PUFchain 4.0: Integrating PUF-based TPM in Distributed Ledger for Security-by-Design of IoT

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ABSTRACT

This work presents a sustainable cybersecurity solution using Physical Unclonable Functions (PUF), Trusted Platform Module (TPM), and Tangle Distributed Ledger Technology (DLT) for sustainable device and data security. Security-by-Design (SbD) or Hardware-Assisted Security (HAS) solutions have gained much prominence due to the requirement of tamper-proof storage for hardware-assisted cryptography solutions. Designing complex security mechanisms can impact their efficiency as IoT applications are more decentralized. In the proposed architecture, we presented a novel TPM-enabled PUF-based security mechanism with effective integration of PUF with TPM. The proposed mechanism is based on the process of sealing the PUF key in the TPM, which cannot be accessed outside the TPM and can only be unsealed by the TPM itself. A specified NV-index is assigned to each IoT node for sealing the PUF key to TPM using the Media Access Control (MAC) address. Access to the TPM's Non-Volatile Random Access Memory (NVRAM) is defined by the TPM's Enhanced Authorization policies as specified by the Trust Computing Group (TCG). The proposed architecture uses Tangle for sustainable data security and storage in decentralized IoT systems through a Masked Authentication Messaging (MAM) scheme for efficient and secure access control to Tangle. We validated the proposed approach through experimental analysis and implementation, which substantiates the potential of the presented PUFchain 4.0 for decentralized IoT-driven security solutions.

CCS CONCEPTS

• **Security and privacy → Tamper-proof and tamper-resistant designs**; **Hardware-based security protocols**; **Distributed systems security**.

GLSVLSI '23, June 5–7, 2023, Knoxville, TN, USA

ACM ISBN 979-8-4007-0125-2/23/06…$15.00
https://doi.org/10.1145/3583781.3590206

KEYWORDS

Security-by-Design (SbD), Hardware-Assisted Security (HAS), Device Security, Data Security, Trusted Platform Module (TPM), Physical Unclonable Function (PUF), Distributed Ledger

ACM Reference Format:
Venkata K. V. V. Bathalapalli, Saraju P. Mohanty, Elias Kougianos, Vasanth Iyer, and Bibhudutta Rout. 2023. PUFchain 4.0: Integrating PUF-based TPM in Distributed Ledger for Security-by-Design of IoT. In *Proceedings of the Great Lakes Symposium on VLSI 2023 (GLSVLSI '23), June 5–7, 2023, Knoxville, TN, USA.* ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/3583781.3590206

1 INTRODUCTION

The IoT is revolutionizing the technological solutions in the areas of Healthcare, Agriculture, and Transportation. Realizing the potential of intelligent electronic devices through edge cloud computing platforms for analysis and processing IoT sensor data has gained much traction and is becoming more viable [17]. However, the trustworthiness of IoT devices and Edge Cloud systems pose a question on the integrity of IoT devices and their data. The Security-by-Design (SbD) paradigm for IoT works by ensuring the root of trust right from the design stage of the device rather than developing security solutions for integrity of IoT devices in the application phase. The deployment of IoT in Smart Healthcare, and Smart Agriculture applications with built-in security modules based on the Security-by-Design approach at the design level can ensure integrity of the intelligent device involved in data analysis [15].

A Trusted Platform Module (TPM) is a hardware security primitive introduced by the Trust Computing Group (TCG), which provides the root of trust for the computing platform as a simple System-On-Chip (Soc) [14, 19]. TPM Non-Volatile memory (NVRAM) can seal and unseal the secret keys generated inside or outside TPM. A specified NV-index is defined for secure storage and retrieval of private keys. Access to TPM NVRAM can be user-defined and password-protected, following TCG's procedures [18]. Computing systems incorporated with a TPM can create key-based platform measurements during the boot process [11, 17].

A PUF-based solution for IoT security provides the hardware-level root of trust by creating a key pattern of random zeros and ones obtained from delays and frequency variation of logic elements inside a chip originated by nanoelectronic manufacturing variations [6]. In this work, we introduce an SbD approach based on TPM-integrated PUF. This approach works by securely sealing

the PUF key from an IC inside the TPM to avoid exposure of the underlying PUF key, which can be susceptible to various sniffing and snooping attacks. A hacker can gain access to PUF key and control critical applications based on PUF integrated security solution. SbD approach in this work also validates a DLT-based data security system with effective access control using TPM-based PUF paradigm. This architecture can work for the power and time constraints of IoT devices in decentralized and distributed systems.

The rest of the paper is organized in the following manner. Section 2 presents the novel contributions of this paper. Section 3 presents the security schemes and various DLT-based security solutions in smart contracts. The working flow of device authentication and transaction validation mechanism of the proposed PUFchain 4.0 are explained in Section 4. Section 5 outlines the implementation details and Section 6 presents the conclusion and directions for future research.

2 NOVEL CONTRIBUTIONS OF THE WORK

2.1 Problem Statement

The integrity and authenticity of devices connected to the Edge Computing platform are essential for smart healthcare applications. The patient's health parameter analysis at an Edge or Cloud platform is based on the physiological data obtained from these devices [9]. The vulnerability of IoT devices to spoofing, brute force attacks on asymmetric and symmetric keys generated by various cryptographic algorithms, and the infeasibility of IoT to sustain the computational power capability of complex crypto-algorithms opened the doors for PUF-based approaches for IoT security [5]. However, PUF keys require reliable storage to store the keys securely. TPM is a hardware-secure crypto-processor and can provide robust storage to the PUF key by sealing it inside TPM NVRAM, which cannot be accessed by the adversary and can only be unsealed by the TPM itself.

2.2 Proposed Solution

From a data perspective, Tangle, a Distributed Ledger Technology (DLT) is providing immutability to data and assisting in Hardware-Assisted security by providing decentralized storage to hardware-secure cryptographic keys. Being a miner-less DLT, it solves the problems of scalability, latency, and power consumption issues in Blockchain technology-based approaches like Smart Contract, which have proven to be computationally infeasible for resource-constrained devices [1]. A hardware TPM can support cryptographic applications, system integrity, and random number generations as these applications are supported through TPM, which works by creating an Endorsement key (EK) and a Storage Root Key (SrK) whose private portion can never be accessed outside the TPM and are proven to be much more reliable [10, 13]. Sealing the PUF key inside the TPM can restrict unauthorized access to the PUF key and can never be accessed outside TPM. The TPM can only unseal the locked PUF key. This approach provides a new security paradigm for PUF-Based TPM-supported security solutions.

2.3 Novelty of Solution

Novel Contributions of this paper are the following:

- A sustainable Hardware-Assisted security approach using TPM and PUF for ensuring the root of trust for Security-by-Design of IoT.
- A security mechanism that utilizes Masked Authentication Messaging (MAM) for secure storage, retrieval, and authentication of IoT device properties and sensor data in Tangle.
- A robust approach for device integrity validation through the secure interface between TPM and PUF hardware security primitives.
- An approach that facilitates hardware level secure storage for PUF key by accessing TPM Non-Volatile memory.
- A robust and lightweight security mechanism that can facilitate Hardware signature-based access control to DLT through a PUF-based TPM approach.
- A sustainable approach for PUF key verification and PUF-enabled TPM-based access control mechanism for miner-free and fee-less DLT for data security in IoT.

The architectural overview of PUFchain 4.0 is illustrated in Fig.1.

3 RELATED PRIOR RESEARCH

To address the device integrity issues in IoMT, a novel TPM-based remote attestation scheme is proposed in [14] where the root of trust is extended from a Trusted system with embedded hardware TPM to all devices without TPM by developing a shadow TPM module in the kernel form at these devices. A software-based device attestation scheme is proposed in [8] to verify the authenticity of IoT, which offers to address proxy attacks and reduce the time required to perform remote attestation. Integrating Blockchain technology with PUF was proposed and implemented in [16] for sustainable IoT devices and data security. This approach works by storing the PUF key of IoT in an immutable Blockchain using PUF and hashing modules. A distributed TPM-based attestation framework was proposed using Blockchain's Hyperledger fabric [12] to decentralize the attestation mechanism. In comparison, the proposed PUFchain 4.0 is developed using Hardware TPM and PUF and facilitates secure storage for the PUF key in TPM. TPM-based remote attestation framework for verifying the integrity of processes running in the device is proposed in [19]. This work is based on a software TPM and uses the Hashed Message Authentication (HMAC) protocol. A robust fog node authentication scheme using TPM [4] uses a TPM based certification scheme to validate the platform integrity of fog nodes in AVISPA under the Dolev-Yao intruder model. This approach is claimed to be resistant to impersonation and replay attacks. However, this method works by evaluating the integrity of the software state's fog node and automating the certification mechanism. In comparison, the architecture proposed in this paper works by assessing the integrity of an IoT node from the hardware level using PUF based security mechanism. A comparison of proposed PUFchain 4.0 with prior research is illustrated in Table 1.

4 ARCHITECTURE OF THE PROPOSED PUF-BASED TPM INTEGRATED NOVEL DLT

4.1 Proposed Architecture of PUF based TPM

Each TPM has an EK which is generated, stored, and protected inside the TPM chip and can never be accessed outside the TPM. Cryptographic keys can be created by TPM, which, once encrypted

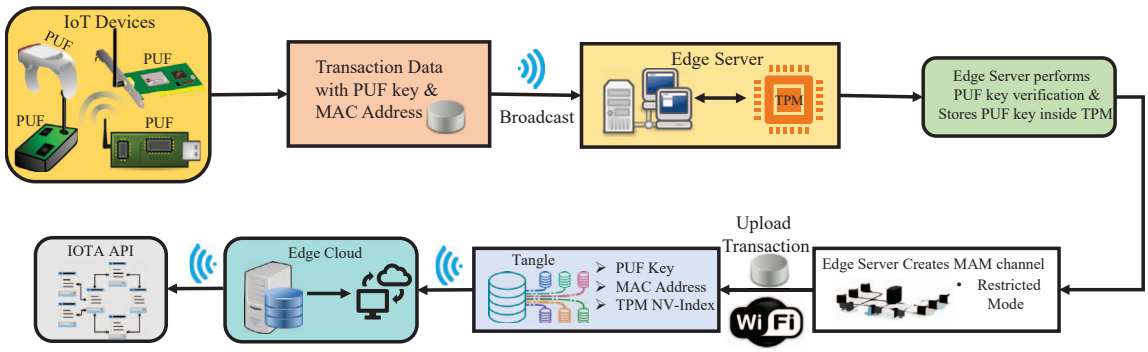
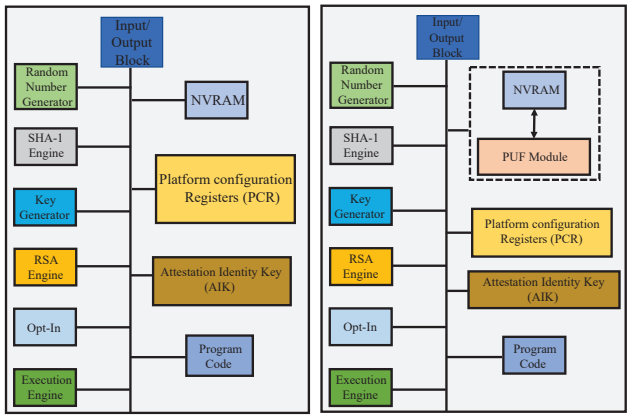


Figure 1: Architectural Overview of Proposed Security-by-Design approach (PUFchain 4.0) for Emerging Internet-of-Everything.

Table 1: Comaparative perspectives of Proposed PUFchain 4.0 with related research

Work	Application	Hardware Security Primitive	Mechanism	TPM	Data Security Primitive
PUFchain[16]	IoT (Device & Data)	Physical Unclonable Functions (PUF)	Proof-of-PUF-Enabled Authentication	N/A	Blockchain (SQLite)
xTSeH [14]	Smart e-Health Device Security	Trusted Platform Module (TPM)	TPM based Remote Attestation	Hardware TPM	N/A
A Software-based TPM remote attestation [8]	IoT device security	N/A	Software based remote attestation	software TPM	N/A
Blockchain-based IoT attestation [12]	IoT	TPM	Blockchain based remote attestation	Hardware TPM	Blockchain (Hyperledger Fabric)
This paper PUFchain 4.0	**IoT Device and Data (SbD)**	**TPM & PUF**	**PUF based TPM**	**Hardware TPM**	**Tangle**



(a) Typical Architecture [2] (b) Proposed Novel PUF based TPM

Figure 2: Comparison of TPM Architectures.

by a TPM, can only be decrypted by the TPM itself, a process called Binding [3]. The system configuration parameters during the boot process are stored in the TPM's Platform Configuration registers (PCR). During the boot process, the firmware can check these parameters using the values stored in PCR to validate the system's integrity. The SrK and EK are non-migratable keys TPM protects. The SrK can be regarded as a unique address of each owner of TPM. A new attestation key is created every time the owner of TPM changes [7].

The TPM NVRAM can be made a permanent place for storing the PUF key. Once the PUF key is stored inside NVRAM, it can be read through NV-Index to perform PUF key verification. Integrating the PUF module with TPM can bring two security primitives together by facilitating TPM-based storage for a PUF design-generated key, as shown in Fig. 2.

4.2 The Proposed PUFchain 4.0

The security framework is proposed to be implemented on an IoT network with decentralized heterogeneous intelligent electronic devices. In this architecture, the PUF module is responsible for generating the device's unique signature based on the PUF module embedded with it. Another device cannot use the PUF key of one IoT as its secure digital signature. The TPM in the proposed architecture is embedded with an Edge Server and is responsible for securely storing the PUF-based digital signature of the cluster of IoT devices connected to an Edge server. If a group of IoT nodes is connected to an ES, then each IoT gets a specified NV-index based on its MAC address using the command "`tpm2_nvdefine`". To unseal or read the sealed PUF key, a user can specify advanced security features to access specified NV-index using user passwords. The effectiveness of the proposed transaction validation process in PUFchain 4.0 compared with the Block validation process in Blockchain is shown in Fig.3. After performing PUF key verification, the ES seals it inside TPM using "`tpm2_nvwrite`" command. Tangle DLT is used in this work to harness the advantages of integrating a DLT that does not require a centralized authority or miner to validate and add a transaction as in Blockchain. While fetching the transaction, a new

root address is obtained to upload the next upcoming transaction onto the channel. This root address will only be sent to the verified IoT node. This reduces the chance for an adversary to gain access to the MAM channel since the access is defined based on the PUF-based identity.

4.3 Working of the Proposed PUFchain 4.0

The proposed method utilizes a Masked authentication messaging (MAM) protocol and traditional network communication schemes for sustainable PUF key verification and TPM-based NVRAM storage for PUF keys. The enrollment and Authentication phases of the proposed consensus methods are illustrated in Algorithms 1, and 2.

Algorithm 1: Device Enrollment Algorithm.

Input: Generating challenge response pairs (CRP) from PUF module of IoMT
Output: Broadcasting transaction to Edge Server (ES)

Edge device generates Challenge Response pairs (*CRP*) from the PUF module
Evaluate PUF keys and create device unique identity P_{ID}
// Calculate Uniqueness, Reliability, Inter-HD & Intra-HD
if *If obtained PUF key Rx is standard* **then**
    $P_{ID} \rightarrow Rx$
    // PUF Key is assigned as pseudo identity of the Client
Edge node creates a transaction (T_{Rx}) and forms a Block of Data
// Block consists of C_{Rx}, Media Access Control Address (MAC) and Block metrics
// [P_{ID}, MAC, Data]$\rightarrow T_{Rx}$
Edge node broadcasts transaction to Miner
// Edge Node$\rightarrow T_{Rx} \rightarrow$ Miner
ES receives the broadcasted transaction from Edge Node
// Edge Node$\rightarrow T_{Rx} \rightarrow$ES
ES stores the transaction T_{Rx} in secure database
// ES$\rightarrow T_{Rx} \rightarrow P_{ID} \rightarrow$ Database

Initially, IoT devices with embedded PUF modules initiate a transaction consisting of a PUF key and MAC Address. The figure of merits of PUF keys are evaluated, and one of the PUF keys *Rx* is selected as P_{ID}: Pseudo identity of the IoT device. The P_{ID} and the IoT's MAC address (MAC) and timestamp are sent as a Block transaction to the Edge Server. The Edge Server receives the transaction T_{Rx} from the IoT node and extracts P_{ID}, and MAC address from T_{Rx} and then stores them securely.

During verification, the Edge server receives an authentication request and transaction data $T_{Rx'}$. The new PUF key of IoT is extracted from $T_{Rx'}$ and compared with the enrolled PUF key P_{ID}. If PUF keys are matched, the MAC address (MAC) is retrieved and assigned a specified NV-Index by Edge Server by accessing TPM. A new NV-Index is assigned to seal the PUF key of IoT based on the MAC address. Once an NV-Index from TPM is assigned to a MAC, it cannot be given to any other device. The PUF key $P_{ID'}$ is then sealed inside TPMs NVRAM using NV-Index. The NV-index can be made as a *'Persistent handle'* in TPM. To unseal or read the PUF key from TPM, the NV-Index corresponding to MAC Address is retrieved and can be used to read the sealed PUF key inside hardware TPM. The edge server will become IOTA's client node and upload the T_Rx' onto Tangle. Working flow of device enrollment and authentication phases of PUFchain 4.0 are illustrated in Fig. 4.

Once P_{ID} is stored inside TPM, the Edge server creates a restricted MAM channel and uploads the verified transaction onto Tangle along with NV-Index. The transaction is then uploaded onto Tangle.

Algorithm 2: Device Authentication Algorithm.

Input: Block of Data $T_{Rx'}$ from Edge Node
Output: Sealing PUF key inside TPM with a specified NV Index and uploads data to Tangle

ES receives transaction data from Edge during verification.
// $T_{Rx'} \rightarrow$ES
Edge server receives the PUF key ($P_{ID'}$) from $T_{Rx'}$
ES extracts newly extracted PUF key of Edge from received Block of data ($T_{Rx'}$)
ES compares enrolled PUF key and obtained PUF key
if *If* $P_{ID} = P_{ID'}$ **then**
    // PUF key is verified successfully
Edge server access Hardware TPM Module
// Edge Server (ES)$\rightarrow$ TPM
ES access TPM'S NVRAM to seal the PUF key $P_{ID'}$
// ES$\rightarrow$TPM$\rightarrow$NV-Index
A specified NV- Index is obtained T_{ID} for specified MAC Address M_{ID}
// TPM$\rightarrow$NVRAM$\rightarrow M_{ID} \rightarrow T_{ID}$
ES writes PUF key to NV-index T_{ID}
// ES$\rightarrow$ $P_{ID'} \rightarrow T_{ID}$
ES creates a MAM channel
// ES$\rightarrow$MAM$\rightarrow$Restricted
ES becomes a new Tangle node, validates and uploads transaction data onto network
// ES$\rightarrow$ $TRx' \rightarrow$Tangle

5 EXPERIMENTAL VALIDATION

A hardware TPM module has been connected to the Edge server to validate the proposed security scheme. Edge nodes with embedded PUF (Arbiter PUF) Broadcast a Block of data with MAC Address and 64-bit PUF key to ES through Universal Data Communication protocol. PUF keys are obtained at a baud rate of 9600, and the TPM module is based on an Infenion SLB9670 chip. The TPM's NV RAM is accessed by specifying an NV Index(0X1500020) for Edge Node 1 to seal the PUF key. The MAC Address "dc:a6:32:c0:77:88" of Edge node 1 (Raspberry pi 4) is locked to the NV Index "0x1500020" by the Edge Server. Arbiter PUF module is used in this experiment with reliability of 99%. The PUF module is implemented on an FPGA. The total On-Chip power for this design is 82 mW.

Table 2: Characterization of the Proposed PUFchain 4.0.

Parameters	Results
Application	IoT
Hardware Security Module	TPM, PUF
Hardware Security Mechanism	PUF-based Hardware TPM
TPM Board Specification	Infineon Optiga™ SLB 9670 TPM 2.0
TPM Storage	NVRAM
Free NV memory	6962 Bytes
Data Security System	Tangle
Communication Protocol	Masked Authentication Messaging
TPM module	Geek Pi TPM 2.0
PUF Module	Arbiter PUF
PUF Key	64 Bit

Edge Node 2 with MAC address of "dc:a6:32:c8:d7:50" undergoes the enrollment and authentication processes. Once the verification is done, an NV-Index of "0x1500021" with 128 Bytes of NV storage is assigned. The PUF key is stored inside the nv.dat file and sealed

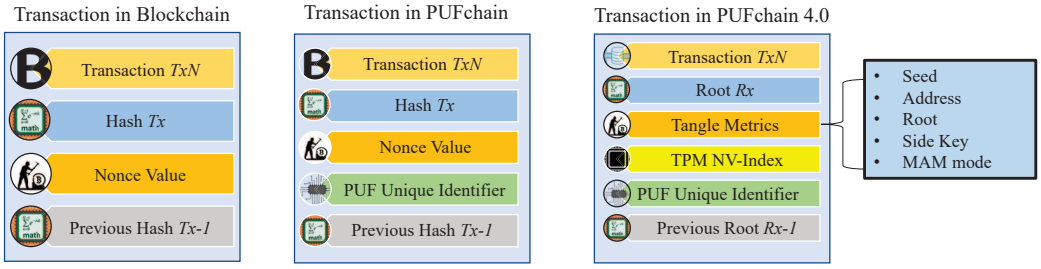
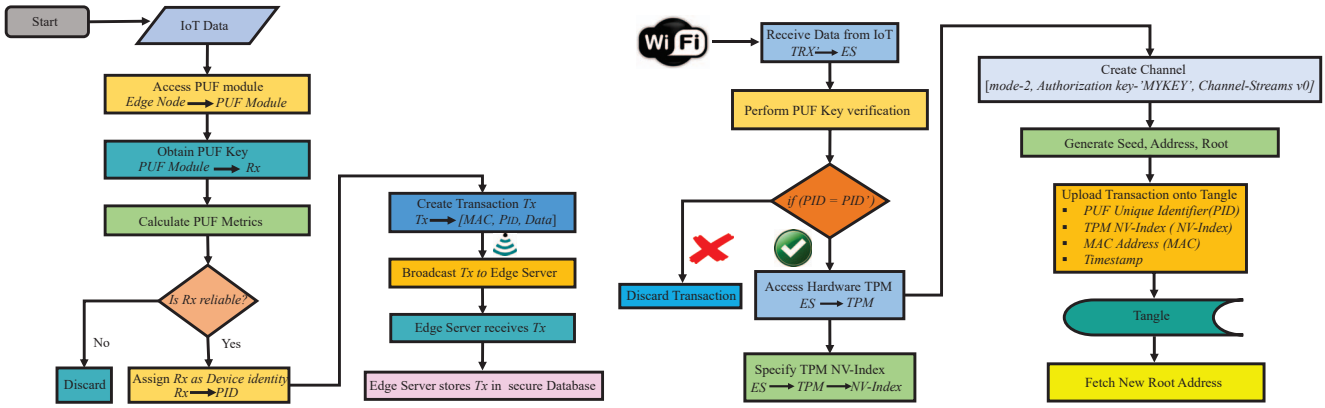


Figure 3: Transaction in Blockchain, PUFchain, and PUFchain 4.0



(a) Enrollment process (b) Authentication Process

Figure 4: Working flow of Enrollment and Authentication process.

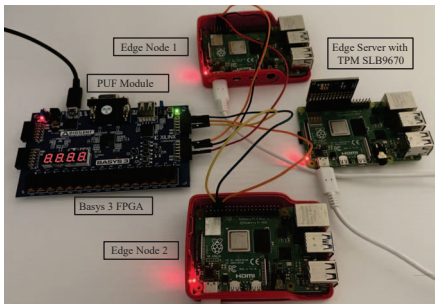


Figure 5: Working Prototype.

to the corresponding NV-Index. Both transactions from Edge nodes 1 and 2 are validated, and a MAM channel with *"Restricted mode"* is created in IOTA Devnet. Two Edge Nodes are connected to the PUF module on the FPGA with the part number "xc7a35tcpg236-1" and an ES embedded with Hardware TPM module (Fig.5). The channel is Streams v0, and the user-defined secret key is "MYKEY". Fig. 6, and Tables 2, and 3 show the obtained outputs from our implementation. To upload and fetch a Tangle transaction from the MAM channel, the overall command execution time is 17,380 ms, including the overall time to perform device PUF key verification and generate seed, address, root, and channel creation. CPU execution time in user mode for the corresponding transaction is 6,700 ms.

6 CONCLUSION AND FUTURE RESEARCH

We proposed and validated a simple, lightweight, energy and time-efficient approach for IoT device authentication using PUF, TPM, and Tangle in this work. Sealing the PUF key to TPM hardware ensures hardware level root of trust. The proposed architecture exhibited an approach for DLT based access control mechanism through PUF-enabled TPM where the TPM's Endorsement and Attestation key can be used to access and control the MAM communication channel to upload data onto Tangle. Simultaneously, the proposed approach used PUF based device authentication scheme for IoT, which generates a digital signature for each IoT based on process variations inside an IC. By integrating the PUF with TPM in this work, we validated the potential of PUF-based TPM security solutions for IoT. In future work, we will explore leveraging the potential of other DLTs for HAS. Our focus will be on generating intelligent TPM-enabled PUF-based approaches for device authentication in IoT through DLT. Our future work will aim to provide sustainable device and data security in IoT to leverage the true potential of IoT-based applications.

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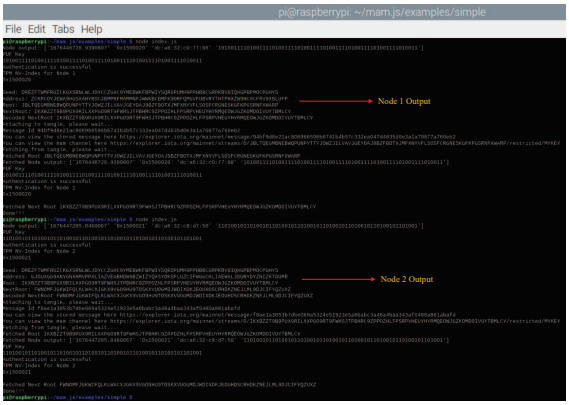
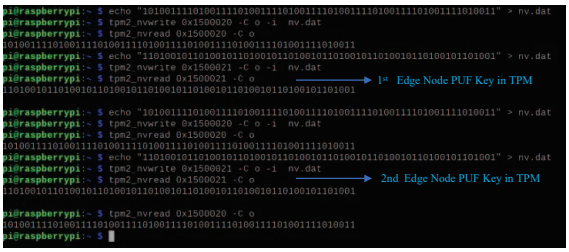
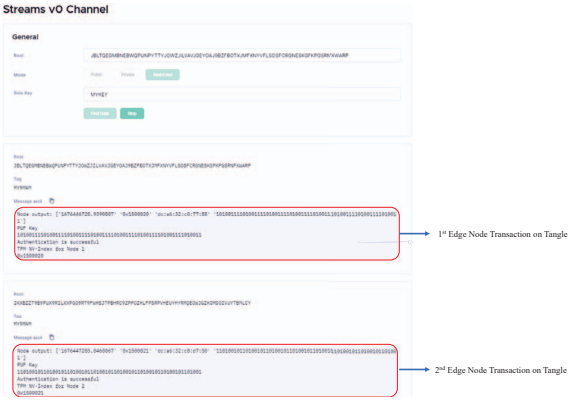


(a) PUF Key Verification at Edge Server



(b) Sealing and unsealing PUF Key inside TPM by accessing NVRAM



(c) Authentication and Transaction verification outputs on IOTA Explorer

Figure 6: Experimental Validation of PUFchain 4.0

Table 3: Performance Analysis of PUFchain 4.0.

Parameters	Results
NV Storage capacity (Read/Write)	768 Bytes
Time to generate PUF key	87 ms
Power Consumption of pi with TPM	2.7-3.3 Watt
Time to perform device authentication	2000 ms
PUF Metrics	Reliability- 99%
Time to write PUF key to TPM	real-299 ms, user-12 ms, and sys-19 ms
Time to read PUF key from TPM	real-411 ms, user-22 ms, and sys-10 ms

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