Section: PUBP-6727

Mutual Monitoring in the Cloud
Progress Report 4

Alexander Stein

Problem Statement

Cloud computing infrastructure is essentially ubiquitous, but adoption is not without challenges. Cloud service providers must cater to customers in regulated sectors, complying with cybersecurity frameworks that create high barriers to entry. One barrier is ongoing evaluation of the provider's cybersecurity posture, often resulting in centralized bureaucracies. FedRAMP oversees a prominent example of such a program, the Continuous Monitoring Program, which is emblematic of these barriers. This program requires hundreds of cloud service providers to contract with one of thirty reputable auditor firms. The providers work with the auditors to send security scans and updated security control documentation for FedRAMP-authorized services monthly to FedRAMP reviewers, in some cases for the largest cloud infrastructures in the world. All three parties collaborate in meetings, emails, and a wiki, forming a unique multi-party bureaucracy that both secures and bottlenecks the government's acquisition of modern cloud services.

Are these bureaucracies an optimal solution, or a last resort that fails to keep pace with cloud technology as it proliferates and evolves? If they are a last resort, is there a better way?

Solution Statement

I will use this research to design and evaluate an alternative to centralized continuous monitoring, mutual monitoring. The foundation of mutual monitoring will be federated data services, known in other security use cases as transparency services. The positives and negatives of FedRAMP's continuous monitoring model will inform its design. Operating such services can change the economics, and thereby the behavior, of cloud service providers and their customers. A new architecture will incentivize auditors to sell value-add analytics via these federated data services, potentially obsoleting centralized authorities for continuous monitoring like FedRAMP.

Completed Tasks (Last 2 Weeks)

1. I updated the architecture specification. I am still waiting for final feedback from subject-matter experts advising me.
2. I continued limited development of the core transparency service and utility classes shared with Relying Party clients, but I deferred further development.
3. I finalized my critical analysis of FedRAMP, waiting for feedback from subject matter experts reviewing my solution.
4. I further developed Monte Carlo simulations in Python and supporting data for cost and duration estimation.
5. I developed a simple quantitative framework for measuring performance of inventory management and configuration management.
6. For evaluating my project with qualitative methods per my plan, I coded the theme, sentiment, and persona of several hundred comments in my archive of past and current FedRAMP 20x working group feedback.

Tasks for the Next Project Report

In the next week, I will complete architecture, analysis, and evaluation. For the following two weeks, I will draft the final paper.

Questions or issues I'm having

Deliverables and Scope

1. I intended to focus on code and accelerate development, but I deferred development to focus on developers which I am closer to completing.

Evaluation and Measurement

1. Properly designing user interview questions for interviews and scheduling are a significant challenge, just like the professors warned and I assumed. This next week will be challenging, but I look forward to it!

Methodology Paragraph Summary

For this project, I will use multiple methods to implement an alternative architecture for monitoring cloud services and modeling its potential impact. To start, I will use a quantitative and qualitative analysis of the current shortcomings and gaps for the current FedRAMP Continuous Monitoring Program. This will be the primary example of centralized continuous monitoring for which I design my mutual monitoring model for comparison. For qualitative analysis, I can perform textual analysis and sentiment analysis. I will leverage academic research, industry analysis, and a new primary source: FedRAMP's web-based forums for the 20x reform initiative and its community working groups. In these forums, stakeholders discuss their praise and criticism of current centralized processes and plans for future ones, often summarizing their pain points highly relevant to designing an alternative process. In addition, I will use publicly available information from FedRAMP and industry analysis to quantify the burden of the current FedRAMP Continuous Monitoring and its manual workflow. As I build a prototype based on my architecture, I will design several use cases to estimate the cost and resource efficiency to compare those costs against the estimated costs for my solution. In addition to these methods, I will use advisors familiar with FedRAMP from different stakeholder perspectives to validate information or analysis where these methods prove lacking and leave gaps.

Timeline

Week #	Description of Task	Status
W6 (June 16-22)	Complete data service client to submit to submission API instances.	Deferred
W6	Design MVP continuous monitoring use cases and quantitative measurements.	Deferred
W6	Implement data service client to submit to submission API instances.	Deferred
W6	Complete data service internals and submission API.	Deferred
W6	Build data export tool for complete, offline archive of 20x forums.	Continued

W7 (June 23-29)	Complete FedRAMP critical analysis document.	In Progress
W7	Build data export tool for complete, offline archive of 20x forums.	Completed
W7	Complete implementation of data service client to submit to submission API instances.	Deferred
W7	Implement MVP continuous monitoring use cases in API quantitative processing module.	Deferred
W7	Design MVP continuous monitoring use cases and quantitative measurements.	Deferred
W7	Finalize architecture specification with advisors' reviews.	Pending
W7	Implement continuous monitoring quantitative processing module for API.	Deferred
W7	Recruit stakeholders to interview for project evaluation.	Completed
W8 (June 30 - July 6)	Start prototype deployment to cloud service tenants for testing.	Pending
W8	Design MVP continuous monitoring use cases and quantitative measurements.	Completed
W8	Implement continuous monitoring quantitative processing module for API.	Deferred
W8	Interview stakeholders for project evaluation.	Deferred
W9 (July 7-13)	Complete prototype deployment to cloud service tenants for testing.	Deferred
W9	Interview stakeholders for project evaluation.	Pending
W9	Complete Monte Carlo simulations and supporting activities for evaluation.	Pending

W10 (July 14-21)	Tie up loose ends on project deliverables and paper.	Pending

Evaluation

Summary

The project, as detailed in the intial proposal, examines the many challenges to effective multi-party security monitoring of cloud service providers and designing a solution based on two areas of work. The first area of work is an analysis of best-in-class contemporary techniques for multi-party cloud security monitoring, typified by FedRAMP's administration of their Continuous Monitoring Program. The second area of work, informed by the first, is a specification and prototype for a novel architecture for multi-party security monitoring of cloud service providers, addressing challenges and shortcomings identified from the first work area.

To evaluate the solution, I plan to use a multi-disciplinary approach to assess the project's final deliverables, identifying benefits to the proposed solutions; confirm and discover limitations to the solution; and propose future areas of work. I categorize this multi-disciplinary approach into qualitative and quantitative methods, which I describe in more detail below.

Quantitative Methods

Evaluating this project will include the quantitative methods below.

1. Model the range of costs for continuous monitoring process, data access, and submission for FedRAMP's current requirements.
2. Model the range of duration for processes related to continuous monitoring activities for FedRAMP's current requirements.
3. Model and estimate the equivalent processes in the proposed mutual monitoring architecture.

Qualitative Methods

Evaluating this project will include the qualitative methods below.

1. Identify challenges and obstacles to current FedRAMP continuous monitoring processes through resources including. but not limited to:
    - literature review of multi-party security monitoring of cloud service providers, as FedRAMP and other regulatory frameworks implement it;
    - sentiment analysis FedRAMP's official forum for its 20x modernization program, in which stakeholders often critique current processes.
2. Use data from 1 to identify features and use cases of the mutual monitoring architecture to address identified challenges with a qualitative analysis of their positive or negative impact.
3. Interview stakeholders with different roles in FedRAMP authorizations and continuous monitoring. Participants will answer questions regarding the relevance and impact of challenges identified and benefits of the mutual monitoring solution's features to their work. The final report will summarize qualitative analysis of their answers to model how a mutual monitoring ecosystem will benefit the persona the stakeholder represents in the ecosystem.

Initial Results

Qualitative Results

Although I am still in the process of scheduling interviews with industry experts and have not completed a significant number of interviews, I have completed coding of all written comments by participants in the FedRAMP 20x Working Groups for the current modernization of its program. These comments are a vital primary source representing the official positions of FedRAMP staff and perspectives from personas of other stakeholders in FedRAMP processes past and present. I have done qualitative analysis to identify twelve themes that represent higher-level requirements for key FedRAMP uses cases. As I will document in my final paper, my mutual monitoring architecture and use of transparency services can effectively address ten of these twelve higher level requirements from FedRAMP, cloud service providers, auditors, and agency customers. These twelve requirements are currently unmet or poorly implemented, as documented by participant feedback. Addressing over 80% of the higher level requirements, often based in precise critical feedback from FedRAMP stakeholders in the public record, is a strong indicator that future prototypes of this

architecture can positively impact the FedRAMP continuous monitoring processes with a radically different approach.

Quantitative Results

As a full analysis and model for development and operations of continuous monitoring infrastructure is pending, preliminary analysis indicates mutual monitoring with a transparency service architecture can significantly improve the submission, measurement, and verification steps of FedRAMP processes. My proposed architecture obsoletes a formal authorization process before continuous monitoring in favor of assessment via continuous monitoring and metrics derived from a rolling window period. Updated analysis indicates that the cumulative average number of days for all FedRAMP authorizations, from beginning to end, is 381 days. Despite significant improvements in the last three months by FedRAMP staff, the improvements offset a previous cumulative average in the months prior of over 390 days. With regards to operation, recording assessments through quantitative measurement for only automation-friendly properties of a service can reduce a 381 day delay to days or weeks. The precise improvement depends on industry risk appetite for a real-world deployment, in which FedRAMP and industry accept the longest minimal rolling window duration for inventory and configuration monitoring use cases. By analyzing transparency services for other use cases, aside from the rolling window of measurements to be assessed, CSP reporting, auditor analysis, and metrics reporting can occurs in minutes. As current continuous monitoring requires monthly synchronous meetings for each authorized cloud service, this improvement is a significant increase in speed and efficiency. As for development, further quantitative study is required, but initial reports from respondents to my inquiries indicates similar implementations are possible for one senior engineer in fourteen days. Other companies have implemented similar architectures in months, once the specifications for those use cases were completed.

Report Outline

I. Introduction
   A. Problem Statement
   B. Solution Statement
      1. Methodology
         a. Architecture specification
         b. Qualitative analysis of gaps in current FedRAMP monitoring processes
         c. Quantitative analysis
            i. Duration and cost for continuous monitoring operations
            ii. Duration and cost for transparency service architecture for mutual monitoring
               - Estimates for development from parallel use cases
                  - certificate transparency
                  - binary transparency
                  - supply chain transparency services
               - Estimates for operation from parallel use cases
                  - certificate transparency
                  - binary transparency
                  - supply chain transparency services
      2. Key components and deliverables
II. Continuous Monitoring for Cloud Services
   A. NIST Risk Management Framework (SP 800-37; SP 800-53)
   B. Cloud Security Alliance CAIQ/STAR
   C. CIS Controls Assessment Specification
   D. ISO 27001:2022
   E. SOC 2
III. FedRAMP Continuous Monitoring
   A. Background
   B. History
   C. 20x Working Programs and Modernization
   D. Critical Requirements, Challenges, and Criticism from FedRAMP Modernization
      1. Infrastructure CSPs support dependent CSPs and agency customer application reporting
      2. Accurately deriving summarized statistics verifiably from raw data
      3. Challenges and limitations of OSCAL and other existing data standards
      4. Effective use of signatures, verifications, and trust indicators
      5. Timely report submission and repeatable report verification
      6. Challenges to current scanning techniques for compliance and vulnerability scanning
      7. Inventory approaches and challenges
      8. Challenges to the current Significant Change Request process and future modernization
      9. Privacy-enhancing and least privilege access to cloud security data
      10. Challenges due to current third-party auditors' staff knowledge and skills
      11. Centralization versus decentralization
      12. Economics and incentives
IV. Transparency Services for Adjacent Security Domains
V. Mutual Monitoring Service
   A. Use Cases
   B. Personas
   C. Components
      1. Core Transparency Service
      2. Adjacent Services
   D. Processes

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Appendix

An Architecture for Mutual Monitoring of Cloud Infrastructures

Author: A.J. Stein **Version:** 7dd0d317fdb3e0d8ed99657efb34d1c3efe02fa2
Modified at: 2025-06-09

The source code from github.com/aj-stein/conmotion at the linked commit generated this copy of the specification, supporting documentation, and related code. You can click this link to download this specification as a PDF document.

Abstract

The transparency of cloud infrastructures is a systemic challenge to industry.

Internal or external stakeholders of a cloud infrastructure may want to publish or verify data about its operational, resiliency, or security properties. However, there are no specifications for common data structures, protocols, or measurement algorithms to transparently demonstrate evidence of those properties at once or over a time intervals. This document proposes an architecture that specializes the Transparency Service architecture for providers of cloud infrastructures. The specialization of this architecture will enable them to publish evidence of security properties with verifiable digital signatures. Providers of cloud infrastructures, their consumers, or external auditors may also publish counter-signatures to verify multi-party evaluation and verification of this evidence, known as a mutual monitoring network.

Conventions

This specification conforms to IETF's best practice in RFC 2119 to capitalize all letters in key words to indicate requirement levels (Bradner, 1997).

This specification also capitalizes certain words or phrases with common meaning when this specification gives them a precise normative definition. See the Terminology section for a complete listing of these terms.

Introduction

Cloud infrastructures require their providers to design, implement, and document security properties against a threat model and actively monitor these properties for their efficacy in mitigating threats. Moreover, cloud infrastructures have essential characteristics that uniquely distinguish them from other deployment models. They have measured services where the provider and consumer control components automatically and precisely through metering capabilities and on-demand self-services for consumers to unilaterally provision components (Mell & Grance, 2011, p. 2).

Despite these essential characteristics and the proliferation of many differentiated, proprietary services for cloud infrastructures, there is no de-facto standard

or vendor-agnostic solution to publish digitally-signed data for a cloud service infrastructure, counter-sign the data to acknowledge and verify its contents, and/or enrich a collection of this data with verifiable measurements. Different providers have monitoring capabilities for security properties of cloud infrastructures, but most are partial, proprietary, confidential, and do not permit scalable multi-party verification of data. Therefore, a Transparency Service architecture is needed for different parties to publish signed data, counter-sign acknowledgements, and publish follow-on measurements for parties to mutually monitor heavily interconnected infrastructures.

This specification specifies an architecture for a Transparency Service to concurrently monitor the security properties of one or more cloud infrastructures by multiple parties, both internal and external to the the infrastructure provider. Previously, experts drafted Transparency Service architectures for monitoring the lifecycle of TLS certificates for encrypted communications on the World Wide Web (Laurie, Messeri, & Stradling, 2021) and another for heterogenous data for software supply chain use cases (Birkholz, Delignat-Lavaud, Fournet, Deshpande, & Lasker, 2025). An industry consortium deployed an emerging de-facto standard, Sigstore and Rekor, for monitoring published open-source software used industry-wide (Sigstore Developers, 2025). Google's Android operating system developers deployed their own to verify the legitimacy of all compiled programs in their operating system releases (Google, 2025). Although they represent similar use cases, the uniqueness of cloud infrastructure requires different design and implementation tradeoffs. Therefore, this specification will inventory use cases; describe the foundation and enhancements to the baseline Transparency Service architecture; the actors in a mutual monitoring network and their roles; specialized components of the architecture; and required protocols for actors to execute their roles with the architecture for given use cases.

Use Cases

This specification addresses the needs of several use cases for mutual multi-party monitoring of security properties for cloud infrastructures.

Monitoring System Inventory

Inventory management of systems that comprise components of a cloud infrastructure is a foundational requirement for many security control frameworks that organizations use whether or not they maintain a cloud infrastructure. Examples include control 5.9 in ISO 27001:2022 (2022), control PM-5 in the Special Publication 800-53 Risk Management Framework (NIST, 2020, p. 206), the control CCC-04 in the Cloud Controls Matrix (Cloud Security Alliance, 2024, p. 79), and numerous others. For a cloud infrastructure to satisfy these control requirements, they must maintain an inventory, often incredibly dynamic due to characteristics of cloud computing, for all systems the compromise the components of that infrastructure. Cloud infrastructure providers have different

actors, performing different roles, where they must produce, consume, and/or verify data about the inventory of that infrastructure.

Cloud Infrastructure Provider A cloud infrastructure provider uses bespoke asset management system(s) predominantly for internal use. The provider's staff can use a Transparency Service as a high-fidelity replica of the asset management system(s) data, tracking changes over time, or as the canonical source of inventory. The provider's staff will integrate inventory management automation to create new entries into the Append-only Log of the Transparency Service, adding digitally signed records one-by-one for the provisioning and deprovisioning of all systems in the infrastructure. The most recent record embeds a linkage by hash to the previous record in the Append-only Log. Staff can check the most recent record to now the latest changes or "replay the log" with the fully exported data of the Append-only Log to understand all changes over time and compose a realistic model of the services monitored.

Cloud Infrastructure Customer A customer of a cloud infrastructure uses the cloud infrastructure provider as a dependency to build their own application services or derivative cloud infrastructure, thereby creating its own need for an asset management system and inventory. By virtue of this architecture, the customer's staff must maintain their own inventory, but the assets they manage will be instances of cloud infrastructure systems provided by the upstream cloud infrastructure provider. The customer will use the upstream cloud infrastructure provider's transparency log, consuming digitally signed records and publishing digitally signed receipts to their own transparency log, acknowledging existence of the upstream infrastructure they use to provision an instance in their own infrastructure. This customer will also generate their own records for both internal and external use for their own downstream customers to confirm accurate inventory management.

Auditor An auditor, accountable to the cloud infrastructure provider, their customer, or both, must review the efficacy of security control implementations through expert review of artifacts. In the case of inventory management, it is important for the auditor to use these artifacts as evidence. The auditor compares the evidence from the provider to their own artifacts they collect independently, and verify the provider's inventory is accurate and has no anomalies. Auditors can consume the Append-only Log of the Transparency Service to ascertain contemporary or historical view of the provider's inventory and thereby the efficacy of their inventory management techniques. Auditors can also digitally sign receipts and append them the transparency log to endorse inventory records, so that customers of the cloud infrastructure provider can analyze auditor endorsements in transparency log records to acquire cloud infrastructure or continue using it.

Monitoring Configuration Management

Configuration management for systems that comprise components of a cloud infrastructure is a foundational requirement for many security control frameworks. Examples include control 8.9 in ISO 27001:2022 (2022), multiple controls in the Configuration Management (CM) control family for the Special Publication 800-53 Risk Management Framework (NIST, 2020, pp. 96–114), the control CCC-03 in the Cloud Controls Matrix (Cloud Security Alliance, 2024, p. 77), and numerous others. For a cloud infrastructure to satisfy these control requirements, the provider's staff must have known configuration baselines for their inventory, apply them, and possibly prevent provisioning outside of approved processes and create or change assets to not conform to the baselines. Cloud infrastructure providers have different actors, performing different roles, where they must produce, consume, and/or verify data about the configuration management for that infrastructure.

Cloud Infrastructure Provider A cloud infrastructure provider uses bespoke configuration management system(s) mostly for internal use. The provider's staff can use a Transparency Service as a high-fidelity replica of the configuration management system(s) data, tracking changes over time, or as the canonical source of inventory. This data will cross-reference which systems link to which configurations with both datasets on the Transparency Service. The provider's staff will integrate inventory management and configuration management automation to create new entries into the Append-only Log of the Transparency Service, adding digitally signed records one-by-one for the creation, modification, and deletion of configurations for different assets in the cloud infrastructure. The most recent record embeds a linkage by hash to the previous record in the Append-only Log. Staff can check the most recent record to now the latest changes or "replay the log" with the fully exported data of the Append-only Log to understand all changes over time and compose a realistic model of the services monitored.

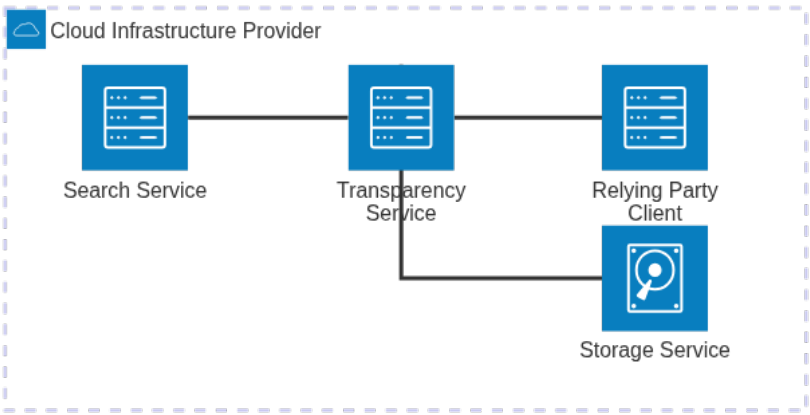
Cloud Infrastructure Customer A customer of a cloud infrastructure uses the cloud infrastructure provider as a dependency to build their own application services or derivative cloud infrastructure, thereby creating its own need for an configuration management system. By virtue of this architecture, the customer's staff must maintain their own inventory and configuration management database, even the assets and their configurations are instances of systems the upstream cloud infrastructure provides. The customer will use the upstream cloud infrastructure provider's transparency log, consuming digitally signed records and publishing digitally signed receipts to their own transparency log, acknowledging existence of the upstream infrastructure they use to provision an instance in their own infrastructure. This customer will also generate their own records for both internal and external use for their own downstream customers to confirm accurate inventory management.

Auditor An auditor, accountable to the cloud infrastructure provider, their customer, or both, must review the efficacy of security control implementations through expert review of artifacts. In the case of configuration management, it is important for the auditor to use these artifacts as evidence. The auditor compares the evidence from the provider to their own artifacts they collect independently, and verify the provider's inventory and related configuration management records are accurate and without anomalies. Auditors can consume the Append-only Log of the Transparency Service to ascertain contemporary or historical view of the provider's configuration management records and thereby the efficacy of their configuration management techniques. Auditors can also digitally sign receipts and append them the transparency log to endorse inventory records, so that customers of the cloud infrastructure provider can analyze auditor endorsements in transparency log records to newly acquire cloud infrastructure or continue using it.

Architecture

The mutual monitoring architecture specializes the architecture of a Transparency Service as defined by the IETF SCITT Working Group (Birkholz et al., 2025). This architecture includes a Transparency Service; Adjacent Services, custom services deployed adjacently to the Transparency Service for log search and storage; and Relying Parties, Transparency Service clients that serve specialized use cases for processing the content of each record in the Append-only Log.

Given the above use cases, a cloud infrastructure provider MAY deploy these components with logical relationships like those in the diagram below.



Components

Transparency Service The Transparency Service is the core component of the mutual monitoring architecture. An implementation MUST conform to the normative requirements in the current draft of the IETF SCITT Architecture (Birkholz et al., 2025). These requirements document the minimally viable features, listed below, for a Transparency Service to function for the mutual monitoring use cases documented above.

1. Transparency Services have an Append-Only Log of Signed Statements in order of Registration so one or more instances can maintain their integrity and prevent equivocation or other forms of misuse.
2. Transparency Services have a Registration Policy API with endpoints for any Relying Party to determine signing and Claim requirements before Registration.
3. Transparency Services have a Submissions API with endpoints for an Issuer to complete Registration of a Signed Claim.
4. Transparency Services have an Entry API with endpoints for any Relying Party to retrieve one or more entries previously registered with in the Append-only Log.

For a fully conformant implementation, Transparency Services for Mutual Monitoring MUST implement minimally required API endpoints in the SCITT Reference API specification draft (Birkholz & Geater, 2025).

Append-only Log The foundation of the Transparency Service is the Append-Only Log. The Append-ony Log is a sequence of Signed Statements that completed Registration through the Submission API and are accessible to a Relying Party from the Entry API. The append-only characteristic is integral to providing the integrity of individual Signed Statements, but the sequence itself. To do so, a Transparency Service needs to serialized Signed Statements in the Append-Only Log with a Verifiable Data Structure.

The Verifiable Data Structure, and supporting algorithms, for serializing data MUST use allow only for Append-only updates that do not permit reordering; enforce Non-equivocation for the Append-only Log; and allow Replayability so any Relying Party can consume the Append-only Log's data and check individual Statements or the full sequence (Birkholz et al., 2025). Transparency services instances for mutual monitoring MUST implement the Verifiable Data Structure the IETF COSE Working Group specifies in its draft specification for COSE Receiptis (2025).

Registration Policy API

Submissions API

Entry API

Adjacent Service for Storage

Adjacent Service for Search

Actors and Roles

Flows

Terminology

- Append-only Log: This document uses the normative definition from the IETF SCITT Architecture (Birkholz et al., 2025).
- Equivocation: This document uses the normative definition from the IETF SCITT Architecture (Birkholz et al., 2025).
- Issuer: This document uses the normative definition from the IETF SCITT Architecture (Birkholz et al., 2025).
- Non-equivocation: This document uses the normative definition from the IETF SCITT Architecture (Birkholz et al., 2025).
- Registration This document uses the normative definition from the IETF SCITT Architecture (Birkholz et al., 2025).
- Relying Party: This document uses the normative definition from the IETF SCITT Architecture (Birkholz et al., 2025).
- Replayability: This document uses the normative definition from the IETF SCITT Architecture (Birkholz et al., 2025).
- Signed Statement: This document uses the normative definition from the IETF SCITT Architecture (Birkholz et al., 2025).
- Transparency: This document uses the normative definition from the IETF SCITT Architecture (Birkholz et al., 2025).
- Transparency Service: This document uses the normative definition from the IETF SCITT Architecture (Birkholz et al., 2025).
- Verifiable Data Structure: This document uses the normative definition from the IETF SCITT Architecture (Birkholz et al., 2025).

Appendix

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