | Fast execution (parallel transactions) |
| **Microtransactions** | ✔ | ✗ | ✗ | ✗ | ✔ | ✔ | ✔ |
| **Transactions fees** | Very low | - | High | High | Very low | Very low | Very low |
| **Limitations** | Early stage of development Potential network stability issues | Scalability issues, high energy consumption | Scalability issues, gas fees | Limited decentralization, complexity | Early stage of adoption | Early stage of adoption | Complexity, potential centralization concerns |

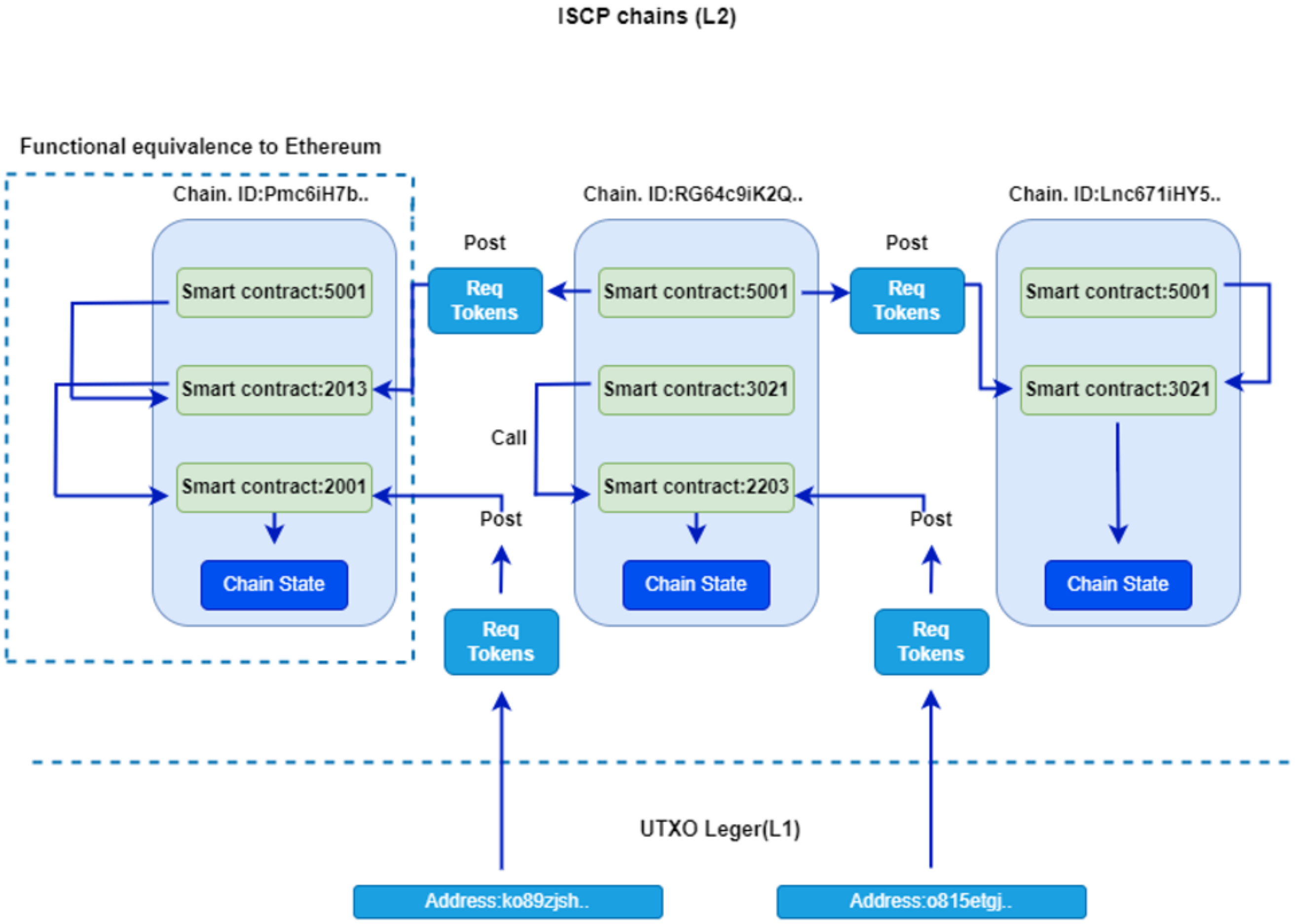


**Figure 2.** IOTA smart contract protocol chains.

## 4. Proposed IOTA–SDN System

This section presents our innovative proposal for an IOTA-based system designed to effectively manage and secure SDN. As illustrated in Figure 3, the architecture of our IOTA-based SDN, where SDN controllers play a central role, guarantees secure horizontal and vertical communication with switches.

IOTA 2.0 has incorporated resilient mechanisms to mitigate the consequences of denial-of-service (DoS) attacks. Nevertheless, ongoing development and testing indicate that the network is not completely immune to such threats. The IOTA Foundation and its community are continually striving to enhance the network's security and scalability, finite resources that diminish over time, and thus impeding their prolonged accumulation. Furthermore, we proposed integrating a smart-contract-based DoS Detector, which is critical in proactively countering potential threats, thereby strengthening the system's security posture.

Our system involves ISPs, with each overseeing its own dedicated controller linked to a set of switches, functioning as primary administrators and standby controllers for other domains. Collaborative efforts among ISPs are essential to extend network coverage across various ISP domains. It is imperative to monitor this collaboration to prevent any ISPs from violating regulations or operating independently within the network. The contracts we designed establish an Access Control framework for controllers, ensuring secure, regulated, and well-organized collaboration in the network's operations. This ecosystem involves three key actors, as illustrated in Figure 4.

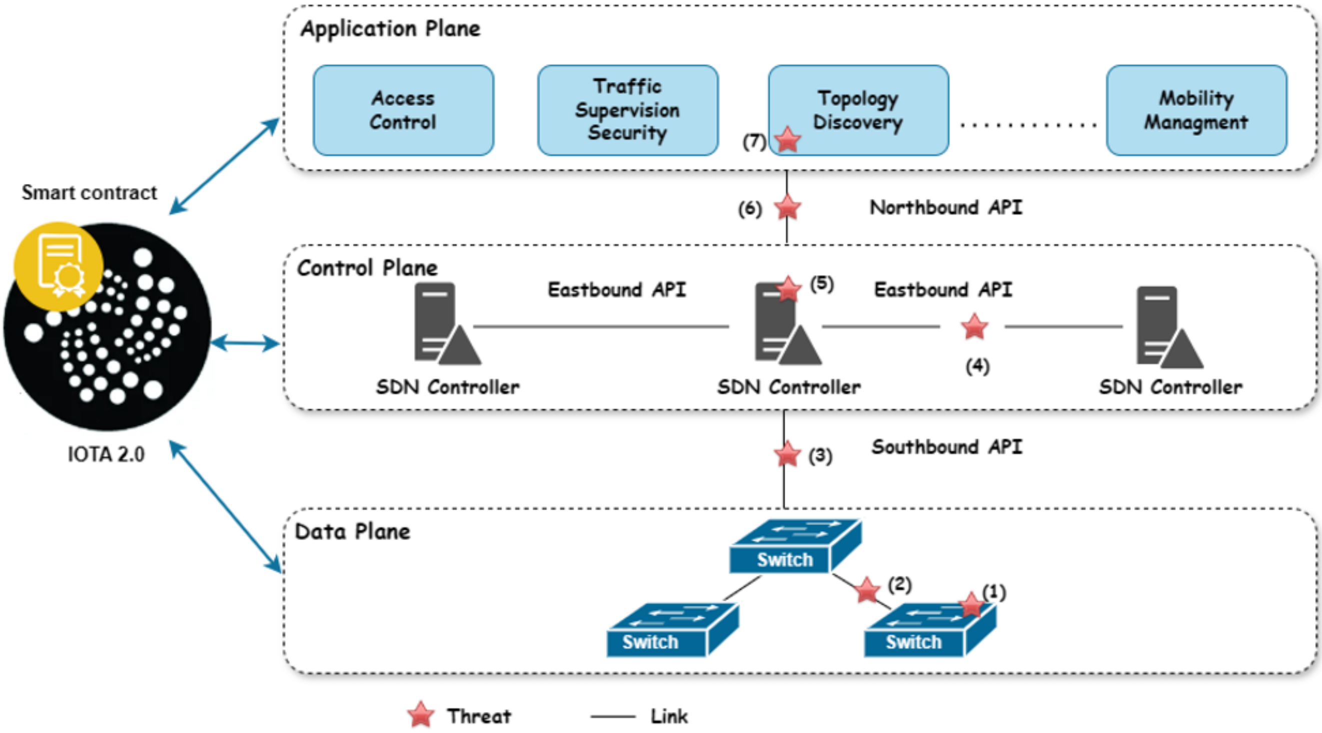


**Figure 3.** IOTA-based SDN.

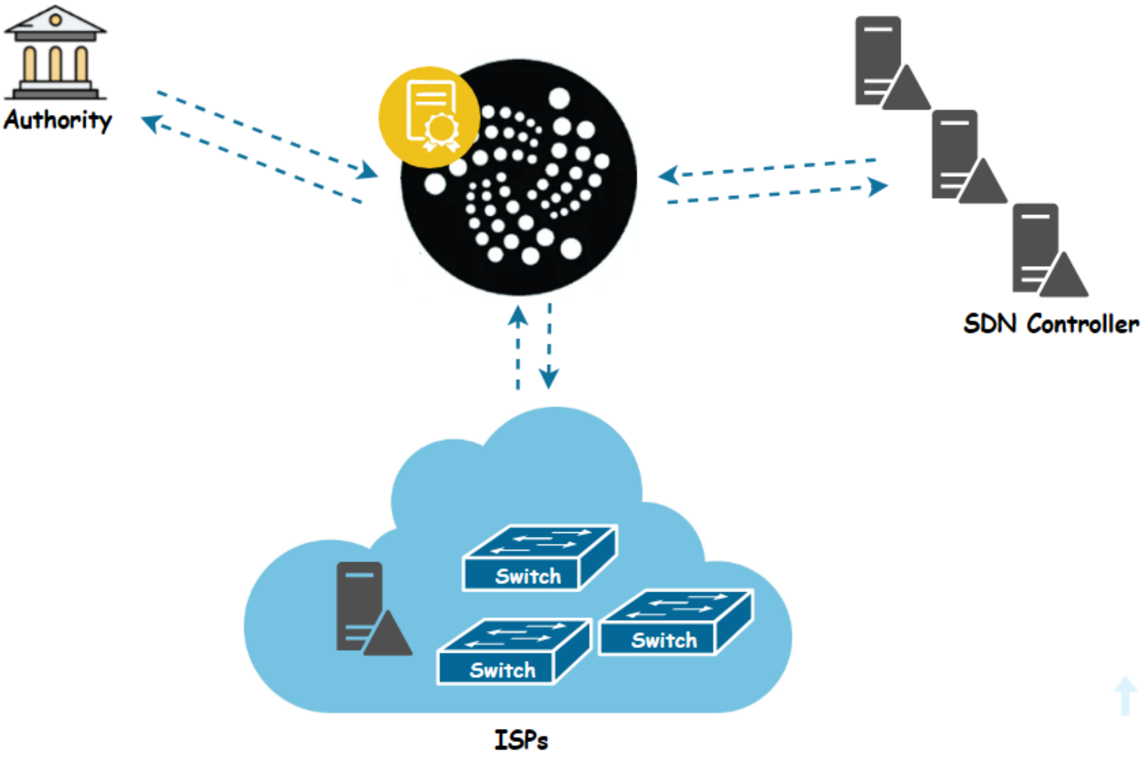


**Figure 4.** IOTA-based system for SDN.

- **The Authority:** Functioning as a Certificate Authority (CA), the Authority holds pivotal responsibility in overseeing the involvement of trusted entities, specifically ISPs, within our proposed system. Its primary role lies in ensuring the exclusive authorization of an ISP to integrate its controller, switches, and standby controller components. Moreover, the CA serves as a cornerstone in upholding the security and integrity of the system by meticulously managing the authorization procedures for these entities. Furthermore, it defines the expiration parameters of digital certificates and offers essential revocation services to invalidate non-expired certificates when necessary.

- **ISPs:** The Authority acting as CA approves only trusted entities (ISPs) to access our system. Each ISP assumes a critical role, maintaining its controller and switches. These controllers serve as primary administrators, and are intricately connected to a network of switches, facilitating efficient data transmission and network management. Notably, ISPs wield the Authority to manage access permissions, authorizing or withdrawing access and integrating or excluding backup controllers across different network domains.
- **The SDN controller:** Within the system architecture, the controller assumes a dual role of paramount importance. Firstly, it functions as the primary administrator within its designated domain, overseeing and orchestrating network operations, managing data flow, and ensuring the smooth functioning of connected switches. As the primary administrator, the controller holds authoritative control over the domain's network infrastructure, making critical decisions to optimize performance and maintain security. Additionally, the controller assumes the crucial responsibility of serving as the standby controller for other domains within the system. In this capacity, it stands ready to assume control in the event of a primary controller failure or disruption [64].

### *4.1. Overview of the Architecture and Components of the Proposed System*

The workflow of our proposed model involves actors and SCs in IOTA-based SDN, which is implemented by three SCs illustrated in Figure 5.

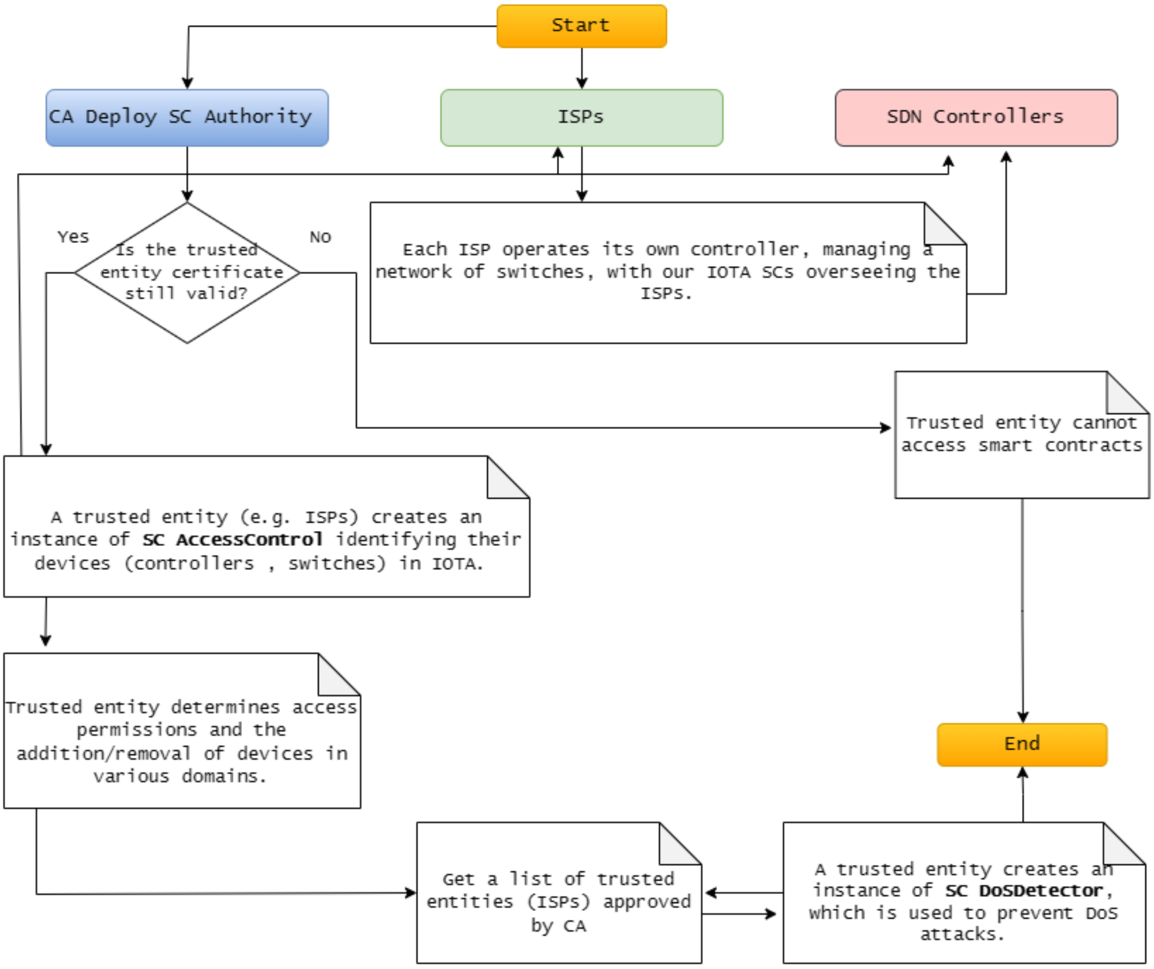

Start
CA Deploy SC Authority
ISPs
SDN Controllers
Yes
Is the trusted entity certificate still valid?
NO
Each ISP operates its own controller, managing a network of switches, with our IOTA SCs overseeing the ISPs.
Trusted entity cannot access smart contracts
A trusted entity (e.g. ISPs) creates an instance of SC AccessControl identifying their devices (controllers , switches) in IOTA.
Trusted entity determines access permissions and the addition/removal of devices in various domains.
End
Get a list of trusted entities (ISPs) approved by CA
A trusted entity creates an instance of SC DoSDetector, which is used to prevent DoS attacks.

**Figure 5.** The workflow of our proposed model.

We clarify our solution's workflow by involving the actors and the previously presented SCs. Initially, the CA deploys an Authority SC instance in IOTA and maps trusted entities (ISPs) by linking their IOTA addresses to their public key certificates. Each ISP then creates an Access Control SC instance to manage its devices (SDN controllers and switches), determine access permissions, and manage devices. Once the CA approves a list of trusted entities, the ISP creates a DoS Detector SC instance to protect against DoS attacks.

Finally, each CA-approved ISP operates its own SDN controller, managing a network of switches. These SDN controllers serve as primary administrators and standby controllers for other system domains. Furthermore, our system facilitates collaboration among ISPs to extend network coverage across various ISP domains, with our SCs overseeing the ISPs to secure SDN environments.

### 4.2. Authority Smart Contract of CA

The Authority smart contract is designed to manage and approve trusted entities, specifically Internet Service Providers (ISPs), that are authorized to participate in our proposed system. To clarify its function, we can provide a practical example where the Authority smart contract maps the public key certificates of ISPs to their IOTA addresses. This mapping ensures that only authorized ISPs can integrate their network components, such as controllers and switches, into the SDN ecosystem. For instance, if an ISP seeks to join the network, the Authority smart contract verifies the ISP's digital certificate, ensuring that it is valid and issued by a trusted Certificate Authority. Upon approval, the ISP is granted access to the network, where it can deploy and manage its SDN controllers and switches securely. This example demonstrates how the Authority smart contract plays a crucial role in maintaining the security and integrity of the SDN environment by controlling the entry of trusted entities. Figure 6 illustrates the functions within the SC and the actors involved.

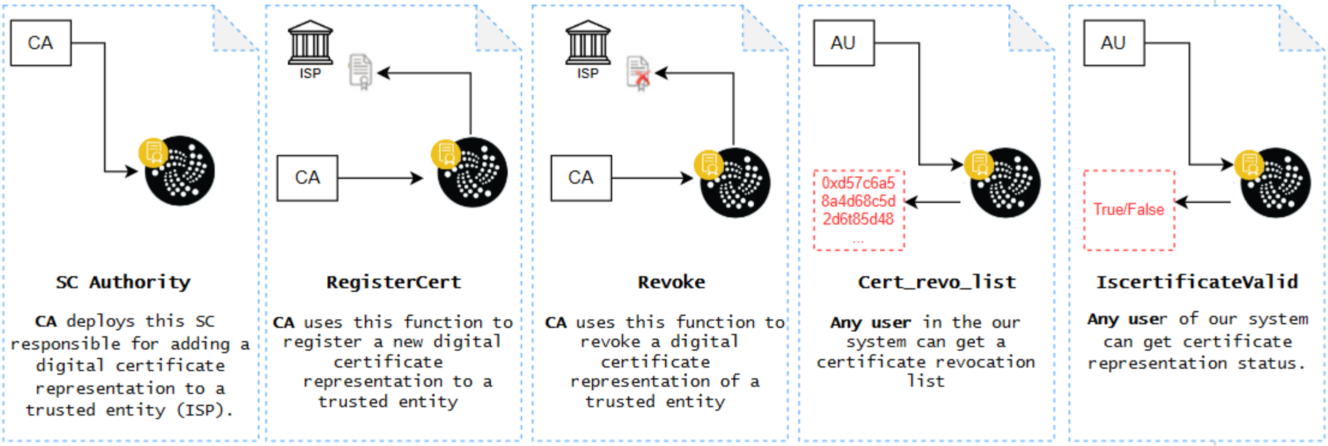

CA
SC Authority
CA deploys this SC responsible for adding a digital certificate representation to a trusted entity (ISP).
ISP
CA
RegisterCert
CA uses this function to register a new digital certificate representation to a trusted entity
ISP
CA
Revoke
CA uses this function to revoke a digital certificate representation of a trusted entity
AU
0xd57c6a5
8a4d68c5d
2d6t85d48
...
Cert_revo_list
Any user in the our system can get a certificate revocation list
AU
True/False
IscertificateValid
Any user of our system can get certificate representation status.

**Figure 6.** The workflow of the Authority SC along with the actors involved in IOTA.

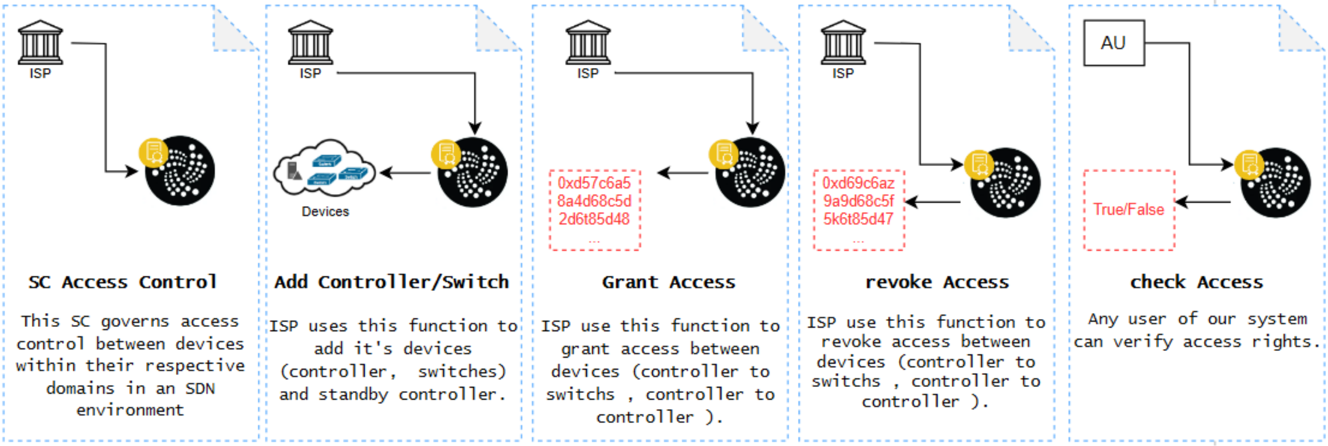
Rectangles labeled "CA" in steps 1, 2, and 3 denote Certificate Authority, while those labeled "AU" in steps 4 and 5 represent any user within the IOTA-based SDN. Step 2 provides the registration certification representation for the ISP, while step 3 presents the revoke registration certification representation for the ISP. Step 4 offers a list of revocation certifications, and step 5 presents the certification representation status.

Further details about the SC Authority are presented in the simulation results section.

### 4.3. Access Control Smart Contract of CA

The Access Control smart contract is implemented to manage the permissions and access rights between controllers and switches within the SDN environment. To provide a clearer understanding, we will include a practical example where an ISP uses the Access Control smart contract to oversee and regulate network device interactions. For instance, within an ISP's domain, the Access Control smart contract could be used to grant a controller permission to communicate with specific switches based on predefined policies. If the controller needs to establish communication with another domain's controller for load balancing, the Access Control smart contract can dynamically adjust the access permissions to allow or revoke this interaction. This real-world scenario illustrates how the Access Control smart contract ensures that network devices operate within secure boundaries, preventing unauthorized access and maintaining the overall security of the SDN environment.

Figure 7 shows the functions in the SC, along with the actors involved.



This SC governs access control between devices within their respective domains in an SDN environment

ISP uses this function to add it's devices (controller, switches) and standby controller.

ISP use this function to grant access between devices (controller to switchs , controller to controller ).

ISP use this function to revoke access between devices (controller to switchs , controller to controller ).

Any user of our system can verify access rights.

**Figure 7.** The workflow of the Access Control SC along with the actors involved in IOTA.

The ISP, approved by CA in steps 1, 2, 3, and 4, is recognized as a trusted entity. Step 2 involves presenting devices such as SDN controllers and switches. Step 3 entails furnishing a list of granted access between devices (controller to switch, controller to controller). Step 4 involves providing a list of revoked access between devices (controller to switch, controller to controller). Step 5, denoted as "AU", represents any user in the IOTA-based SDN. The simulation results section provides more information about the Access Control SC.

### 4.4. DoS Detector Smart Contract of CA

The DoS Detector smart contract is designed to protect the network from denial-of-service (DoS) attacks by monitoring the frequency and volume of requests made by network devices. To better illustrate its function, we propose adding a case study example where the DoS Detector smart contract is deployed in an SDN environment to monitor request activity. For instance, consider a scenario where a malicious entity attempts to overwhelm the network by sending an excessive number of requests to a controller within a short period. The DoS Detector smart contract tracks these requests, and if the number exceeds a predefined threshold, the contract temporarily blocks further requests from the offending device, effectively mitigating the attack. This practical example demonstrates how the DoS Detector smart contract actively safeguards the network by enforcing rate limits and preventing potential disruptions caused by DoS attacks. Figure 8 shows the functions in the SC along with the actors involved.

The CA establishes the ISP as a trusted entity in steps 1, 2, and 3. Step 2 evaluates the DoS protection criteria, including maximum requests, timestamp, request count, and cooldown period, for each device address. Step 3 entails taking action (granting or stopping access) based on the DoS protection criteria. The simulation results section provides more information about the DoS Detector SC.

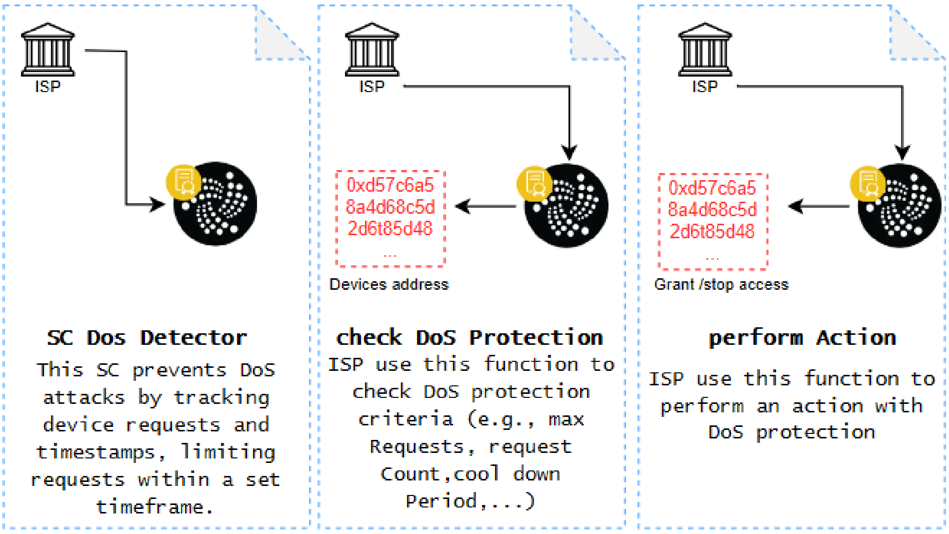

ISP
SC Dos Detector
This SC prevents DoS attacks by tracking device requests and timestamps, limiting requests within a set timeframe.
ISP
0xd57c6a5
8a4d68c5d
2d6t85d48
...
Devices address
check DoS Protection
ISP use this function to check DoS protection criteria (e.g., max Requests, request Count,cool down Period,...)
ISP
0xd57c6a5
8a4d68c5d
2d6t85d48
...
Grant /stop access
perform Action
ISP use this function to perform an action with DoS protection

**Figure 8.** The workflow of the DoS Detector SC along with the actors involved in IOTA.

### *4.5. Key Benefits of the Proposed System*

Our innovative system integrates an IOTA 2.0 layer, enhancing the security of the SDN infrastructure. Utilizing SCs ensures robust security for both horizontal and vertical communication channels. This system also establishes a trusted entity to oversee its domain, including controllers, switches, and standby controllers. This trusted entity meticulously manages access permissions in collaboration with other accredited entities, bolstering the system's overall security framework. Furthermore, our proposed model includes a CA serving as the trusted service provider for safeguarding the SDN infrastructure. It achieves this by authenticating trusted entities through the mapping of their IOTA addresses to their corresponding public key certificates. Specifically, our proposal entails the inclusion of trusted entities possessing valid certificates authorized by the CA, permitting them to actively engage within our system.

## 5. Simulation Results and Discussion

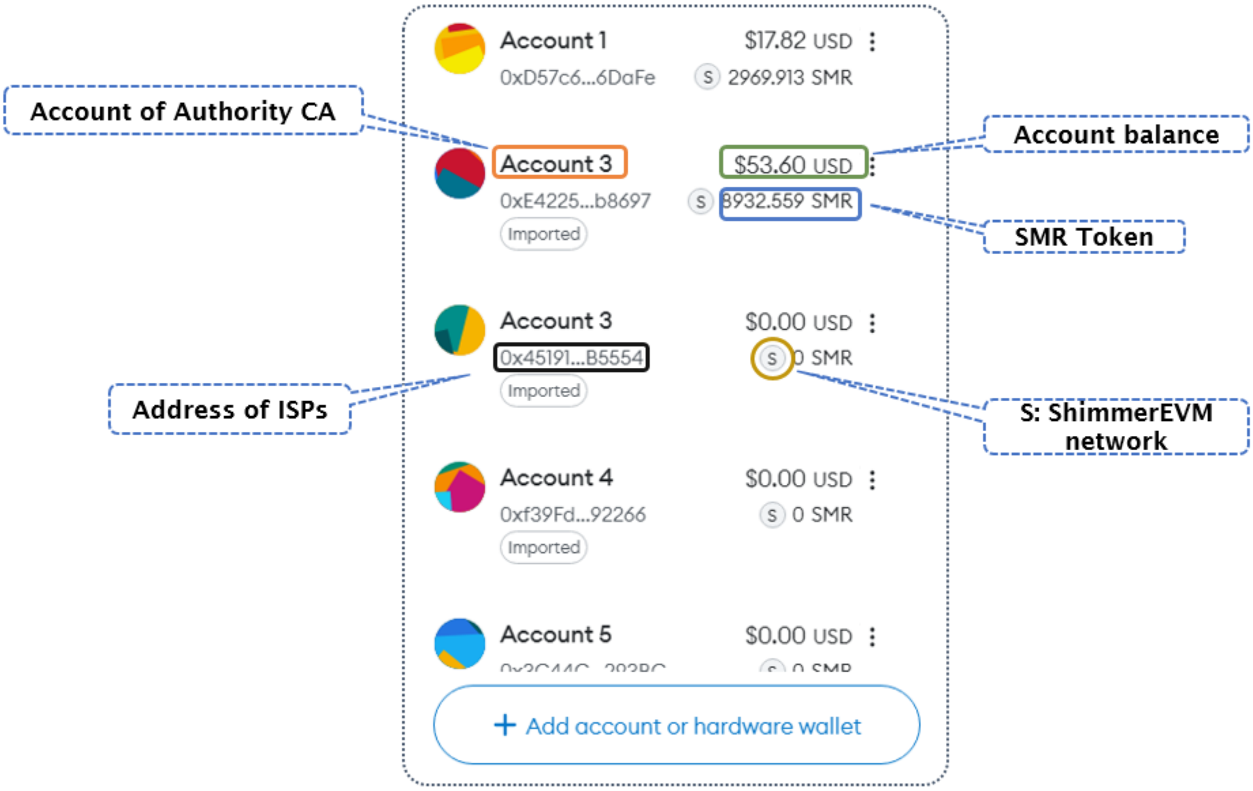
In this section, we present the simulation results and discuss the effectiveness of our proposed system. The simulation environment was carefully constructed using various platforms and tools to evaluate the integration of IOTA 2.0 smart contracts within an SDN environment. The following subsections provide an overview of the platforms used, the simulation setup, and an analysis of the results obtained from the tests.

### *5.1. Simulation Environment*

#### 5.1.1. Platforms Used

- **Mininet**: is a leading emulator in the field of SDN, providing academics and developers with a flexible platform for creating virtual networks, exploring SDN concepts, and examining network applications. Mininet effortlessly combines with prominent SDN controllers like OpenDaylight, ONOS, and Ryu, enabling customers to evaluate the effectiveness of their SDN applications across various controller platforms. Mininet (version 2.3.1b4) was selected because it is a widely used SDN emulator that allows for the creation of virtual networks, enabling the testing and development of network applications. It supports integration with major SDN controllers and is highly valued in academia for its flexibility, ease of use, and ability to efficiently replicate real-world network environments. This made Mininet the ideal tool for simulating our SDN environment, providing a robust and reliable platform for testing our proposed system.
- **ShimmerEVM**: is a test network in the Shimmer ecosystem, that is specifically designed to emulate the Ethereum Virtual Machine (EVM) environment on IOTA's Tangle

2.0. This network allows developers to deploy and test smart contracts in a simulated Ethereum environment, but with the added benefits of IOTA's unique features. Unlike traditional BC networks, ShimmerEVM leverages the IOTA Tangle, a DAG structure that enables the parallel processing of transactions, leading to higher scalability, lower energy consumption, and feeless transactions. We chose ShimmerEVM for our project to harness these advantages, allowing us to develop and test our IOTA 2.0 smart contracts in a secure, efficient, and scalable environment before moving them to the IOTA mainnet. After connecting to the ShimmerEVM Network and adding SMR funds to the MetaMask wallet, Figure 9 shows the account balance.



Account 1 $17.82 USD
0xD57c6...6DaFe S 2969.913 SMR

Account 3 $53.60 USD
0xE4225...b8697 S 8932.559 SMR
Imported

Account 3 $0.00 USD
0x45191...B5554 S 0 SMR
Imported

Account 4 $0.00 USD
0xf39Fd...92266 S 0 SMR
Imported

Account 5 $0.00 USD
0x2C44C...293BC S 0 SMR

+ Add account or hardware wallet

Account of Authority CA

Account balance

SMR Token

Address of ISPs

S: ShimmerEVM network

**Figure 9.** Account balance after adding the ShimmerEVM Network and obtaining SMR funds in the MetaMask wallet.

### 5.1.2. Simulation Setup

Algorithm 1 outlines the setup and execution process for integrating IOTA 2.0 smart contracts within an SDN environment using Mininet. The steps involve configuring the necessary tools and networks, deploying smart contracts on the ShimmerEVM Test Network, and validating the integration to enhance the security and efficiency of SDN operations (see Appendix A). This structured approach ensures a seamless interaction between the SDN components and IOTA's DLT, enabling secure and scalable network management.

Table 3 provides a summary of the key parameters and tools used in the simulation, highlighting the configuration of the network, the development environment, and specific settings for smart contract implementation.

Our system was developed using Remix IDE and Solidity and deployed on the ShimmerEVM IOTA Test Network. After funding the MetaMask wallet (version 10.26.0) with SMR and connecting to the ShimmerEVM Network, we used Mininet and Python to create a secure and scalable SDN environment integrated with IOTA 2.0.

**Algorithm 1** Simulation setup for IOTA–SDN integration.

```
Initialize MetaMask and Connect to ShimmerEVM Network
Set network parameters:
    • Network name: ShimmerEVM
    • RPC URL : https://json-rpc.evm.shimmer.network
    • Chain ID: 148
    • Currency symbol: SMR
    • Explorer URL: https://explorer.evm.shimmer.network
Fund EVM account using EVM Toolkit and transfer SMR funds to MetaMask account.
Deploy smart contracts on ShimmerEVM Network
Open Remix IDE, compile solidity smart contracts, and deploy them to ShimmerEVM
    Network.
Configure Mininet for SDN simulation
Define network topology:
    • Topology 1: 1 controller, 2 switches, 4 hosts.
    • Topology 2: 1 controller, 2 switches, 4 hosts.
Initialize network infrastructure by linking controllers, switches, and hosts.
Start SDN controllers and establish network communication.
Integrate IOTA 2.0 with Mininet network
Use Python libraries to connect to the Shimmer Network.
Deploy IOTA 2.0 smart contracts within the Mininet environment.
Configure smart contracts for seamless operation with network components.
Validate integration
Ensure secure communication among network devices using IOTA 2.0 smart contracts.
Monitor network behavior to verify correct deployment and operation of smart contracts.
Run simulation and record results
Execute various network scenarios using the configured Mininet environment.
Collect data on network performance, security, and transaction processing times.
Analyze results to evaluate the effectiveness of IOTA 2.0 in enhancing SDN security.
```

**Table 3.** Simulation details.

| Attribute | Value |
|---|---|
| Simulation time | 8.42 s |
| Number of nodes | 14 |
| Network | The ShimmerEVM IOTA Test Network |
| Mininet controller | OpenFlow |
| Mininet switch | OVSKernelSwitch |
| Integrated development environment (IDE) | Remix IDE (version 0.22.2) |
| Smart contract programming language | Solidity (version 0.8.26) |
| Interacting with our system | Python (version 3.8) |
| DoS Detector smart contract simulation **Settings**: max_same_Requests = 2; Cooldown period = 60 s | The device was stopped after 2 transactions during the cooling off period |

The setup included 14 nodes—2 controllers, 4 switches, and 8 hosts—designed for redundancy, load balancing, and efficient traffic management, as shown in Figure 10. We selected OpenFlow and OVSKernelSwitch for their reliability and compatibility with Mininet, ensuring effective network emulation. Remix IDE and Solidity were chosen for their ease of use and mature ecosystem, facilitating the development and deployment of secure smart contracts.

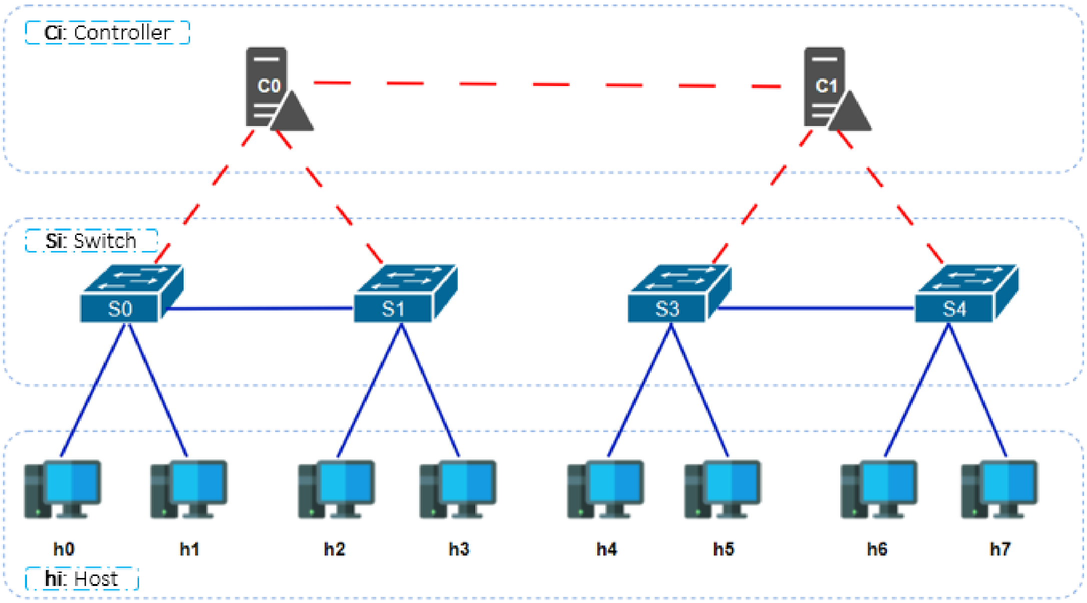


**Figure 10.** Topology of our system for securing SDN based on IOTA 2.0.

Our smart contracts controlled the SDN environment by regulating the participation of trusted ISPs, each represented by a certificate issued by our Authority (CA) smart contract. Access Control between controllers and switches was managed within their domains, while the DoS Detector smart contract monitored devices, enforcing limits on identical requests to prevent DoS attacks.

We tested multiple scenarios to validate our system. First, we verified the connection to the Shimmer Network using Web3 and checked the certificate validity through the *isCertificateValid()* function. Access Control was tested across various devices using functions like *check_access_Controller_to_switch()*, *check_access_Switch_to_switch()*, and *check_access_Controller_to_controller()*. To counter DoS attacks, we set a limit of two identical requests per minute.

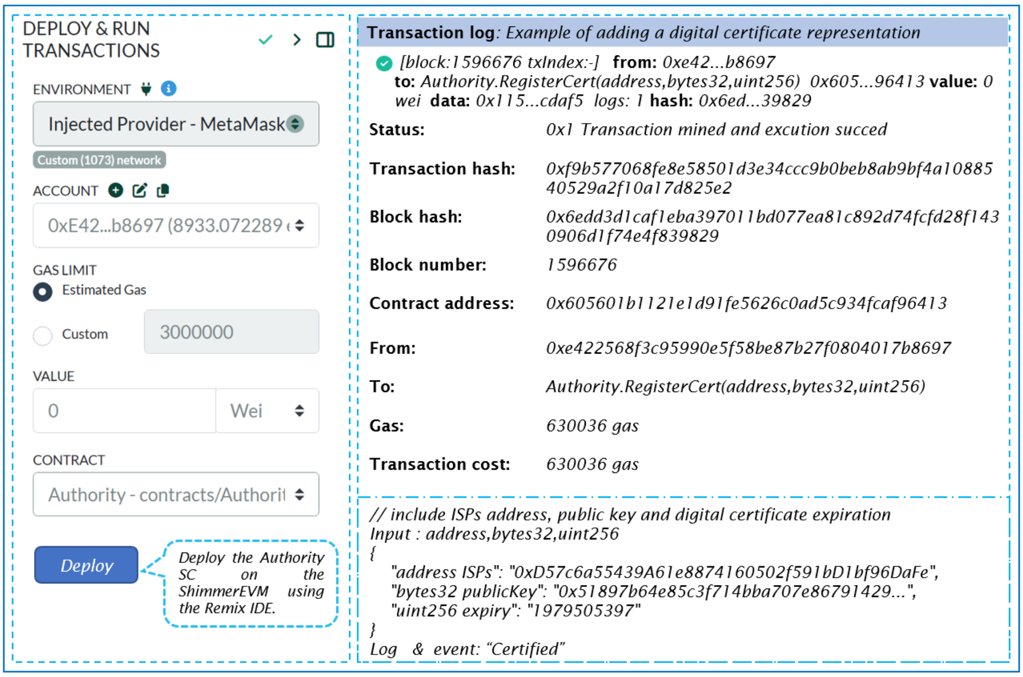
The system was validated through repeated simulations, with an average processing time of 8.42 seconds over 10 trials, ensuring its reliability.

## *5.2. Results and Discussion*

### 5.2.1. Authority Smart Contract

We use this SC to regulate which trusted entities (ISPs) can participate in our proposed system. Figure 11 details the transaction specifics for deploying an instance of 'SC-Authority'. This indicates the transaction status, as well as the contract and sender addresses. Additionally, it specifies the transaction destination, which is the smart contract constructor.

Once deployed on the ShimmerEVM Network, the Authority can invoke the SC's functions using the Authority SC address shown in Figure 11. Specifically, to add a digital certificate representation within the ShimmerEVM Network, the Authority utilizes the *RegisterCert* function. Figure 12 illustrates the ShimmerEVM Network's deployment and interaction with the Authority SC.



DEPLOY & RUN TRANSACTIONS

ENVIRONMENT: Injected Provider - MetaMask

Custom (1073) network

ACCOUNT: 0xE42...b8697 (8933.072289

GAS LIMIT: ● Estimated Gas ○ Custom 3000000

VALUE: 0 Wei

CONTRACT: Authority - contracts/Authorit

Deploy

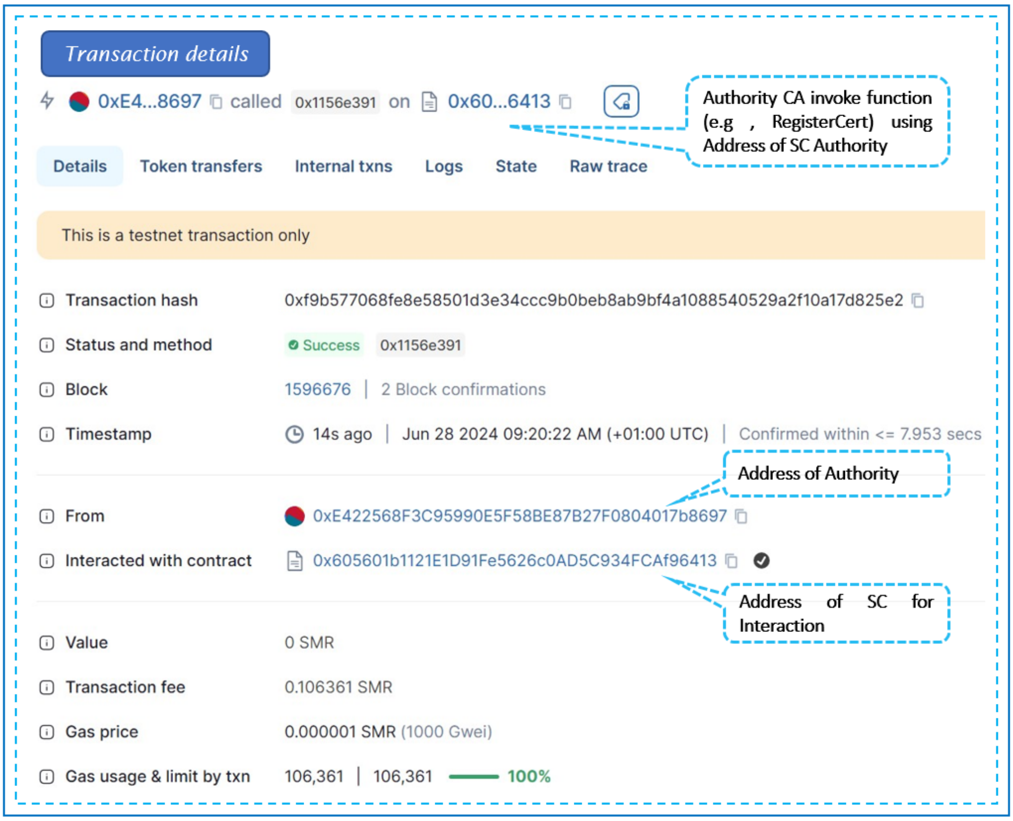
Deploy the Authority SC on the ShimmerEVM using the Remix IDE.

**Transaction log**: *Example of adding a digital certificate representation*

```
[block:1596676 txIndex:-]  from: 0xe42...b8697
to: Authority.RegisterCert(address,bytes32,uint256)  0x605...96413 value: 0
wei  data: 0x115...cdaf5  logs: 1 hash: 0x6ed...39829
Status:              0x1 Transaction mined and excution succed
Transaction hash:    0xf9b577068fe8e58501d3e34ccc9b0beb8ab9bf4a10885
                     40529a2f10a17d825e2
Block hash:          0x6edd3d1caf1eba397011bd077ea81c892d74fcfd28f143
                     0906d1f74e4f839829
Block number:        1596676
Contract address:    0x605601b1121e1d91fe5626c0ad5c934fcaf96413
From:                0xe422568f3c95990e5f58be87b27f0804017b8697
To:                  Authority.RegisterCert(address,bytes32,uint256)
Gas:                 630036 gas
Transaction cost:    630036 gas
```

```
// include ISPs address, public key and digital certificate expiration
Input : address,bytes32,uint256
{
   "address ISPs": "0xD57c6a55439A61e8874160502f591bD1bf96DaFe",
   "bytes32 publicKey": "0x51897b64e85c3f714bba707e86791429...",
   "uint256 expiry": "1979505397"
}
Log  & event: "Certified"
```

**Figure 11.** Remix IDE screen of our deployed Authority smart contract.



Transaction details

0xE4...8697 called 0x1156e391 on 0x60...6413

Authority CA invoke function (e.g , RegisterCert) using Address of SC Authority

This is a testnet transaction only

Transaction hash: 0xf9b577068fe8e58501d3e34ccc9b0beb8ab9bf4a1088540529a2f10a17d825e2

Status and method: Success 0x1156e391

Block: 1596676 | 2 Block confirmations

Timestamp: 14s ago | Jun 28 2024 09:20:22 AM (+01:00 UTC) | Confirmed within <= 7.953 secs

Address of Authority

From: 0xE422568F3C95990E5F58BE87B27F0804017b8697

Interacted with contract: 0x605601b1121E1D91Fe5626C0AD5C934FCAf96413

Address of SC for Interaction

Value: 0 SMR

Transaction fee: 0.106361 SMR

Gas price: 0.000001 SMR (1000 Gwei)

Gas usage & limit by txn: 106,361 | 106,361 100%

**Figure 12.** EVM Test Net Shimmer Network screen of interaction with our Authority SC.

Additionally, events are implemented for each addition in the IOTA network, allowing listening applications to access these events. For example, Listing 1 demonstrates the log of the "certified" event, which is triggered when the smart contract owner executes the 'RegisterCert' function.

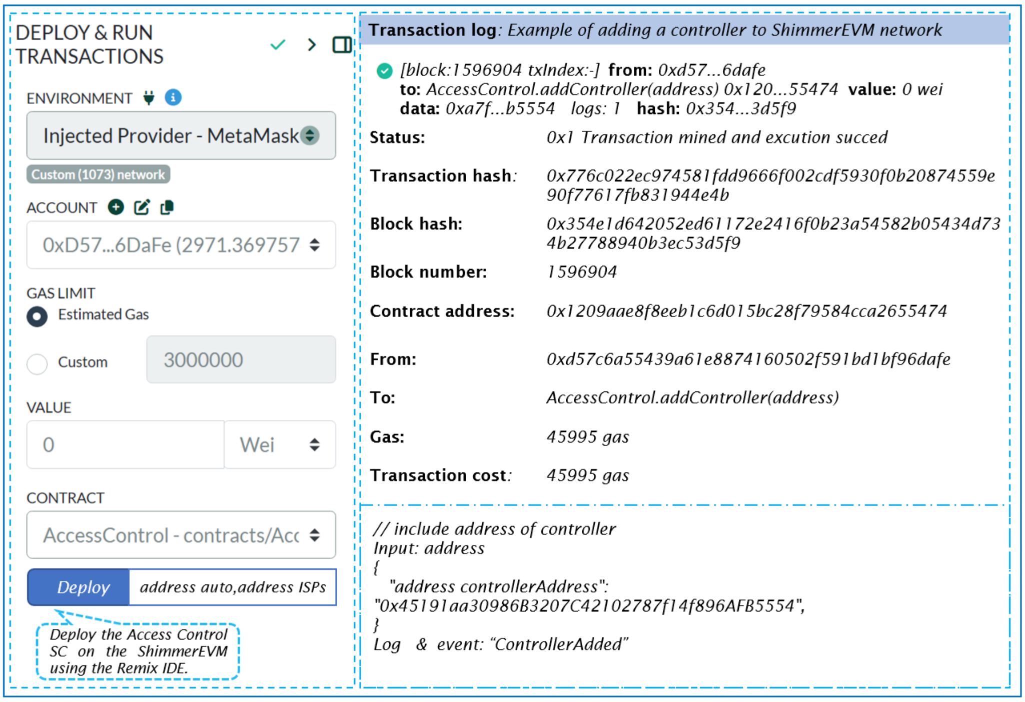
**Listing 1.** An example of the event register certificate.

```
event Certified(address from, address to, unit date);
logs[
{
"from": "0x8d9df211b95dc762ce18d8a732bd78dd92b044a0",
"event": "Certified",
"args":{
"from": "0xE422568F3C95990E5F58BE87B27F0804017b8697",
"to": "0xD57c6a55439A61e8874160502f591bD1bf96DaFe",
"date": "1717521759"
}
}]
```

The validation of the ISP certificate's authenticity is obtained through the *isCertificateValid* function. Additionally, the Authority has the ability to revoke a digital certificate using the *revoke* function. Furthermore, a digital certificate is rendered invalid upon expiration. The function *cert_revo_list* provides an array of addresses belonging to trusted entities whose certificates have been revoked.

### 5.2.2. Access Control Smart Contract

This contract manages Access Control between controllers and switches within their respective domains in an SDN setup. The AccessControl constructor designates ISPs as the owners of the SC, which is achieved by incorporating the address of the previously deployed Authority contract and the address of the trusted entity with a valid certificate. Figure 13 outlines the transaction details for instantiating 'SC-AccessControl'. It includes the transaction status, followed by the contract and sender addresses, and specifies the transaction's destination, which is the SC constructor.



ENVIRONMENT: Injected Provider - MetaMask

Custom (1073) network

ACCOUNT: 0xD57...6DaFe (2971.369757

GAS LIMIT
● Estimated Gas
○ Custom 3000000

VALUE: 0 Wei

CONTRACT: AccessControl - contracts/Acc

*Deploy the Access Control SC on the ShimmerEVM using the Remix IDE.*

**Transaction log**: *Example of adding a controller to ShimmerEVM network*

```
✓ [block:1596904 txIndex:-] from: 0xd57...6dafe
  to: AccessControl.addController(address) 0x120...55474  value: 0 wei
  data: 0xa7f...b5554  logs: 1  hash: 0x354...3d5f9
Status:              0x1 Transaction mined and excution succed
Transaction hash:    0x776c022ec974581fdd9666f002cdf5930f0b20874559e
                     90f77617fb831944e4b
Block hash:          0x354e1d642052ed61172e2416f0b23a54582b05434d73
                     4b27788940b3ec53d5f9
Block number:        1596904
Contract address:    0x1209aae8f8eeb1c6d015bc28f79584cca2655474
From:                0xd57c6a55439a61e8874160502f591bd1bf96dafe
To:                  AccessControl.addController(address)
Gas:                 45995 gas
Transaction cost:    45995 gas
```

```
// include address of controller
Input: address
{
  "address controllerAddress":
"0x45191aa30986B3207C42102787f14f896AFB5554",
}
Log  &  event: "ControllerAdded"
```

**Figure 13.** Remix IDE screen of our deployed Access Control SC.

Once deployed on ShimmerEVM, ISPs can invoke the SC's functions using the address of the AccessControl SC shown in Figure 13. Specifically, to add controllers to the ShimmerEVM Network, ISPs utilize the *addController* function.

Listing 2 displays the log of the "ControllerAdded" event that occurs after the SC owner triggers the *addController* function.

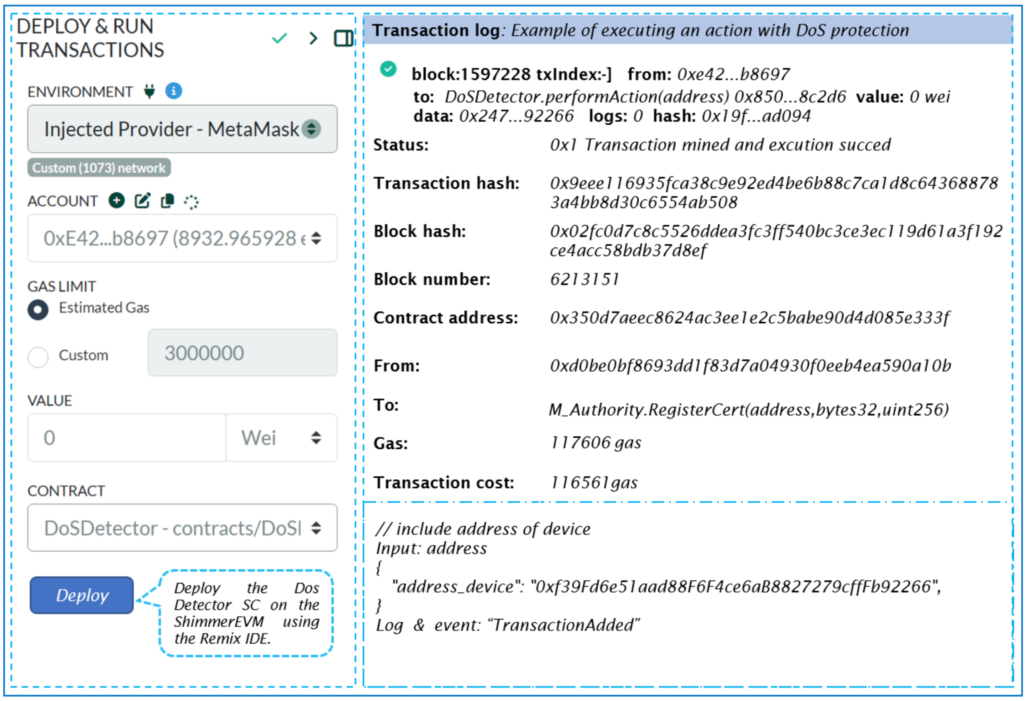
**Listing 2.** An example of the event add controller.

```
event ControllerAdded(address from, address to, uint date);
logs[
{
"from": "0xdd913e4bde911a89f96a16cbe3d410fe0e10348c",
"event": "ControllerAdded",
"args":{
"to": "0x73C964F73738931B54686bF02E6Cc774f2Db44e8",
"date": "1702817133"
}
}]
```

ISP administrators can grant or revoke Access Controls, add or remove standby controllers across domains, and manage controllers and switches within this contract. The contract features functions like *checkAccess* to verify access rights and *grantControllerAccess/revokeControllerAccess* to regulate communication among controllers. These functionalities enhance security and facilitate efficient management within the SDN environment.

### 5.2.3. DoS Detector Smart Contract

This contract monitors individual devices by tracking their request counts and timestamps, enforcing a limit on the maximum number of same requests permitted within a specified cooldown period. Figure 14 outlines the transaction specifics for deploying an instance of the DoS Detector SC. This includes the transaction status, followed by the contract and sender addresses, and details the transaction destination, which points to the SC constructor.



DEPLOY & RUN TRANSACTIONS

ENVIRONMENT: Injected Provider - MetaMask
Custom (1073) network

ACCOUNT: 0xE42...b8697 (8932.965928 e

GAS LIMIT
● Estimated Gas
○ Custom 3000000

VALUE: 0 Wei

CONTRACT: DoSDetector - contracts/DoSl

Deploy the Dos Detector SC on the ShimmerEVM using the Remix IDE.

**Transaction log**: *Example of executing an action with DoS protection*

✓ **block:1597228 txIndex:-]** **from:** *0xe42...b8697*
**to:** *DoSDetector.performAction(address) 0x850...8c2d6* **value:** *0 wei*
**data:** *0x247...92266* **logs:** *0* **hash:** *0x19f...ad094*

| | |
|---|---|
| **Status:** | *0x1 Transaction mined and excution succed* |
| **Transaction hash:** | *0x9eee116935fca38c9e92ed4be6b88c7ca1d8c64368878 3a4bb8d30c6554ab508* |
| **Block hash:** | *0x02fc0d7c8c5526ddea3fc3ff540bc3ce3ec119d61a3f192 ce4acc58bdb37d8ef* |
| **Block number:** | *6213151* |
| **Contract address:** | *0x350d7aeec8624ac3ee1e2c5babe90d4d085e333f* |
| **From:** | *0xd0be0bf8693dd1f83d7a04930f0eeb4ea590a10b* |
| **To:** | *M_Authority.RegisterCert(address,bytes32,uint256)* |
| **Gas:** | *117606 gas* |
| **Transaction cost:** | *116561gas* |

```
// include address of device
Input: address
{
  "address_device": "0xf39Fd6e51aad88F6F4ce6aB8827279cffFb92266",
}
Log & event: “TransactionAdded”
```

**Figure 14.** Remix IDE screen of our deployed DoS Detector SC.

The address of the DoS Detector SC shown in Figure 14 enables access to the contract's functions once deployed on the ShimmerEVM Network. Specifically, the *performAction* function is used to execute the actions related to DoS protection.

Listing 3 shows the changes made to requests within our system. Specifically, it defines the maximum number of permitted requests within a given time period and sets the cooldown duration in seconds.

**Listing 3.** The adjustment of requests within our system.

```
// Maximum allowed requests per time period
uint256 constant public maxRequests = 10;

//Cooldown period in seconds
uint256 constant public cooldownPeriod = 1 minutes;
```

Our SC adopts a comprehensive approach to prevent DoS attacks, which includes checks on frequency, time, Boolean values, and request volumes. Upon calling *performAction*, the contract verifies whether the user's request count breaches the predefined maximum limit within the cooldown period. If the limit is not exceeded, the action is executed, and both the request count and timestamp are duly updated.

### 5.2.4. In-Depth Analysis of Results

The simulation results indicate that the integration of IOTA 2.0 smart contracts significantly enhances the performance and security of SDN environments. A detailed examination of the latency and throughput metrics reveals a considerable reduction in transaction processing times, which is largely attributed to the unique architecture of the IOTA Tangle. Unlike traditional BC systems that process transactions sequentially, the DAG structure of IOTA allows for the concurrent validation of multiple transactions.

### 5.2.5. Potential Explanations for Observed Behaviors

The observed improvements in system performance can be explained by the distinctive features of the IOTA Tangle. The absence of miners and transaction fees reduces the computational overhead and energy consumption, leading to a more efficient network. Additionally, the decentralized nature of the IOTA Tangle minimizes the risks associated with single points of failure, further enhancing the security and reliability of the SDN environment.

### 5.2.6. Comparative Analysis with Existing Solutions

When compared to traditional BC-based solutions, such as those utilizing Ethereum or Bitcoin [7,39–44], the IOTA-based system offers distinct advantages in terms of scalability, energy efficiency, and transaction speed. Traditional BCs often face limitations due to their linear block validation process, which can lead to increased latency and higher energy consumption (see Table 4). In contrast, the IOTA Tangle's parallel processing and feeless transaction model provide a more sustainable and scalable solution for securing SDN environments.

**Table 4.** Comparative analysis of the proposed IOTA-based system with other existing solutions.

| Criteria | Our System (IOTA 2.0) | [39] | [40] | [41] | [42] | [43] | [44] |
|---|---|---|---|---|---|---|---|
| **Scalability** | High | Medium | Medium | Medium | Medium | Medium | Medium |
| **Efficiency** | High | Medium | Medium | High | Medium | High | Medium |
| **Energy efficiency** | Very high | Low | Medium | Medium | Medium | Medium | Medium |
| **Transaction time** | Fast | Medium | Medium | Medium | Medium | Medium | Medium |
| **Latency** | Low | Medium | Medium | Low | Medium | Medium | Medium |
| **Security** | High | High | High | High | High | High | High |
| **Cost (fees)** | No Fees | Medium | Medium | Medium | Medium | Medium | Medium |
| **Complexity** | Medium | High | Medium | Medium | High | High | Medium |
| **Interoperability** | High | Medium | Low | Medium | Medium | Low | Medium |

### 5.2.7. Limitations of the Proposed System

While promising, the proposed system leveraging IOTA 2.0 smart contracts for securing SDN environments presents several challenges. The complexity of the IOTA Tangle could impact the network performance and scalability, particularly in large-scale deployments, potentially increasing latency and affecting quality of service. The security of the system heavily depends on the proper implementation of smart contracts, which, if flawed, could introduce vulnerabilities. Integration with existing SDN infrastructures may require significant modifications, posing challenges in terms of resource allocation and complexity. Additionally, the system's reliance on IOTA Tangle may involve a steep learning curve for developers and administrators, with potential issues in computational and energy efficiency. Finally, the decentralized nature of IOTA raises concerns about compliance with data privacy regulations, which could complicate its adoption in regulated environments.

### 5.2.8. Ethical and Security Considerations

In deploying the proposed IOTA 2.0 smart-contract-based system in real-world SDN environments, it is essential to address the ethical and security implications associated with its use. One of the primary ethical concerns is the potential for the misuse of the system, particularly in environments where privacy and data integrity are paramount. To mitigate these risks, it is recommended that strict Access Controls and encryption protocols be implemented, ensuring that only authorized entities can interact with the network. Additionally, the system must comply with relevant data protection regulations, such as GDPR, to safeguard personal information and maintain user trust. It is crucial to regularly update and audit the smart contracts to identify and address any vulnerabilities that could be exploited by malicious actors. Furthermore, deploying this technology in a way that maintains transparency and accountability is vital for ensuring that it does not inadvertently reinforce existing power imbalances or lead to unintended consequences in the broader network infrastructure. By adopting these recommendations, the system can be deployed ethically and securely, contributing positively to the advancement of SDN technologies.

## 6. Conclusions and Future Work

This research presents an innovative approach to securing SDN environments using IOTA 2.0 smart contracts. By leveraging the IOTA Tangle, our proposed system enhances scalability and efficiency while eliminating transaction fees and reducing energy consumption. We introduced three smart contracts—Authority, Access Control, and DoS Detector—to ensure secure network operations, prevent unauthorized access, and mitigate denial-of-service attacks. Comprehensive simulations using Mininet and the ShimmerEVM IOTA Test Network demonstrated the efficacy of our approach in enhancing SDN security. Our findings highlight the potential of IOTA 2.0 smart contracts to provide a robust, decentralized solution for securing SDN environments. Our approach offers a scalable and efficient solution, addressing the limitations of traditional BC-based systems. However, to further enhance the robustness of our system, future work will focus on integrating machine learning (ML) and deep learning (DL) techniques to develop adaptive and intelligent security mechanisms. Specifically, we plan to design ML/DL models that can dynamically identify and mitigate evolving cyber threats, such as distributed denial-of-service (DDoS) attacks, by learning from network traffic patterns in real time. Additionally, we aim to explore the deployment of reinforcement learning algorithms to optimize the performance of smart contracts under varying network conditions, reducing latency and enhancing decision-making processes.

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## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| BC | Blockchain |
| CA | Certificate Authority |
| DAG | Directed Acyclic Graph |
| DL | Deep Learning |
| DLT | Distributed Ledger Technology |
| DoS | Denial of Service |
| ECDSA | Elliptic Curve Digital Signature Algorithm |
| EdDSA | Edwards-Curve Digital Signature Algorithm |
| EVM | Ethereum Virtual Machine |
| HLF | Hyperledger Fabric |
| IDE | Integrated Development Environment |
| ISP | Internet Service Provider |
| IoT | Internet of Things |
| IOTA | Internet of Things Application |
| ISCP | IOTA Smart Contracts Protocol |
| ML | Machine Learning |
| PoW | Proof of Work |
| SCs | Smart Contracts |
| SDN | Software-Defined Networking |
| TPS | Transaction per Second |

## Appendix A

- We presented the complete implementation of our proposed system, IOTA 2.0-based SDN Smart Contracts, at https://github.com/MedFartitchou/SDN_IOTA (accessed on 20 June 2024).
- We tested IOTA 2.0-based SDN Smart Contracts at https://rb.gy/g0esua (accessed on 20 June 2024).

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