

Decentralized Consent Orchestration: A Framework for Auditable, Revocable, and Forward-Compatible Data Sharing in Solid

Abstract

The Solid ecosystem provides a foundation for decentralized data storage and selective sharing, yet managing consent for data access remains challenging due to the complexities of evolving regulations, interoperability across applications, and varying user control requirements. I present Decentralized Consent Orchestration (DCO), a framework for managing, auditing, and revoking consent in Solid environments. DCO extends the current Solid authorization mechanisms with a semantic consent layer that provides fine-grained control over personal data sharing while maintaining regulatory compliance and user autonomy. The framework introduces three key components: 1) a consent vocabulary that bridges legal requirements with technical implementation, 2) a consent receipt infrastructure for auditable data transactions, and 3) a revocation propagation mechanism that ensures consent changes are respected throughout the ecosystem. Evaluation through a prototype implementation and user studies shows that DCO enables more compliant, transparent, and user-friendly data sharing, while reducing implementation complexity for developers integrating with Solid. This work contributes to making Solid a viable infrastructure for personal data spaces that align with emerging regulations like the GDPR, DGA, and EUDI wallet framework.

1 Introduction

The Solid Project [1] offers a promising architectural approach to decentralized personal data management, allowing individuals to store their data in personal online datastores (Pods) and selectively share it with applications and services. This architecture aligns well with emerging regulatory frameworks such as the General Data Protection Regulation (GDPR) [2], the Data Governance Act (DGA) [3], and the European Digital Identity (EUDI) Wallet [4], which emphasize individual control over personal data.

However, implementing effective consent management within Solid remains challenging due to several factors:

1. **Complexity of consent:** Legal frameworks require consent to be specific, informed, unambiguous, and revocable, which is difficult to translate into technical mechanisms.
2. **Interoperability challenges:** As data flows between different applications and services in the Solid ecosystem, consistent application of consent preferences becomes problematic.
3. **Revocation propagation:** When users withdraw consent, ensuring that this withdrawal propagates effectively across all data recipients is technically complex.
4. **Audit requirements:** Regulations increasingly require demonstrable evidence of consent processes, challenging in decentralized environments.

In this paper, I present Decentralized Consent Orchestration (DCO), a framework that addresses these challenges by extending Solid's authorization mechanisms with a semantic consent layer. DCO enables users to express nuanced consent preferences, tracks consent across data flows, simplifies revocation, and generates auditable consent receipts, all while maintaining compatibility with existing Solid specifications.

The primary contributions of this paper are:

1. A formal model for representing and reasoning about consent in decentralized environments that aligns with legal requirements
2. An architecture for consent orchestration that extends Solid's authorization mechanisms
3. A protocol for consent propagation and revocation that ensures changes to consent preferences are respected throughout the ecosystem
4. A mechanism for generating and validating consent receipts that provide auditable evidence of consent processes
5. An evaluation of the framework through a prototype implementation and user studies

2 Related Work

2.1 Consent Management Systems

Existing consent management systems typically focus on centralized environments where a single entity controls both the consent collection and the data processing. Techniques range from simple cookie banners [5] to more sophisticated preference-based systems [6]. However, these approaches are ill-suited for decentralized environments like Solid, where data may flow across multiple independent entities.

In the realm of healthcare data, Advanced Consent Directives [7] offer more granular control but are domain-specific and lack the technical mechanisms for enforcement in open ecosystems.

2.2 Access Control in Solid

Solid's access control mechanisms have evolved from Web Access Control (WAC) [8] to Access Control Policies (ACP) [9]. While these provide means to specify who can access specific resources, they lack the semantics to express the nuances of consent such as purpose limitations, temporal constraints, and conditional processing.

Recent work by Smets et al. [10] and Steffan et al. [11] has explored extending Solid's authorization framework to accommodate regulatory requirements but does not provide a comprehensive solution for consent orchestration across the ecosystem.

2.3 Semantic Web Approaches to Consent

Several ontologies have been proposed to represent consent in semantic web contexts, including GConsent [12] and DPV [13]. These provide valuable vocabularies but lack the operational components needed for dynamic consent management in decentralized systems.

Pandit et al. [14] introduced the Consent Receipt specification, which provides a standardized way to document consent for audit purposes. My work builds on this concept but extends it to operate within Solid's decentralized architecture.

3 Decentralized Consent Orchestration Framework

The DCO framework extends Solid's architecture with components for managing, tracking, and enforcing consent across decentralized data flows. Figure 1 illustrates

the high-level architecture.

3.1 Consent Vocabulary

I develop a consent vocabulary that bridges legal requirements with technical implementation. This vocabulary extends existing ontologies like DPV and GConsent with Solid-specific constructs, enabling the expression of:

- Fine-grained resource specifications using Solid resource paths and patterns
- Purpose limitations that constrain how data can be used
- Temporal constraints defining when consent is valid
- Processing conditions that must be met for data use
- Delegation rules specifying whether recipients can share data further

The vocabulary is formalized in OWL and includes reasoning rules to facilitate automated compliance checking. A simplified example of a consent expression is:

```
@prefix dco: <http://example.org/dco#> .
@prefix solid: <http://www.w3.org/ns/solid/terms#> .
@prefix ex: <http://example.org/> .

ex:consent123 a dco:ConsentRecord ;
  dco:dataSubject <https://alice.pod.example/profile/card#me> ;
  dco:dataController <https://app.example/#controller> ;
  dco:resource <https://alice.pod.example/health/fitness.ttl> ;
  dco:purpose dco:ServiceProvision, ex:FitnessAnalysis ;
  dco:temporalConstraint [
    a dco:TimeConstraint ;
    dco:startTime "2025-01-01T00:00:00Z"^^xsd:dateTime ;
    dco:endTime "2025-12-31T23:59:59Z"^^xsd:dateTime ;
  ] ;
  dco:processingCondition [
    a dco:LocalProcessingOnly ;
  ] ;
  dco:delegation dco:NoDelegation ;
  dco:status dco:Active .
```

3.2 Consent Receipt Infrastructure

DCO implements a consent receipt infrastructure that generates cryptographically verifiable records of consent interactions. When a user grants access to their data, the system:

1. Creates a consent record in the user's Pod
2. Generates a consent receipt signed by the user's key
3. Provides this receipt to the data recipient

The receipt serves multiple purposes:

- It acts as proof of consent for auditing
- It contains the constraints that the recipient must adhere to
- It includes cryptographic elements to prevent tampering

The receipt structure follows:

```
{
  "consentReceiptID": "CR-12345",
  "dataSubject": "https://alice.pod.example/profile/card#me",
  "dataController": "https://app.example/#controller",
  "resources": ["https://alice.pod.example/health/fitness.ttl"],
  "purposes": ["ServiceProvision", "FitnessAnalysis"],
  "conditions": {
    "temporalConstraints": {
      "startTime": "2025-01-01T00:00:00Z",
      "endTime": "2025-12-31T23:59:59Z"
    },
    "processingConstraints": ["LocalProcessingOnly"],
    "delegation": "NoDelegation"
  },
  "timestamp": "2025-01-01T09:30:00Z",
  "signature": {
    "type": "RsaSignature2018",
    "created": "2025-01-01T09:30:00Z",
    "verificationMethod": "https://alice.pod.example/keys/1",
    "signatureValue": "eyJhbGciOiJSUzI1NiIsImI2NCI6ZmFsc2UsImNyaXQiOlsiYjY0Il19..."
  }
}
```

3.3 Consent Enforcement

DCO extends Solid's authorization mechanisms by adding a consent validation layer. When a data request is made, the system:

- 1. Validates the requester's identity
- 2. Checks for a valid consent receipt
- 3. Evaluates the current consent status by checking the user's consent record
- 4. Verifies that the request complies with all consent constraints

This process is implemented through a middleware component that integrates with the Solid server authentication flow. The middleware uses a rule engine to evaluate complex consent conditions and generates detailed logs for audit purposes.

3.4 Revocation Propagation

A key innovation in DCO is its mechanism for propagating consent revocations throughout the ecosystem. When a user revokes consent, the framework:

- 1. Updates the consent record in the user's Pod
- 2. Generates a revocation notification
- 3. Pushes this notification to all affected data recipients
- 4. Tracks acknowledgments to ensure compliance

For cases where direct notification is impossible (e.g., offline recipients), DCO implements a discovery protocol that requires recipients to check consent status before each significant data use.

The revocation propagation uses a WebSocket-based notification system for immediate updates and falls back to HTTP polling for less time-sensitive scenarios.

4 Implementation and Evaluation

4.1 Prototype Implementation

I implemented a DCO prototype as an extension to the Community Solid Server [15]. The implementation consists of:

- 1. A consent management module for the Solid Pod server
- 2. Client libraries for applications to integrate with the consent framework
- 3. A user interface for managing consent preferences

The implementation uses RDF for consent records, JSON-LD for consent receipts, and WebSocket for notification delivery. All components are open-source and available at [repository URL].

4.2 Performance Evaluation

I evaluated the performance impact of adding DCO to a Solid server through benchmark testing. Table 1 shows the results:

Scenario	Without DCO (ms)	With DCO (ms)	Overhead (%)
Resource access (cached consent)	85	92	8.2%
Resource access (consent			

validation) Scenario	85 Without DCO (ms)	118 With DCO (ms)	38.8% Overhead (%)
Consent grant operation	-	156	-
Consent revocation	-	143	-
Notification delivery (per recipient)	-	47	-

The results show that DCO adds modest overhead for resource access when consent status is cached (8.2%) and acceptable overhead for full consent validation (38.8%). Consent management operations themselves show reasonable performance, with grant and revocation operations completing in under 160ms.

4.3 User Study

I conducted a user study with 24 participants to evaluate the usability of the consent management interface and user understanding of the consent mechanisms. Participants completed tasks related to granting, reviewing, and revoking consent for various data sharing scenarios.

Key findings include:

- 87% of participants successfully completed all consent management tasks
- Participants rated the clarity of consent information at 4.2/5 on average
- 79% reported increased confidence in sharing data when using DCO
- The most valued features were granular purpose specification (92%) and easy revocation (88%)
- The main usability challenges related to understanding the implications of different constraint combinations

4.4 Developer Experience

I also evaluated the developer experience through workshops with 10 developers who integrated DCO into Solid applications. Developers completed integration tasks and provided feedback through interviews and surveys.

Findings include:

- 90% reduction in code required to implement GDPR-compliant consent flows
- 70% reduction in time needed to implement revocation functionality
- All developers successfully implemented consent validation checks
- Challenges included handling complex constraint combinations and performance optimization for frequent consent checks

5 Discussion and Limitations

5.1 Legal Compliance Assessment

I conducted a legal analysis with data protection experts to evaluate DCO’s compliance with key regulations. The framework was found to align well with GDPR requirements for consent, particularly Articles 7 (conditions for consent) and 13-14 (information provision). It also supports emerging requirements in the Data Governance Act related to data intermediaries.

However, several limitations were identified:

1. The framework currently lacks specific accommodations for children's data and other special categories requiring enhanced protections
2. Cross-border data transfers require additional mechanisms beyond what DCO currently provides
3. Some edge cases in the eIDAS and EUDI Wallet frameworks may not be fully addressed

5.2 Integration with Existing Solid Ecosystem

DCO is designed to extend rather than replace existing Solid authorization mechanisms. This brings benefits in terms of backward compatibility but also creates challenges:

1. Applications must be updated to take advantage of DCO's enhanced consent features
2. There is some duplication between access control rules and consent constraints
3. Performance optimizations may be needed for large-scale deployments

5.3 Future Work

Based on the evaluation and limitations, several directions for future work emerge:

1. Extending the consent vocabulary to address special data categories and cross-border transfers
2. Further integration with the EUDI Wallet specification to enable portable consent preferences
3. Developing privacy-preserving analytics to help users understand their consent patterns
4. Creating improved visualization tools to make complex consent relationships more understandable
5. Exploring decentralized governance mechanisms for consent policies across communities

6 Conclusion

The Decentralized Consent Orchestration framework addresses a critical gap in the Solid ecosystem by providing comprehensive support for managing, tracking, and enforcing consent in decentralized data sharing scenarios. By extending Solid’s authorization mechanisms with a semantic consent layer, DCO enables more nuanced, auditable, and legally compliant consent processes.

The evaluation demonstrates that the framework adds reasonable performance overhead while significantly improving both user experiences and developer workflows. DCO makes it feasible to implement complex regulatory requirements within the Solid ecosystem, potentially accelerating adoption of Solid as an infrastructure for personal data spaces.

As regulations continue to evolve and personal data sovereignty becomes increasingly important, frameworks like DCO will play a critical role in ensuring that technical implementations can keep pace with legal requirements and user expectations. The open-source implementation provided with this paper offers a starting point for the Solid community to incorporate these capabilities into the ecosystem.

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