AudiWFlow: Confidential, Collusion-resistant Auditing of Distributed Workflows

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***Abstract*—We discuss the problem of accountability when multiple parties cooperate towards an end result such as multiple companies in a supply chain or departments of a government service under different authorities. In cases where a full trusted central point does not exist, it is difficult to obtain a trusted audit trail of a workflow when each individual participant is unaccountable to all others. We propose AudiWFlow, an auditing architecture which makes participants accountable for its contributions in a distributed workflow. Our scheme provides confidentiality in most cases, collusion detection and availability of evidence after the workflow terminates. AudiWFlow is based on verifiable secret sharing and real-time peer-to-peer verification of records; it further supports multiple levels of assurance to meet a desired trade-off between the availability of evidence and the overhead resulting from the auditing approach.**

We propose and evaluate two implementation approaches for AudiWFlow. The first one is fully distributed except for a central auxiliary point that, nevertheless, needs only a low level of trust. The second one is based on smart-contracts running on a public blockchain which is able to remove the need of any central point but requires the integration with a blockchain.

***Index Terms*—auditing, distributed workflows, confidentiality, blockchains, smart-contracts**

I. Introduction

Distributed workflows with multiple organisations involved, cooperating towards a certain outcome (such as a supply chain), is now a common way of work leveraging the potential of the Internet. This is common in many domains including governments, digital health, education, engineering, supply chains, goods distribution, etc. Collaboration is enabled by interoperable applications through which each organisation contributes to a workflow. A key enabler is trust: organisations need to trust each other in that each will deliver their part as contracted. When a problem occurs, the workflow needs to be audited in order to determine what failed.

We start with a simple example. A shopper orders a book online. After payment using an independent payment processor, the book is collected from the warehouse and sent for post dispatch. An independent courier picks up the book and transports to the destination hub. The book is then delivered by a person to the door of the shopper. The shopper signs a form and the workflow is completed. One can see that all the participating parties are, for the most part, unknown to each other. If a problem occurs, the shopper needs to be refunded and an audit to the particular workflow is started. Such an audit is typically time-consuming and lengthy and, most of the times, the costs does not justify the effort. A full refund, "no questions asked", is then issued to the shopper. A key obstacle is that, if an audit does happen, a dishonest party is able to easily hide or create evidence so to waive its liability. The likelihood is that one runs into an inconclusive "finger-pointing" problem which only a human judge can resolve using the law and principles such as the "balance of probabilities". The problem AudiWFlow tackles is how to generate evidence, as the workflow happens, that is able to guarantee that all the evidence is stored with integrity, is unforgeable, is available and cannot be repudiated.

With massive digitisation, nearly every domain has similar needs – supply chains [1], inter-department business processes [2], e-government services [3], [4], etc. To note that the problem becomes trivial if a central party is able to coordinate and gather evidence; however, trusting a central party is a difficult problem in itself especially in a distributed workflow, where parties may not even know each other beyond their adjacency. Furthermore, simple log recording is not enough as any valid evidence cannot be open to manipulation [5]. A further problem is, collusion both with a central entity managing the workflow or between two adjacent parties in the workflow topology to tamper with digital evidence. Even if the orchestration of the workflow is managed in the cloud, a privileged insider can tamper with the logging process. Finally, the confidentiality requirements should be noted [6]. In a pure distributed workflow, organisations may want to only deliver the expected outcome and not disclose any other information.

A. Scenario

To illustrate the challenge, we present and informally analyse a simple working scenario of health insurance – see Figure 1.

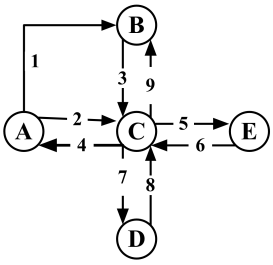


Figure 1: The example scenario of health insurance

Alice (A) wants health insurance from insurer Bob (B). Alice has to provide her medical history to Bob and allow Bob to contact her doctor, Dr. Cathy (C). Insurer Bob also needs Alice's family medical history but this has to go through Dr. Cathy who, following a confidentiality friendly approach, will provide an overall report after she contacts the family doctors Dr. Dippy (D) and Dr. Eva (E).

To save on insurance costs, Alice asks her doctor, Dr. Cathy, to provide an untruthful medical record. Bob thus obtains Alice's medical history from Dr. Cathy (which includes reports from Dr. Dippy and Dr. Eva). Happy with the outcomes, insurer Bob offered a deal with which Alice was happy.

After two years, Alice claimed a compensation after a medical incident. Referring to Alice's insurance claims, Bob investigated all documents of Alice and found that Alice's medical records provided by Dr. Cathy contradicts records in the hospital. Insurer Bob rejects Alice's claim. Alice counter-argued that the insurance company was responsible for collecting her medical history and is thus entitled to a compensation. Insurer Bob then tries to obtain the contacts of Dr. Dippy and Dr. Eva which Dr. Cathy refuses to give on behalf of confidentiality.

As we see, there are a number of parties (A, B, C, D, E), which are independent and, a prior, individually unaccountable to any other party. All have to collaborate towards the end result, which is health insurance for Alice. A further component is that some parties are not known to other parties: B does not know who are D and E and, in fact, only knows that there are other parties beyond C. Overall, we have a workflow topology (as in Figure 1) where vertices are the collaborating parties and the directed edges the sequence of actions and deliverables. The *audit trail* consists of all the interactions represented by the edges of the graph.

In the absence of perfectly shared information, there is no way for any party to verify the accuracy of the information provided. For example, insurer Bob is in a position where he cannot prove Alice is at fault. This is because Alice can claim that insurer Bob colluded with doctors from the hospital and modified her original documents to close a sale. Insurer Bob also cannot find any traces of a collusion attack between Dr. Cathy and Alice. Finally, Dr. Cathy denies ever signing the records that insurer Bob holds and raises the suspicion that her signature was forged.

This scenario illustrates the challenges of obtaining strong evidence in case of a distributed multi-party workflow. The key requirements are the following. First, all participants must be accountable for their actions either by denying a past action or manipulating an audit record. Second, no participant should be able to destroy evidence as this can be a way to waive liability. Third, one should be able to detect if dishonest parties collude even if it is not impossible to prevent false records between themselves. Fourth, and final, there are important use-cases where confidentiality is required. This comes in two forms: (1) confidentiality of information exchanged and (2) identity of the participants themselves beyond a certain point in the workflow graph. We discuss these requirements in more detail when formalising our problem in section IV.

B. Organisation of This Paper

Section II reviews the literature on existing schemes of audit trails built. Section III formally defines the problem, presents a threat model and introduces notation and terminology. Section IV presents two architectural approaches to achieve the problem. The first is based on a peer-to-peer distributed architecture but relies on an accessory central node. The second removes the central node by replacing it with a public blockchain; we used Ethereum, a public blockchain and one that now has proven the ability to deliver complex requirements while maintaining the security and integrity expected from blockchains. In Section V, we describe how we implemented both approaches and discuss experimental results. In Section VI we conclude our paper and discuss future work.

II. Related Work

Despite its crucial importance, workflow auditing is a topic which has not been abundantly discussed in literature. We split this section in two subsections: conventional systems auditing and using properties of blockchain to secure evidence and records.

A. Secure Auditing and Logging System

Literature about conventional auditing systems commonly review cloud and database storage of logs in order to store proof of evidence. This raises the problem of protecting audit records at storage for which encryption is a commonly used technique followed in the literature [7]–[9]. However, encryption requires the management of keys which raises problems of confidentiality or destruction of evidence. In simple terms, whoever owns the keys can modify or breach the confidentiality of evidence. To mitigate these problems, some approaches using secret sharing have been proposed [7], [10]; other approaches rely on integrating secret sharing with multi-parties workflows, such as adopting in software-defined network controller [5]. The problem of trusted auditing is also pervasive and is a requirement across many different fields, such as in the e-government services [8].

Zawoad, Dutta, and Hasan built a secure logging service model, named "SecLaaS", to achieve confidentiality and integrity of logs in cloud storage [6]. Although this approach minimizes the risk of unauthorized modifications of the logs, the cloud service provider is entrusted with the generation of the audit trail without any means to verify the accuracy of the audit records. Flores [11] presents a salting-based authentication module to target credential protection in user registration and authentication. A database intrusion detection module is also mentioned to report and record insider login attempts to the database within the network. Although it concerns malicious behaviours in the back-end and application levels, the irreversibility of records for login attempts in the database is not discussed.

Rajalakshmi, Rathinraj, and Braveen [8] propose a mechanism addressing the requirements of secure logging and auditing between untrusted parties that uses homomorphic encryption. It aims to prevent exposure of private information and save logs in the tamper-proof cloud so that the logs can be used as audit forensics. Ma and Tsudik [9] use hash chains to verify the logging entity. They aim to detect attempts to modify logs generated before a compromise of the logging entity and rely on trusted storage for their approach. However, approaches of [8], [9] do not consider collusion-related attacks between involved participants.

B. Distributed Ledgers in Auditing

Distributed ledger technology (DLT) in auditing is a promising direction at present. Blockchain is the popular technology in the DLT. A number of approaches in the literature based on blockchain technology have been applied on data auditing and provenance for different industry fields currently, such as adopting in business collaborative process [2] and in health data sharing [12], [13]. Different proposals achieve a different level of security and data confidentiality in auditing and some of them do not target the same trust level for the logging entity. These approaches typically rely on smart-contracts to produce audit trails and verify the records on the blockchain network.

Cucurull and Puiggalí [14] propose to add checkpoints to storage that generate logs which are then published to the Bitcoin blockchain; however, tampering with logs is possible between the checkpoint intervals. Putz, Menges, and Pernul [15] target this limitation by enabling integrity verification of each log entry through hashes published on a permissioned blockchain. They verify each log collected from different organisations. Tian [1] uses blockchain with distributed databases to track a food supply chain process. Each participant in the supply chain generates and maintains audit records of its part of the process, and submits proof of authenticity to the blockchain. Lu and Xu [16] present another application of blockchain to verify whether a product is genuine in a supply chain. Ahmad, Saad, Bassiouni, and Mohaisen [17] show a blockchain-based application 'BlockAudit' that save logs into the relational database management system and convert logs into the JSON package as a transaction reported to the Hyperledger blockchain. These approaches reflect a common assumption that an entity is trusted to produce digital evidence; we argue that there needs to be a (near) real-time verification of the audit data, as it is generated.

Tapas, Merlino, Longo, and Puliafito [18] propose an approach to leverage DLT in order to detect misconducts between customers and providers in the cloud storage. They rely on mutual challenges between clients and cloud service providers to verify the authenticity of evidence reporting but do not consider workflows including multiple administrative domains, which is a requirement we take into account in this paper. Weber et al. [2] use smart-contracts to check and control interactions in the execution of business processes. Audit trails are generated following smart-contracts execution. However, this model requires the data not to be encrypted at the level of smart-contracts which jeopardises the confidentiality of their approach. Pourmajidi and Miranskyy [19] present a prototype of a blockchain-based log system to store and verify the collected logs from different cloud storage providers. They save logs and its hashes into the hierarchical ledger, and design APIs for clients to interact with the storage. Not requiring encryption at rest is a threat to the confidentiality of the records.

C. Contributions of This Paper

In this paper, we introduce AudiWFlow, which is a confidentiality friendly and collusion-resistant auditing approach for distributed workflows. We discuss two implementations of AudiWFlow; one uses a central coordination point to has minimal trust requirements between involved third party and participants, and the other relies on a public blockchain with smart-contracts to replace with a third party for audit trail record and sharing. The double lock with key pairs of the workflow and of a participant in the workflow enables the encrypted exchange of messages and of encrypted audit records between participants. Both of our implementation approaches offer the same assurances for the confidentiality, integrity at generation and storage, and the availability of audit records reflecting the contribution of each participant in a workflow.

Our analysis of approaches in the literature [7]–[9] that rely on a centralised mechanism for auditing of distributed/general workflows concludes that a collusion between participants and a party trusted to record audit trails makes tampering with or destroying digital evidence possible, as well as breaching the confidentiality of workflow transactions. Our approach using a central point builds a complete audit trail through timely following exchanged messages with encrypted audit records and requires the nodes to push these audit records into the central server. The audit trail and timely verification in both sides of the server and the client prevent malicious behaviours from participants such as collusion attacks. It also solves the problem of data accuracy and integrity discussed in the literature [6], [20]. On the other hand, prior practices [1], [14], [16], [17] that use blockchain for auditing of workflow collaborations spreading across multiple organisations fall short on providing assurances for the combination of the availability, confidentiality, and correctness of reported audit records. Our

approach using a public blockchain runs smart-contracts to exchange a valid digest of an audit record for an attestation of the integrity of the verified record, which minimizes risk in the involvement and affection of third-party on malicious act. The audit record is shared, alongside the exchanged message, with the next participant. Both of the sender and recipient store the audit record to compare it with a digest of the message in the blockchain. All transactions are encrypted with a secret key of workflow or node key pair including in smart contract, it addresses the problem of data disclosure that may happen in the model of [2], [19]. For any arbitrary distributed workflow, our approach offers a robust and confidentiality-friendly way to record and verify audit records at any desired granularity, while giving auditing capability to key shares of participants in a distributed workflow.

III. Problem Statement

The key requirements an auditing architecture needs to satisfy are *accountability*, *non-repudiation*, *confidentiality* (records and graph), *availability* and *collusion detection*.

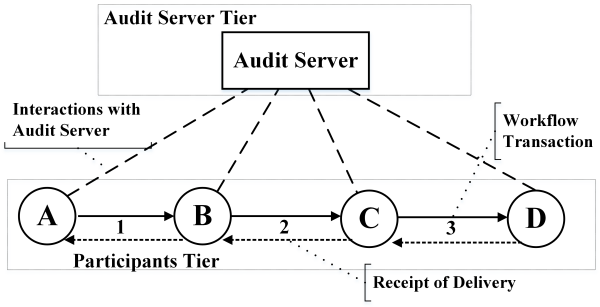


Figure 2: The representation of system structure

Figure 2 shows a linear workflow which has an auditing component (the Coordination Point - CP). The specific role of CP will be discussed later. Whereas in our first approach we use a central coordination point, in the blockchain approach this is replaced with smart-contracts running on a public blockchain. In the simple topology of Figure 2, participant A starts by requesting work from B; B then requests work from C in order to complete the request from A. Then it continues to D. When D performs the expected action based on the request from C, the workflow terminates. The evidence generated while the workflow progresses is composed of the individual audit records. Should a dispute arise at a point in the future, this evidence must hold all participants accountable for their contributions.

Each workflow $\mathcal{W}$ is modelled as a topology with a directed graph $G = (V, E)$. Figure 3 gives a working example where participants are $V = \{A, B, C, ...\}$ and edge set are $E = \{1, 2, 3, ...\}$. Each participant contributes to the overall work done, in sequence. We assume the topology of a particular workflow is established before it starts and is static for its duration. We further assume, without loss of generalisation, that the graph is acyclic when annotating each participant as a requester or responder. In other words, the workflow uses a path over the graph such that no node is a requester or a responder twice. If a particular workflow uses the same participant twice at different times, the workflow graph is different.

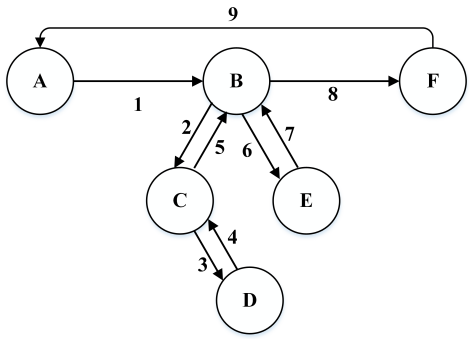


Figure 3: The representation of an example workflow [20]

A. notation

We use the following notation:

- a workflow $\mathcal{W}$ executes over a directed graph $G = (V, E)$ and associated audit evidence $\mathcal{A}$ produced during execution of the workflow.
- $V = \{A, B, C, ...\}$ is the set of members of a workflow.
- $E = \{1, 2, 3, ...\}$ is a set of the sequence of participants actions in a workflow.
- CP is an auxiliary Coordination Point.
- $pk_{\mathcal{W}}$, $sk_{\mathcal{W}}$ are, respectively, the public and private keys of a workflow $\mathcal{W}$.
- pk_i, sk_i is, respectively, a public and private key of participant $i = 1, 2, ..., N$ with $|V| = N$ participants.
- k_j is the j-th share of a threshold key, in the sense of secret sharing, and $j = 1, 2, ..., N$. It is derived from $sk^{\mathcal{W}}$ and any threshold $K \leq N$ members can recover the key.
- $M_1 \| M_2$ denotes concatenation of messages M_1 and M_2.
- $M_{i,j}$ is a message sent from participant i to j.
- $\text{sign}_i(M)$ is a message M signed by participant i.
- $\text{enc}_i(M)$ is message M encrypted with pk_i.
- $\text{enc}_{\mathcal{W}}(M)$ is message M encrypted with $pk_{\mathcal{W}}$.
- $\text{hash}(M)$ is a digest of message M using a one-way collision-resistant function (a "hash").

We use the following messages formats in our signalling diagrams:

- authenticity

$$P_{ij} = \text{enc}_j(\text{sign}_i(M_{ij}))$$

  Node i is sending a plaintext output M_{ij} to j and, to assure authenticity in a future audit, it signs the message. For confidentiality, node i encrypts the result with j's public key.
- receipt

$$R_{ij} = \text{sign}_j(\text{sign}_i(M_{ij}))$$

  After i sends an output to j, j is returning a receipt of delivery to i.

- audit record

$$A_{ij} = \text{sign}_i(\text{enc}_{\mathcal{W}}(\text{sign}_i(M_{ij}))$$

This message generates an audit record which, for confidentiality, is encrypted with the public key of the workflow. The resulting object is then signed again with i's private key as we will need a quick verification of the record without the need of inspecting its contents. The full audit trail of workflow $\mathcal{W}$ is $\mathcal{A}^{\mathcal{W}} = \{A_{1,2}, A_{2,3}, ..., A_{ij}, ...\}$ with indexes matching the graph path of the workflow.

- integrity proof

$$I_{ij} = \text{hash}(A_{ij})$$

This message simply extracts digest of an audit record.

B. Threat Model

Our architecture takes into account the following security requirements for our threat model:

- *completeness, integrity and authenticity* The audit evidence $\mathcal{A}^{\mathcal{W}}$ generated as workflow $\mathcal{W}$ executes needs to capture all inputs and outputs, in the sequence as they were generated, with participants identities embedded in the evidence.
- *non-repudiation* No participant should be able to dispute recorded evidence.
- *confidentiality* The evidence should be confidential to a certain agreed level; furthermore, it should be possible to protect the graph (participants identities and associations) if desired.
- *availability* No participant should be able to destroy evidence, at any time after releasing.
- *collusion detection* No two or more participants should not be able to collude and not be detected. Note that the effort is in detection.

IV. Architectures

Our approach to the problem is to store audit records, as they are produced, in all nodes participating in the workflow. This will assure the availability of the audit trail. In this section we present our approaches to the problem.

A. Overview

The degree of availability of the audit trail is bound to the size of the subset of participants which are allowed to inspect the evidence as all evidence is, primarily, stored in encrypted form. The key technique is to use a workflow-wide secret key $sk_{\mathcal{W}}$ which is split in $K \leq N$ shares. The shares are then distributed to all participants and it requires K out of N to open the full audit trail. All audit records are encrypted with $pk_{\mathcal{W}}$. A dispute can be resolved if K nodes decide independently to open the evidence and verify the claims. K is dependent on the case but it should be at $K > 2$ as we will not be able to detect collusion in case 2 adjacent nodes are malicious.

As the audit records are generated, they are verified by both nodes involved. If B responds to a request from A, both A and B will verify the records of each other; if a discrepancy exists, the detecting node will alert the whole workflow. If no discrepancy exists, the audit record is sent to the Coordination Point, CP. The CP then displays the individual record, encrypted with $pk_{\mathcal{W}}$ to all participants who keep a copy of the encrypted audit records.

To note that the CP only exists to manage the distribution of the individual records. As a malicious actor, its effects are limited to availability as it could help distribute corrupted evidence. The CP is challenged by every participant to verify that it is not acting maliciously. Details about our approach to challenge the CP are discussed in section IV-E. In this sense, we propose two alternative architectures:

- *using a coordination point.* If the availability of the CP can be trusted for the only purpose of displaying encrypted audit records during the workflow, using a CP makes our architecture simple to adopt.
- *using smart-contracts with a public blockchain.* If full assurances are required, we propose to replace the CP with a public blockchain which, being not managed centrally but behaving as if it were, cleanly provides a trust anchor. It brings its own security challenges, however, which we will discuss later.

After the workflow terminates, and there is a dispute, K out of the N nodes can decide to join their threshold keys and recover the complete audit trail. To note that all N nodes have a copy of the audit trail albeit encrypted with $pk_{\mathcal{W}}$ to protect confidentiality.

B. Key Management

Our scheme involves several keys which need to be securely generated, distributed and locally validated. This preparatory step is common to both of our approaches. There are two sets of keys involved.

1) Node Keys: We assume that identity credentials pk_i and sk_i for every participant are managed before the workflow starts– for example, with conventional certificates that can be verified. It should be noted that storing public keys for a particular workflow can potentially disclose the number and identity of participants. We assume this is an acceptable relaxation and leave this case for future work.

2) Workflow Keys: We need to generate and distribute, for each workflow $\mathcal{W}$, the keys $pk_{\mathcal{W}}$ and $sk_{\mathcal{W}}$. The threshold keys k_j are derived from $sk_{\mathcal{W}}$: we use a verifiable secret sharing mechanism [21]–[23] to create N shares where K are enough to reconstruct the secret. Workflow key distribution can either be done through direct messages to each participant over a secure channel or by encrypting each share of the key with the corresponding participant's private key and posting them to CP.

We adopt a pragmatic approach and task the participant with the least incentive to corrupt the audit trail to generate and distribute the key shares. This is generally the first or last participant depending on the workflow: a first participant in a workflow can be a gift shop salesman required to keep track of orders for its customers; and the last participant in another

workflow can be a supermarket manager that needs to keep track of which food, ordered by customers, are from.

Furthermore, using a publicly verifiable secret sharing (PVSS) scheme enables any participant to verify that other participants have received authentic shares of the same secret without revealing this secret. PVSS was first proposed by Stadler [23] and used by Schoenmakers [24] for an electronic voting application. D'Souza et al [25] paper later adopted PVSS and explicitly required the secret shared among participants to be a legitimate private key equivalent for a public key in their approach to support key recovery. In our context, this enables any entity knowing the public keys of workflow participants as well as equivalent public key $pk_{\mathcal{W}}$ of the shared secret k_i to verify that the key generator was honest with the key distribution, and that the secret key $sk_{\mathcal{W}}$ can be reconstructed with key shares.

C. Approach Using a Coordination Point

This approach uses a centralised Coordination Point (CP) as shown in Figure 4 with the corresponding signalling diagram in Figure 5. The CP is a special node which can be hosted by any participants or a third party. It is only responsible for distributing the audit records A_{ij} across all participants. It does not permanently store any data.

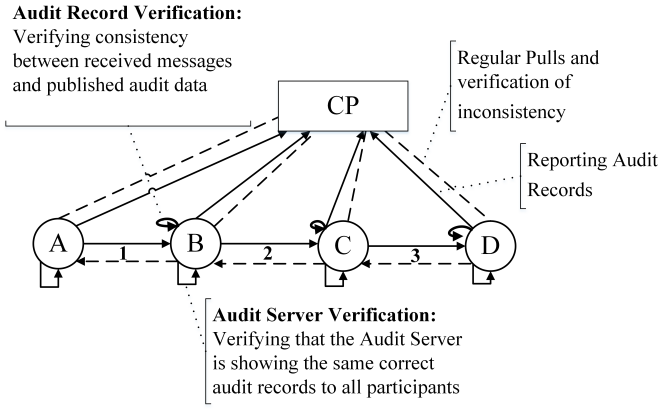


Figure 4: Architectural approach using a coordination point [20]

We do not strictly need a CP in the topology of the graph because of confidentiality. In that case, nodes can distribute individual audit records (and keys) between themselves. The trade-off incurs in added coordination complexity which may not acceptable.

Node i sends message P_{ij} to node j. Node j extracts the original output M_{ij} and is now able to continue the workflow. Node j further performs the following verification. First, it verifies that the signature in P_{ij} is valid. Second, it uses its private key to extract $\text{sign}_i(M_{ij})$ which it keeps as a receipt. As for i, it gets receipt R_{ij} from j. In parallel, i sends to CP the audit record A_{ij}.

Furthermore, node j needs to confirm that i sent the expected audit record A_{ij} to CP in order to prevent the corruption of the audit trail. Node j extracts $\text{sign}_i(M_{ij})$ and

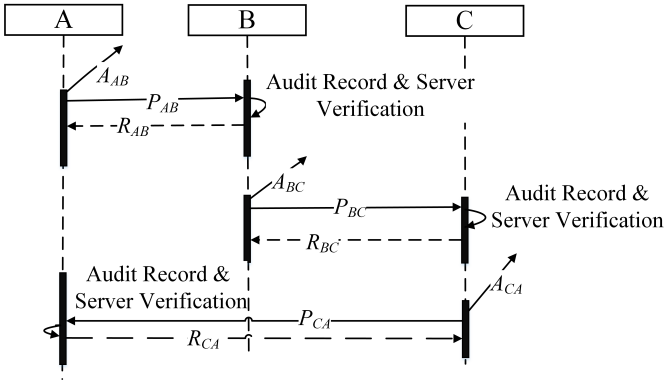


Figure 5: Signalling diagram using a coordination point [20]

encrypts it with $pk_{\mathcal{W}}$. The result is compared to what was stored in CP by i. Should there be any discrepancy between this record and what i stored in CP, the workflow is stopped. This is the gist of our approach for Audit Records Verification. The precise way of notifying all participants of a halted workflow is out of scope; solutions could pass by using a messaging protocol based on gossip (peer-to-peer propagation of direct messages)

An important aspect of our proposal is that all participants verify and keep the whole of the audit trail. Each participant will independently verify that the audit records they periodically pull from CP are validly signed by the node that generated it. This is done by verifying that the records on the CP are correctly signed. This is important in order to prevent the destruction or corruption of the audit trail by either a node or by CP. To note that a potential attack is that CP will selectively distribute incorrect audit records depending on which node is requesting. To mitigate that, nodes verify that they all received the same copy of the encrypted records by displaying a digest of the records and their signature over the digest on the CP.

Overall, all participants will have the full audit trail when the workflow terminates. No participant will be able to inspect the actual audit trail since it is encrypted with the workflow key $pk_{\mathcal{W}}$. However, each participant has a share of the key. Upon open dispute, a subset K of all participants can decide to gather their key shares and open the whole audit trail and resolve the dispute.

D. Approach Using a Public Blockchain

The previous approach uses a central Coordination Point. We envision that, in most practical cases, simplicity of use outweighs the weaknesses it introduces. In this section we show how a public blockchain able to run smart-contracts can fully replace any central point while reducing the surface attack area. The trade-off is, essentially, complexity of integration. Figure 6 depicts this approach.

We did not consider any private blockchain for two main reasons. Firstly, projects have been abandoning the idea of private blockchains and have been moved to public blockchain such as Ethereum, Cardano or Algorand. Second, a private

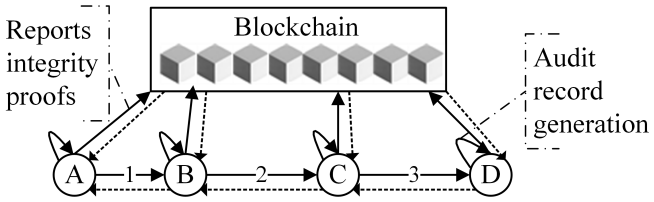


Figure 6: Architectural approach using public blockchain

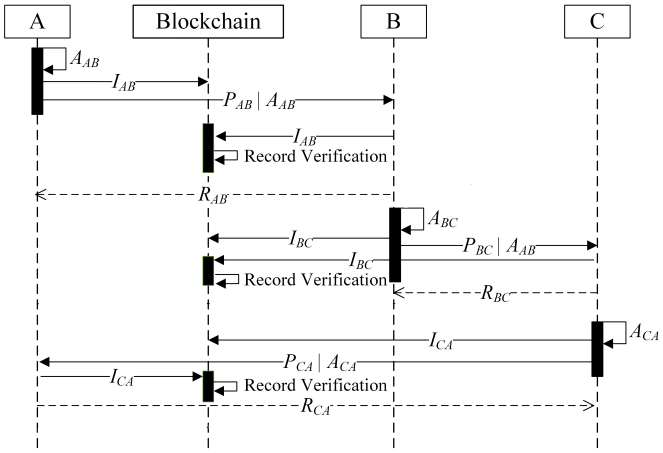


Figure 7: Signalling diagram using public blockchain

blockchain cannot deliver the same security assurances as a public blockchain due to its very high scale. For example, where it is virtually impossible to modify a block of Bitcoin or Ethereum, and even less modify without detection, a private blockchain, necessarily much smaller, suffers from governance and administration weaknesses and, should access control not be perfect, modification without detection is much easier. We have used Ethereum and adopted the consensus mechanism used by the technology.

The blockchain fully replaces CP. Since we use a public blockchain, with auditable and open code, any participant can independently verify the code meets the intended requirements. Public keys of all nodes need to be stored in the blockchain and are always available. Audit records hashes can be verified at any time, etc. Note that reading a hash of the public records does not disclose the identity of the participant, albeit the number of participants needs attention (which we will presume acceptable). This depends on the smart-contract code which, to reiterate, is publicly available for inspection.

The anonymity of the individuals participating in the workflow is not jeopardised by the use of a public blockchain. The identity of the individual approving or requesting a transaction at the level of each participant (node) is part of the encrypted payload in the audit record. The nodes in Figure 2 represent the platform (a mobile app or website) that the individuals are using. The signature of the service provider only shows on the public ledger, and this is a reasonable level of privacy given that the list service providers is public in most use cases.

The blockchain can also act as a trusted messaging channel such as halting a workflow and notifying all nodes. To note that one still needs to store audit records somewhere outside the blockchain. Participant can choose this location for the record storage. The hash of the records (on the blockchain) will assure nodes of authenticity and integrity. The audit records are immediately accessed by each node and locally stored. If a particular node attempts to retrieve an audit record but fails to find the correct record or does not gets a response from the data storage that is chosen by nodes to store the encrypted audit record, it can broadcast an alert on the blockchain to warn other workflow nodes about this failure.

Our protocol using a public blockchain, which consists of four phases: initialisation, data exchange, records verification and distribution. See message diagram in Figure 7.

In the *initialisation phase*, there involves key generation and nodes registration. We need to create a key pair for the wide workflow, $pk_{\mathcal{W}}$ and $sk_{\mathcal{W}}$. Similarly to the previous case, we still need a trust anchor (may the first node of workflow) to bootstrap the process. We once more delegate the choice of the entity who coordinates the distribution to the specific use-case, such as to the participant with least incentives to be malicious. Whereas $pk_{\mathcal{W}}$ is stored in the blockchain for public access, the k_i split shares of $sk_{\mathcal{W}}$ are distributed to each participant. We further assume that each participant has a cryptographic key pair previously generated and all have stored and made available their public keys in the blockchain. When a participant wants to get a public key from the blockchain, a smart contract is called in order to find the respective key. In the first phase, all involved workflow nodes are required to register in the blockchain network before any act start. Nodes can push and pull records to/from the blockchain.

During the *data exchange* phase, the actual execution of the workflow happens and interactions between each participant are similar as in the CP approach. Nodes will cycle through a *records distribution and verification* phase. The essential difference is that message I_{ij} (audit record integrity), along with metadata and a location to the actual audit record, is pushed and stored in the blockchain. The messages are never stored on the public Blockchain; only the integrity proofs I_{ij} of the audit records are stored and verified through the smart contracts. Once published, any participant can verify the records and obtain the actual audit record from a public location. Algorithm 1 shows the pseudo code of the smart-contract for record verification; the algorithm shows that the smart-contract only performs a string comparison operation, without any additional cryptographic operations to the ones dictated by the concensus mechanism of the blockchain, to verify that the integrity proof (the digest value of an audit record) has been published on the blockchain.

E. Security Analysis

In this section we discuss our approach by revisiting our key requirements: completeness, integrity and authenticity, non-repudiation, confidentiality, availability, and collusion detection.

Algorithm 1 Smart Contract on Record Verification

Input: $HashAudit\_Rec$[]
▷ hash value of an audit record reported by a participant
$Integrity\_Rec$[]
▷ integrity proofs reporting by the recipient
Output: Boolean indicating if a record is stored or verified successfully

```
if HashAudit_Rec[] !=∅ then
    func(saveHash)                ▷ save Hash into blockchain
    return True
end if
Blockchain.push(Integrity_Rec[])
  ▷ upload an integrity proof to blockchain for comparison
if Blockchain.push(Integrity_Rec[]) !=∅ then
    func(getHash)
    func(compareHash)
    for each Audit_Rec[] ∈Integrity_Rec[] do
        while Audit_Rec[hashId]==Integ_Rec[hashId] do
            return True
        end while
    end for
else
    return False
end if
```

1) Completeness, Integrity, Authenticity and Non-Repudiation: We consider a dishonest participant who attempts to tamper with data in the existing audit records or disseminate an incorrect audit record. Our approach can detect these situations since each individual audit record (A_{ij}) is verified immediately after generation while each node keeps receipts R_{ij} of locally exchanged (between pairs of nodes) audit records. Unless two adjacent nodes collude (as discussed below), and assuming the key distribution (as below) is secure, this assures non-repudiation. All participants also perform the Audit Record Verification mechanism after the exchanged data is received. In this sense, there are a few points where data corruption or concealment is checked.

In the CP case, the central element can potentially modify audit records. It can also provide invalid records, perhaps even selectively depending on which participant is requesting. This is prevented since all records need to be signed and verified by all nodes. For the blockchain-based case, the code of the smart-contracts is publicly auditable while not disclosing any important information about the workflow itself.

2) Availability and Confidentiality: The full audit trail, if desired, can be kept by all participants while not jeopardizing the confidentiality of any participation in the workflow given that the records are encrypted with the workflow key which no participant holds. The protected audit trail can be opened in case of a dispute and a pre-defined (configurable) K number of participants agree. Availability of the audit trail is, in the limit, guaranteed since (up to) all nodes keep the whole audit trail. To note that we use a verifiable shared scheme scheme in order to prevent distribution of invalid key shares.

3) Collusion-detection: Our scheme, and we informally argue none other, cannot prevent collusion between two adjacent nodes. Consider the following workflow: $A \rightarrow B \rightarrow C \rightarrow D$. Nodes B and C are free to decide to forge, modify or entirely destroy its internal audit records since no-one else can verify or attest integrity. There will, however, be proof of collusion.

It should be noted that this attack can be made much less likely, for small workflows (say, up to 10 participants), if every node is to link the previous audit records in their own record. At least 4 nodes would have to collude. However, the generated audit records need to be open for verification and inspection among the 4. This scheme could be expanded to any number of nodes and, depending on the topology, quickly expand to the whole graph. In this case, no CP would be needed as the trail of records could be made to propagate across the entire topology. We leave this approach out for simplicity.

Collusion involving the CP could be far more harmful but, as explained before, the CP only serves to coordinate the distribution of the audit trails and has special verification mechanisms associated.

4) Key Management: Participants are assumed to protect their credentials which are assumed to use well-known means such as those in Public Key Cryptography eXchange. As such, we leave this particular aspect out of scope of our paper.

Following the Public Verifiable Secret Sharing Scheme for the key distribution of the shares k_i of $sk_{\mathcal{W}}$, participants can verify that the key generation and distribution is correct such that each of them has a correct share of the same secret key. This still raises the problem that $sk_{\mathcal{W}}$ is exposed by the participating node that generates the key. This is common to both the CP and blockchain cases. To minimise the risk of breaching the confidentiality of audit records, we assign the key generation role to the participants that have the least incentive to cheat which is, in the case, a participant that does not hold the audit trail yet has interest in it succeeding – such as the user requesting the workflow. We, nevertheless, acknowledge this is an open problem is, seemingly, only resolved by either a collaborative generation of the shares could resolve or case-based design.

5) Complexity: A CP approach is attractive given its simplicity. The CP is little more than a simple file server with some verification logic. It however requires a high availability of a CP. The blockchain approach seems to elegantly resolve those problems but at the cost of integration of complexity which, in itself, provides possibility for implementation vulnerabilities both at the code of the smart contracts and also at a system level. For example, the audit records need to be sent securely (in some form) to be stored out of the blockchain. Considering this is specific to an actual implementation, we do not discuss it further.

V. Evaluation

In this section, we present experimental evaluation results[1] of our implementation of the two described approaches[2], using a Coordination Point and using Smart Contracts running on a public blockchain.

The workflow topologies were generated using BRITE[3], a network topology generator. Even though BRITE was designed to generate Internet topologies, we hold the expectation that BRITE is sufficiently representative of real-world workflows for a small number of nodes (say, up to 20). We configured BRITE to generate a connectivity graph based on Barabasi-Albert algorithm with two key parameters:

- the number of nodes N, where we use $N = \{10, 15, 20\}$.
- the connectivity degree m which is, on average, the number of nodes each node connects to. For example, for $m = 1$ the topology is linear and for $m = N$ the topology was a full mesh with all nodes connected to all nodes. We used $m = \{2, 5, 7, 10\}$

For every pair of parameters (N, m), we generated 5 different random topologies in order to generate enough randomness and extract statistical parameters such as averages. In total, we had about 100 different topologies.

Above the working nodes topology, we added either a special server (the Coordination Point, CP) or an interface to the Ethereum blockchain.

In terms of the software implementation, we should stress that this is experimental code which is not designed for performance but only to demonstrate and validate our approaches. For this demonstration, we used OpenSSL genrsa function to generate the key pairs for the participants and workflow; 2048 bit was selected as the size of each of the keys. We also used a public implementation of Shamir Secret Sharing[4] to generate the shares of the workflow private key. At the level of the workflow participants, we relied on Nimbus-JOSE library[5] for the cryptographic functions including the encryption of the audit records, the generation and verification of the integrity proofs. We further used common desktop hardware or low-end, but modern, servers such as Intel Core i7 at 2.6 GHz with 32GB RAM. As such, we are only interested in overall behaviour and orders of magnitude. All source code is open and available on request. Specifically,

- for the CP approach, we used Apache Tomcat application servers which uses Java SE 8.
- for the blockchain approach, we combined an Apache Tomcat application server for the workflow nodes and then implemented an interface which called an Ethereum smart-contract written in Solidity. We run our approach in the local test environment of Ethereum.

To evaluate the performance of each implementation, we record the response time for each transaction which includes the message propagation time, the generation and reporting time of audit record, and the time taken by the verification mechanisms, often using cryptography.

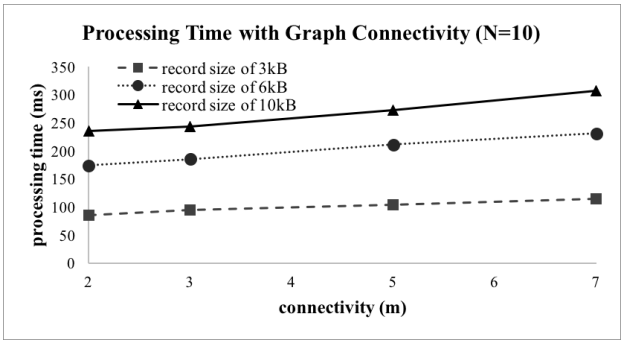
[1]Relevant Data: https://github.com/Jency/AudiWFlow.git

[2]https://github.com/antonionehme/AuditingWorkflows-Blockchain

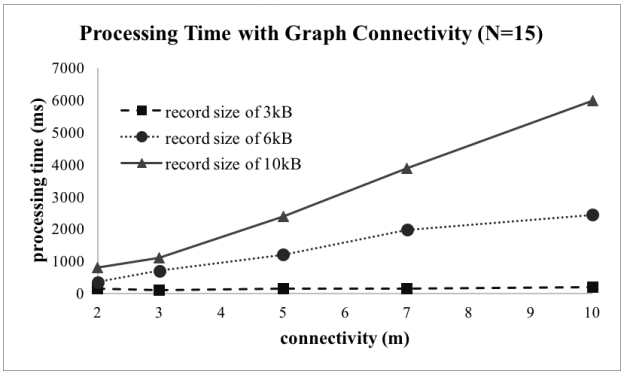
[3]https://github.com/nsol-nmsu/brite-patch

[4]Shamir Secret Sharing Scheme: https://github.com/iancoleman/shamir/blob/master/src/js/secrets.js

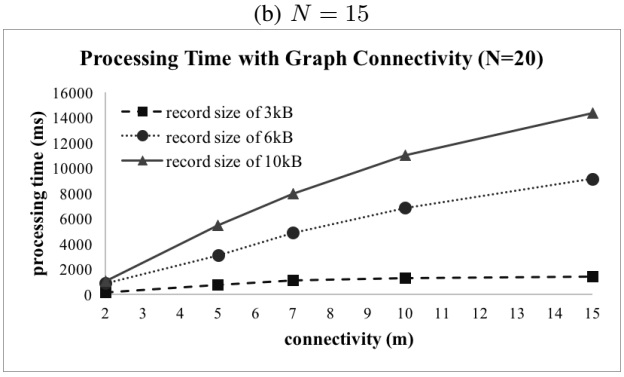
[5]Nimbus JOSE: https://connect2id.com/products/nimbus-jose-jwt



(a) $N = 10$



(b) $N = 15$



(c) $N = 20$

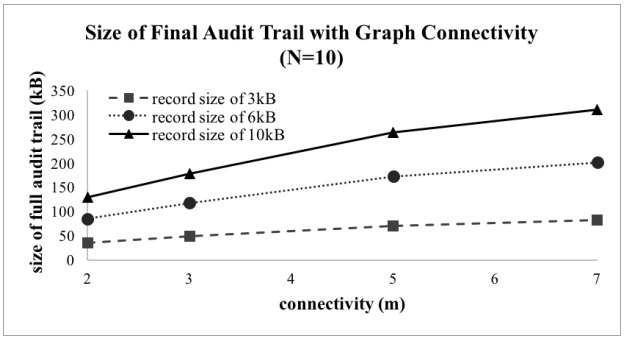
Figure 8: Evaluation of response time using a CP

A. Using a Coordination Point

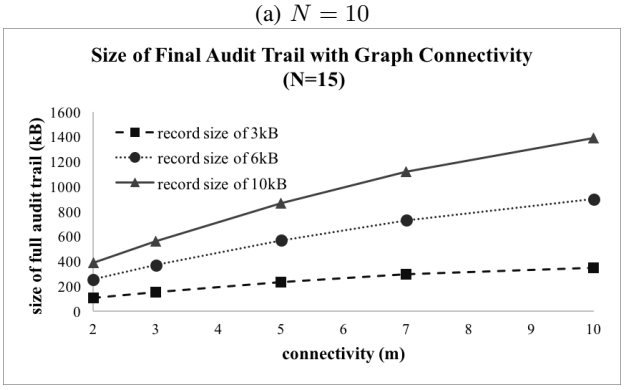
We evaluate our CP implementation with different size for the individual record. For a fair and consistent evaluation, we separated the results according to the number of participants N; this gives comparable computational resource allocation for each iteration of the experiment after dedicating the resources required to bootstrap participants and the audit server.

Figure 8 shows the average response time. The key parameter we evaluate is the response time (vertical axis). We used three sizes for the individual audit records each node generates: 3KB, 6KB and 10KB.

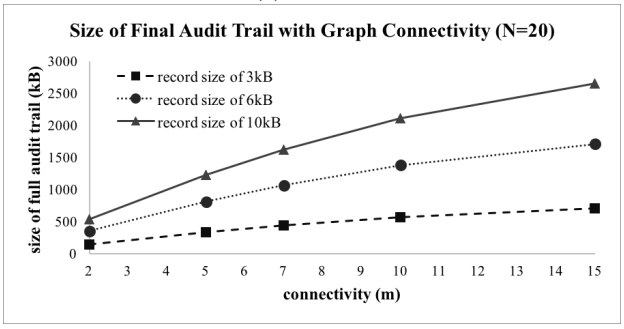
For small topologies up to $N = 20$, we obtained an approximate linear relation. This is likely to be shaped like a logarithmic curve if we allowed the size of the topology to scale to different orders of magnitude.



(a) $N = 10$



(b) $N = 15$

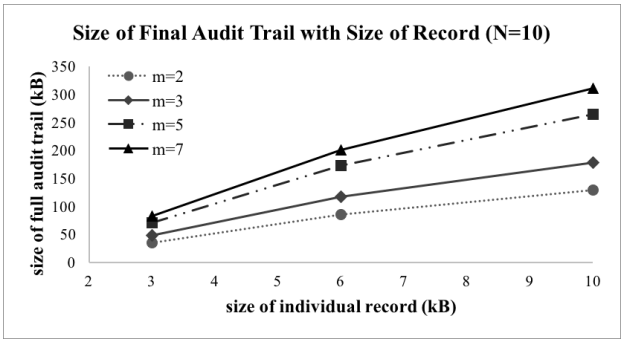


(c) $N = 20$

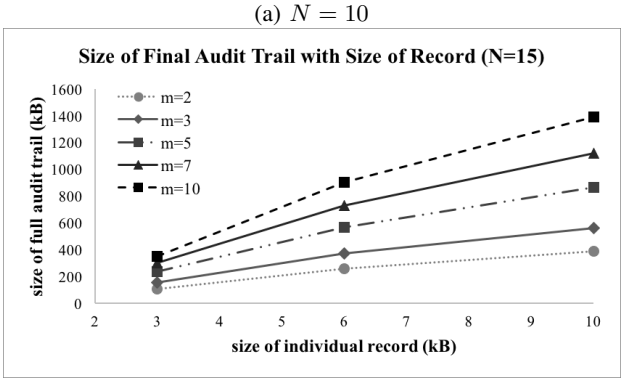
Figure 9: Evaluation of size of audit trail using a CP

Figure 9 shows the size of the final audit trail. We evaluated the size of the audit trail (vertical axis) against three sizes of the individual audit record (fixed for the set of runs). It follows the generic pattern and the size of the total audit trail increases sub-linearly with increasing of size of the individual record at the $N = 20$. This was expected since the emulated workflows run increasingly in parallel with increasing m which reduces the size of pair-wise messages.

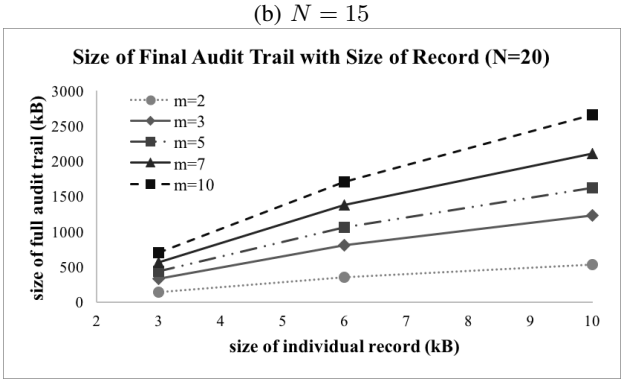
Figure 10 shows the impact of the connectivity degree m. We evaluated the size of individual records (horizontal axis) and size of final audit trail (vertical axis) when we allowed the increasing of the connectivity degree m of each node connects: 2, 3, 5, 7. If the topology is larger, the size of final audit trail also increase, as expected, but, once again, we see a sub-linear relation.



(a) $N = 10$



(b) $N = 15$



(c) $N = 20$

Figure 10: Evaluation of size of audit trail and individual record using a coordination point

In absolute terms, we note that the delay of our approach is on the order of seconds. If one considers that (1) each node will have to perform some kind of task which is likely to last more than a few seconds, and (2) that our code is likely to not be optimised, these results suggest our scheme can support fully automated workflows in real-time.

B. Using a Public Blockchain

To reduce the time it takes to mine a block, we set up the variable of difficulty to a low value. We evaluated and discussed the processing time and gas cost, and compared the performance of implementations by CP and Blockchain.

1) Processing Time: Figure 11 shows the average response time. The key parameter involved is the numbers of records (vertical axis) which are generated and shared in each iteration. We chosen that each node generates 10KB for the individual audit record. With topology $N = 20$, we found a stable relationship between the average response time and numbers of records at the different graph connectivity. The time to process a set of records is essentially dominated by the mining delay.

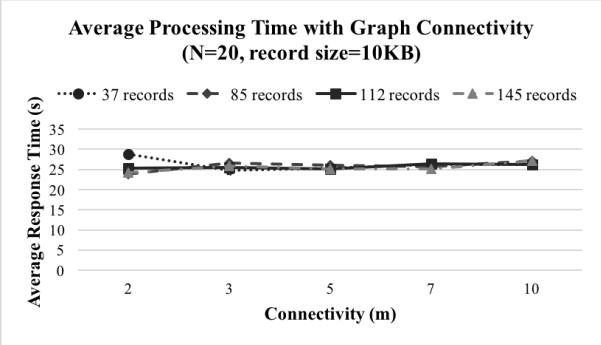


Figure 11: Evaluation using a public blockchain. $N = 20$ nodes, size of audit record is 10KB

2) Cost: Figure 12 shows the gas cost for different sizes of records. We took the gas spent for each transaction and record size and calculated averages for topologies of N=20. As expected, we see a linear dependency with the record size. This is because we only store in the blockchain the minimum information which is digests of the records. Since each node will generate 1 record, the gas used will be $G \propto N \cdot hash(M) + g_{alg} + g_{setup}$, where g_{alg} is the gas spent to execute the storage procedure (fixed and independent of the topology), and g_{setup} is any initial, one-time, setup of the smart-contract. As such, and using the O-notation, the the costs will be $C = O(hash(M) \cdot N \cdot C_{gas}$. $C_{gas})$ is the actual monetary cost per unit of gas. This is dependent on the actual platform (such as Ethereum) and on market conditions.

A remark about Ethereum. We selected this platform purely on the basis of a proof-of-concept. Even though it is the most popular currently, we do not set any expectations or make any recommendations as to which platform to use. In other words, any blockchain able to store a value (the hash of the records), is fit for use. We do make the assumption that the cost structure will be similar in any smart-contract platform even if current alternatives (such as Algorand or EOS operate differently).

Furthermore, we note that the gas as measured in our implementation may not be accurate as we used the source-code of Ethereum as of early 2021. Ethereum changed how gas is calculated and spent recently (in the London upgrade). The structure of costs, however, did not change and still is $C = O(hash(M) \cdot N \cdot C_{gas})$. A similar structure of costs will exist when Ethereum, and perhaps most other platforms, change to Proof-of-Stake instead of Proof-of-Work.

3) Performance Comparison: In Figure 13 we compare the performance, in time to store the complete audit trail, of our two implementations. We used $N = 20$ and record size of 10KB. For Figure 13a, the relationship of response time and numbers of records in the implementation of coordination point and blockchain behave significantly different. The comparison of relationship between average response time and specified numbers of records in Figure 13b is a similar result as Figure 13a. When using a coordination point, the response time is essentially linear as audit records are generated. For the blockchain implementation, we see jumps of about 15 seconds which corresponds to the mining period.

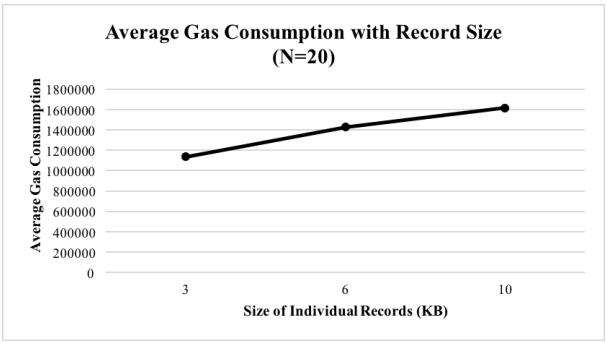
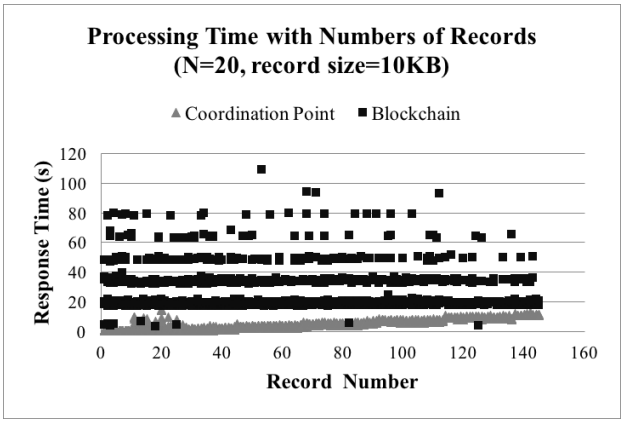


Figure 12: Average processing gas cost of each iteration with size of record. $N = 20$ nodes

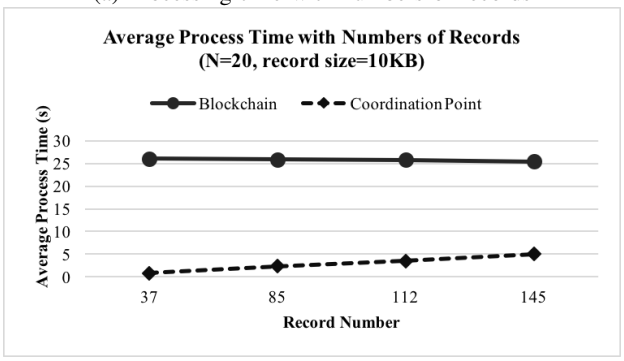
VI. Conclusion and Future Work

We presented an architecture that tackles the problem of auditing workflows satisfying *accountability*, *non-repudiation*, *confidentiality* of records and graph, *availability* and *collusion detection*. We proposed and evaluated two implementations based on either a coordination point or a blockchain. Whereas the CP approach is simpler and could meet real-world requirements of most cases, we showed that using a central point target the minimal trust requirements and using a public blockchain makes our approach more robust at the expense of processing delay. Although AudiWFlow is designed with confidentiality, integrity and availability requirements in mind, its tight security measures can be relaxed for applications that do not require, for example, strict confidentiality requirements between participants. Different implementation of our approach can be adopted in different cases; offering both implementations enable the adoption of the approach for organisations that have legal, political, or corporate culture restrictions on the technology that can be used. While the blockchain-based implementation of our approach offers a stable processing time and permanently stored integrity proofs of the audit records on the public blockchain, the implementation with the central coordination point requires less processing time (limited nodes involved) subject to the availability of a central server. Our discussion and evaluation of each implementation enable adopters to make an informed decision on which implementation is a better fit for their business context.

There remains a number of questions for future work. Two of them are the following. First, we will strengthen our ap-



(a) Processing time with numbers of records



(b) Average processing time of each iteration with numbers of records

Figure 13: Comparison evaluation using CP and blockchain in response time with numbers of records. N = 20 nodes, record size = 10KB.

proach to satisfy identity confidentiality: at present our scheme relaxes this requirement and the identity of nodes needs to be known beforehand – for example, to distribute cryptographic material such as public keys. Second, our approach requires a starting point that needs to be trusted for some tasks such as generating the threshold keys. Solving this particular problem will necessarily raise the complexity by, for example, making use of multiparty secure computation techniques. Finally, the overall architecture of an approach using blockchain needs elaboration.

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