The PEACE Protocol[1]

A protocol for transferable encryption rights.

Logical Mechanism LLC[2]

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[1]This project was funded in Fund 14 of Project Catalyst.
[2]Contact: support@logicalmechanism.io

Contents

1 Abstract

In this report, we introduce the PEACE protocol, an ECIES-based, multi-hop, unidirectional proxy re-encryption scheme for the Cardano blockchain. PEACE solves the encrypted-NFT problem by providing a decentralized, open-source protocol for transferable encryption rights, enabling creators, collectors, and developers to manage encrypted NFTs without relying on centralized decryption services. This work fills a significant gap in secure, private access to NFTs on Cardano. Project Catalyst[1] funded the PEACE protocol in round 14.

2 Introduction

The encrypted NFT problem is one of the most significant issues with current NFT standards on the Cardano blockchain. Either the data is not encrypted, available to everyone who views the nft, or the data encryption requires some form of centralization, with some company doing the encryption on behalf of users. Current solutions [1] claim to offer decentralized encrypted assets (DEA), but lack a publicly available, verifiable cryptographic protocol or an open-source implementation. Most, if not all, of the mechanics behind current DEA solutions remain undisclosed. This report aims to fill that knowledge gap by providing an open-source implementation of a decentralized re-encryption protocol for encrypted assets on the Cardano blockchain.

Several mandatory requirements must be satisfied for the protocol to function as intended. The encryption protocol must allow tradability of both the NFT itself and the right to decrypt the NFT data, implying that the solution must involve smart contracts and a form of encryption that allows data access to be re-encrypted for another user without revealing the encrypted content in the process. The contract side of the protocol should be reasonably straightforward. It needs a way to price a token that holds the encrypted data and allows other users to receive it. To ensure decryptability, the tokens may need to be soulbound. On the encryption side of the protocol is some form of encryption that enables the re-encryption process to function correctly. Luckily, this type of encryption has been in cryptography research for quite some time [2] [3] [4]. There are even patented cloud-based solutions already in existence [5]. There is no open-source, fully on-chain, decentralized re-encryption protocol for encrypting NFT data on the Cardano blockchain. The PEACE protocol aims to provide a proof-of-concept solution to this problem.

The PEACE protocol will implement an ambitious yet well-defined, unidirectional, multi-hop proxy re-encryption scheme that utilizes ECIES [6] and AES [7]. Unidirectionality means that Alice can re-encrypt for Bob, and Bob can then re-encrypt it back to Alice, using different encryption keys. Unidirectionality is important for tradability, as it defines the one-way flow of data and removes any restriction on who can purchase the NFT. Multi-hop means that the flow of encrypted data from Alice to Bob to Carol, and so on, does not end, in the sense that it cannot be re-encrypted for a new user. Multi-hopping is important for tradability, as a finitely tradable asset does not fit many use cases. Typically, an asset should always be tradable if the user wants to trade it. The encryption primitives used in the protocol are considered industry standards at the time of this report.

The remainder of this report is as follows. Section 4 discusses the preliminaries and background required for this project. Section 5 will be a brief overview of the required cryptographic primitives. Section 6 will be a detailed description of the protocol. Sections 7, 8, and 9 will delve into security and threat analysis, the limitations of the protocol, and related topics, respectively. The goal of this report is to serve as a comprehensive reference and description of the PEACE protocol.

[1] https://projectcatalyst.io/funds/14/cardano-use-cases-concepts/decentralized-on-chain-data-encryption

3 Background And Preliminaries

Understanding the protocol will require some technical knowledge of modern cryptographic methods, a basic understanding of elliptic curve arithmetic, and a general understanding of smart contracts on the Cardano blockchain. Anyone comfortable with these topics will find this report very useful and easy to follow. The report will attempt to use research standards for terminology and notation. The elliptic curve used in this protocol will be BLS12-381 [8]. Aiken is used to write all required smart contracts for the protocol.

Table 1: Symbol Description [9]

Symbol	Description
p	A prime number
$\mathbb{F}_p$	The finite field with characteristic p
$E(\mathbb{F}_p)$	An elliptic curve E defined over $\mathbb{F}_p$
E'	A twisted elliptic curve
$\#E(\mathbb{F}_p)$	The order of $E(\mathbb{F}_p)$ (also denoted n)
r	A prime number dividing $\#E(\mathbb{F}_p)$
δ	A non-zero integer in $\mathbb{Z}_n$
$\mathcal{O}$	The point at infinity of an elliptic curve E
$\mathbb{G}_1$	A subgroup of order r of $E(\mathbb{F}_p)$
$\mathbb{G}_2$	A subgroup of order r of the twist $E'(\mathbb{F}_{p^2})$
$\mathbb{G}_T$	The multiplicative target group of the pairing: $\mu_r \subset \mathbb{F}_{p^{12}}$
$e : \mathbb{G}_1 \times \mathbb{G}_2 \to \mathbb{G}_T$	A type-3 bilinear pairing
R	The Fiat-Shamir transformer
H_κ	A hash to group function for $\mathbb{G}_\kappa$

The protocol, including both on-chain and off-chain components, will heavily utilize the `Register` type. The `Register` stores a generator, $g \in \mathbb{G}_\kappa$ and the corresponding public value $u = [\delta]g$ where $\delta \in \mathbb{Z}_n$ is a secret. We shall assume that the hardness of ECDLP and CDH in $\mathbb{G}_1$ and $\mathbb{G}_2$ will result in the inability to recover the secret $\delta \in \mathbb{Z}_n$. When using a pairing, we additionally rely on the standard bilinear Diffie-Hellman assumptions over ($\mathbb{G}_1, \mathbb{G}_2, \mathbb{G}_T$). We will represent the groups $\mathbb{G}_1$ and $\mathbb{G}_2$ with additive notation and $\mathbb{G}_T$ with multiplicative notation.

The `Register` type in Aiken:

```
pub type Register {
  // the generator, #<Bls12_381, G1> or #<Bls12_381, G2>
  generator: ByteArray,
  // the public value, #<Bls12_381, G1> or #<Bls12_381, G2>
  public_value: ByteArray,
}
```

Where required, we will verify Ed25519 signatures [10] as a cost-minimization approach; relying solely on pure BLS12-381 for simple signatures becomes costly on-chain. There will be instances where the Fiat-Shamir transform [11] will be applied to a Σ-protocol for non-interactive purposes. In these cases, the hash function will be Blake2b-256 [12].

4 Cryptographic Primitives Overview

This section provides brief explanations of the cryptographic primitives required by the protocol. If a primitive has an algorithmic description, then it should be included in the respective section. The `Register` type will be a tuple, $(\ g, u\ )$, for simplicity inside the algorithms. We shall assume that the decompression of the $\mathbb{G}_1$ points is a given. Proofs for many algorithms are in Appendix A. In any algorithm, $\mathbb{G}_1$ may be switched with $\mathbb{G}_1$ without any required changes.

4.1 Register-based

There may be instances where we need to create a new `Register` from an existing `Register` [13] via a re-randomization. The random integer δ' is considered toxic waste. Randomization allows a public register to remain stealthy, which can be beneficial for data privacy and ownership.

Algorithm 1: Re-randomization of the Register type

Input: $(\ g, u\ )$ where $g \in \mathbb{G}_\kappa$, $u = [\delta]g \in \mathbb{G}_\kappa$
Output: $(\ g', u'\ )$

select a random $\delta' \in \mathbb{Z}_n$
compute $g' = [\delta']g$ and $u' = [\delta']u$
output $(\ g', u'\ )$

The protocol may require proving knowledge of a user's secret using a Schnorr Σ-protocol [14] [15]. This algorithm is both complete and zero-knowledge, precisely what we need in this context. We can use simple Ed25519 signatures for spendability, and then utilize the Schnorr Σ-protocol for knowledge proofs related to encryption. We will make the protocol non-interacting via the Fiat-Shamir transform.

Algorithm 2: Non-interactive Schnorr's Σ-protocol for the discrete logarithm relation

Input: $(\ g, u\ )$ where $g \in \mathbb{G}_\kappa$, $u = [\delta]g \in \mathbb{G}_\kappa$
Output: bool

select a random $\delta' \in \mathbb{Z}_n$
compute $a = [\delta']g$
calculate $c = R(g, u, a)$
compute $z = \delta * c + \delta'$
output $[z]g = a + [c]u$

There will be times when the protocol requires proving some equality using a pairing. In these cases, we can use something akin to the BLS signature, allowing only someone with the knowledge of the secret to prove the pairing equivalence. BLS signatures are a straightforward yet important signature scheme for the protocol, as they enable public confirmation of knowledge of a complex relationship beyond the limitations of Schnorr's Σ-protocol. BLS signatures work because of the bilinearity of the pairing [16].

Algorithm 3: Boneh-Lynn-Shacham (BLS) signature method

Input: $(\ g, u, c, w, m\ )$ where $g \in \mathbb{G}_1$, $u = [\delta]g \in \mathbb{G}_1$, $c = H_2(m) \in \mathbb{G}_2$, $w = [\delta]c \in \mathbb{G}_2$, and $m \in \{0, 1\}^*$
Output: bool

$e(u, c) = e(g, w)$
$e(q^\delta, c) = e(q, c^\delta) = e(q, c)^\delta$

4.2 ECIES + AES-GCM

The Elliptic Curve Integrated Encryption Scheme (ECIES) is a hybrid protocol involving asymmetric cryptography with symmetric ciphers. The encryption used in ECIES is the Advanced Encryption Standard (AES). ECIES and AES, combined with a key derivation function (KDF) such as HKDF [17], form a complete encryption system.

Algorithm 4: Encryption using ECIES + AES

Input: $(\ g, u\ )$ where $g \in \mathbb{G}_\kappa$, $u = [\delta]g \in \mathbb{G}_\kappa$, m as the message
Output: $(\ r, c, h\ )$

select a random $\delta' \in \mathbb{Z}_n$
compute $r = [\delta']g$
compute $s = [\delta']u$
generate $k = KDF(s|r)$
encrypt $c = AES(m, k)$
compute $h = BLAKE2B(m)$
output $(\ r, c, h\ )$

Decrypting the ciphertext requires rebuilding the data encryption key (DEK), k, from the KDF. The DEK is rebuildable because r is public and the user knows the secret δ, allowing them to decrypt the data.

Algorithm 5: Decryption using ECIES + AES

Input: $(\ g, u\ )$ where $g \in \mathbb{G}_1$, $u = [\delta]g \in \mathbb{G}_1$, $(\ r, c, h\ )$ as the cypher text
Output: $(\ \{0,1\}^*, \mathsf{bool}\ )$

compute $s' = [\delta]r$
generate $k' = KDF(s'|r)$
compute $m' = AES(c, k')$
compute $h' = BLAKE2B(m')$
output $(\ m'$, h' = h $)$

Algorithm 4 describes the case where a `Register` is used to generate the DEK, k, from the KDF function. Anyone with knowledge of k may decrypt the ciphertext. The algorithm shown differs slightly from the PEACE protocol, as the protocol allows transferring k to another `Register`; however, the general flow remains the same. The key takeaway here is that encrypting a message and decrypting the ciphertext requires a KDF. Both algorithms 4 and 5 use a simple hash function for authentication. In the PEACE protocol, we will use AES-GCM with authenticated encryption with associated data (AEAD) for authentication.

4.3 Re-Encryption

There are various types of re-encryption schemes, ranging from classical proxy re-encryption to hybrid methods. These re-encryption schemes involve a proxy, an entity that performs the re-encryption process and verification. The PRE used in the PEACE protocol is modeled as an interactive flow between the current owner and a prospective buyer, utilizing a smart contract as part of the proxy. We need an interactive scheme because in many real-world use cases, there are numerous off-chain checks, such as KYC/AML and various legal requirements, that must occur before transferring the decryption rights to the new owner. The PEACE protocol may obtain interactivity in one of two ways, either via an owner signature using classical PRE or via a hybrid method; ultimately, in each case, the current owner must agree to the exchange.

The method described below is a hybrid approach. The current owner's wallet performs the re-encryption of the symmetric content key for the buyer (decapsulation + re-wrapping). At the same time, the Cardano smart contract acts as a proxy, verifying BLS12-381 re-encryption keys, enforcing the correct binding between capsules and ciphertext, and updating the on-chain owner field. This design explicitly supports off-chain processes, such as KYC or contractual agreements, before delegation: the owner only submits the re-encryption transaction once these off-chain conditions are satisfied. This method will allow for the most use cases for real-world assets. This type of method is unidirectional, meaning the re-encryption flow is one-way: from the current owner to the next owner. If Alice delegates to Bob, Bob does not automatically gain the ability to 'go backwards' and create ciphertexts for Alice using the same re-encryption material. This flow differs from a bidirectional method, where the PRE is symmetric, enabling a two-way encryption relationship between the parties. So, Alice can transform a ciphertext into one for Bob, and Bob can transform a ciphertext into one for Alice, without either Alice or Bob having to re-run the entire encryption flow. That is not what we want for this implementation. Each direction is a separate, explicit delegation with its own re-encryption material, matching the tradability requirements.

Note that in the original Catalyst proposal, the protocol defines itself as a bidirectional, multi-hop PRE. However, during the design phase, it became clear that the actual Cardano use case requires a unidirectional, multi-hop PRE. This change is fully compatible with the original proposal's PRE goals (transfer of decryption rights without exposing plaintext or private keys), but reflects the reality of trading tokens via Cardano smart contracts within the PRE landscape.

Algorithm 6: Owner-mediated re-encryption from Alice to Bob

Input: (g, u_A) where $g \in \mathbb{G}_1$, $u_A = [x_A]g \in \mathbb{G}_1$ (Alice's public key),
(u_B, v_B) where $u_B = [x_B]g \in \mathbb{G}_1$, $v_B = [x_B]h \in \mathbb{G}_2$ (Bob's public keys),
$R_{\mathsf{msg}} = [s_{\mathsf{msg}}]g \in \mathbb{G}_1$ (fixed message capsule header),
$k_{\mathsf{msg}} \in \{0,1\}^\lambda$ (symmetric message key already in use),
$\mathsf{tag}_{\mathsf{key}}$ (domain separation tag for key capsules),
Alice's secret key $x_A \in \mathbb{Z}_n$

Output: Bob's key capsule $(R_{\mathsf{key}}, \mathsf{nonce}_{AB}, c_{AB}, \mathsf{aad}_{AB})$ and re-encryption key $\mathsf{rk}_{A\to B}$

select a random $s_{\mathsf{key}} \xleftarrow{\$} \mathbb{Z}_n$
compute $R_{\mathsf{key}} = [s_{\mathsf{key}}]g$
compute $S_{AB} = [s_{\mathsf{key}}]u_B \in \mathbb{G}_1$
compute $\mathsf{kem\_key} = \mathsf{BLAKE2B}(\mathsf{enc}(S_{AB}))$
compute $\mathsf{salt}_{AB} = \mathsf{BLAKE2B}(\mathsf{enc}(R_{\mathsf{key}}) \,\|\, \mathsf{enc}(R_{\mathsf{msg}}) \,\|\, \mathsf{tag}_{\mathsf{key}})$
derive $k_{AB} = \mathsf{HKDF}_{\mathsf{SHA3\text{-}256}}(\mathsf{kem\_key}, \mathsf{salt}_{AB}, \mathsf{tag}_{\mathsf{key}})$
compute $\mathsf{h}_{\mathsf{key}} = \mathsf{BLAKE2B}(\mathsf{enc}(R_{\mathsf{key}}))$ and $\mathsf{h}_{\mathsf{msg}} = \mathsf{BLAKE2B}(\mathsf{enc}(R_{\mathsf{msg}}))$
set $\mathsf{aad}_{AB} = \mathsf{h}_{\mathsf{key}} \,\|\, \mathsf{h}_{\mathsf{msg}} \,\|\, \mathsf{tag}_{\mathsf{key}}$
select a random $\mathsf{nonce}_{AB} \xleftarrow{\$} \{0,1\}^{96}$
encrypt $c_{AB} = \mathsf{AES\text{-}GCM}_{k_{AB}}(k_{\mathsf{msg}}, \mathsf{nonce}_{AB}, \mathsf{aad}_{AB})$
compute $x_A^{-1} \leftarrow x_A^{-1} \bmod n$
compute $\mathsf{rk}_{A\to B} = [x_A^{-1}]v_B \in \mathbb{G}_2$
return $(R_{\mathsf{key}}, \mathsf{nonce}_{AB}, c_{AB}, \mathsf{aad}_{AB}),\ \mathsf{rk}_{A\to B}$

Algorithm 6 describes the actual re-encryption process for Alice, giving the decryption rights to Bob.

5 Protocol Overview

5.1 Design Goals And Requirements

5.2 On-Chain And Off-Chain Architecture

5.3 Key Management And Identity

5.4 Protocol Specification

6 Security Model

6.1 Trust Model

6.1.1 Assumptions

7 Threat Analysis

7.1 Metadata Leakage

8 Limitations And Risks

8.1 Performance And On-Chain Cost

9 Conclusion

A Appendix A - Proofs

Lemma A.1. *Algorithm 1 re-randomizes a* `Register`*.*

Proof. We start with (g, u) where $g \in \mathbb{G}_1$ and $u = [\delta]g \in \mathbb{G}_1$ and we are given (g', u'). Let us assume that $k \in \mathbb{Z}_n$ is a random integer.

Let's assume $g' = [k]g$ and $u' = [k]u$. We know $u = [\delta]g$ so $u' = [k][\delta]g = [\delta][k]g = [\delta]g'$.

Thus the discrete-logrithm relation that binds (g, u), $u = [\delta]g$, is the same relationship between (g', u'), $u' = [\delta]g'$, showing that (g', u') is just the re-randomization of (g, u).

□

Lemma A.2. *Correctness for Algorithm 2, a non-interactive Schnorr's Σ-protocol for the discrete logarithm relation.*

Proof. We start with (g, u, a, z) where $g \in \mathbb{G}_1$, $u = [\delta]g \in \mathbb{G}_1$, $a \in \mathbb{G}_1$, and $z \in \mathbb{Z}_n$. Let us assume that $z = r + c * \delta$ and $a = [r]g$.

Use the Fiat-Shamir transform to generate a challenge value $c = R(g, u, a)$.

$[z]g = [r + c * x]g$

$[z]g = [r]g + [c][x]g$

$[z]g = a + [c]u$

An honest `Register` can produce an a and z that will satisfy $[z]g = a + [c]u$ proving knowledge of the secret $/delta$.

□

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