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, bidirectional 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 fund 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, 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 actual implementation for current DEA solutions remain unavailable to the public. 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.

There are several requirements 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 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. The contract needs a way to price some the token where the datum holds the encrypted data and allow other users to purchase the token. To ensure decryptability, the tokens will need to be soulbound. On the encryption side of the protocol is some form of encryption that enables the process of re-encrypting the data 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 solve this problem.

The PEACE protocol will implement an ambitious yet well-defined, bidirectional, multi-hop re-encryption scheme that utilizes ECIES [6] and AES [7]. Bidirectionality means that Alice can re-encrypt for Bob, and Bob can then re-encrypt back to Alice. Bidirectionality is important for tradability, as there should be no 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 the data cannot be re-encrypted for some new user. Multi-hopping is also 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 mechanisms 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 the security and threat analysis, and the limitations of the protocol, 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 Cardano. 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 [9] is used to write all required smart contracts for the protocol.

Table 1: Symbol Description [10]

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, both the on-chain and off-chain components, will make heavy use of 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 [11] as a cost-minimization approach; relying solely on pure BLS12-381 for simple signatures becomes too costly on-chain. There will be instances where the Fiat-Shamir transform [12] will be applied to a Σ-protocol for non-interactive purposes. In these cases, the hash function will be the Blake2b-256 hash function [13].

4 Cryptographic Primitives Overview

This section provides brief explanations of the cryptographic primitives required by the protocol. Where applicable, an algorithm describing the primitives will be in its respective algorithm segment. The `Register` type will be a tuple, $(\ g, u\ )$, for simplicity inside the algorithms. We shall assume that the decompression of the $\mathbb{G}_1$ and $\mathbb{G}_1$ points are a given. Proofs for many algorithms are in Appendix A. In any algorithm, either $\mathbb{G}_1$ or $\mathbb{G}_2$ may be used in the algorithm.

There may be instances where we need to create a new `Register` from an existing `Register` [14] 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: $(\ g', u'\ )$

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

The protocol may require proving knowledge of a user's secret using a Schnorr Σ-protocol [15] [16]. This algorithm is both complete and zero-knowledge, precisely what we need in this context. When combined with Ed25519 signatures for spendability, the Schnorr Σ-protocol can then be used for knowledge proofs related to the re-encryption process. We will make the Schnorr Σ-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

1 select a random $\delta' \in \mathbb{Z}_n$
2 compute $a = [\delta']g$
3 calculate $c = R(g, u, a)$
4 compute $z = \delta * c + \delta'$
5 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 [17] of the pairing.

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

1 $e(u, c) = e(g, w)$
2 $e(q^\delta, c) = e(q, c^\delta) = e(q, c)^\delta$

4.1 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 [18], 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 secret δ is known to the user, who can then 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: ($\{0,1\}^*$,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`, but the general flow is the same. The key takeaway here is that a KDF is required to both encrypt a message and decrypt the ciphertext. 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.

4.2 Re-Encryption

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 $u_B \in \mathbb{G}_1$, $v_B = [x_B]h \in \mathbb{G}_2$ (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 $\mathsf{kem\_key} = \mathsf{BLAKE2B}(S_{AB})$
compute $\mathsf{salt}_{AB} = \mathsf{BLAKE2B}(R_{\mathsf{key}} \,\|\, R_{\mathsf{msg}} \,\|\, \mathsf{tag}_{\mathsf{key}})$
derive $k_{AB} = \mathsf{HKDF}(\mathsf{kem\_key}, \mathsf{salt}_{AB}, \mathsf{tag}_{\mathsf{key}})$
compute $\mathsf{h}_{\mathsf{key}} = \mathsf{BLAKE2B}(R_{\mathsf{key}})$ and $\mathsf{h}_{\mathsf{msg}} = \mathsf{BLAKE2B}(R_{\mathsf{msg}})$
set $\mathsf{aad}_{AB} = \mathsf{h}_{\mathsf{key}} \,\|\, \mathsf{h}_{\mathsf{msg}} \,\|\, \mathsf{tag}_{\mathsf{key}}$
select a random $\mathsf{nonce}_{AB} \in \{0,1\}^{96}$
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 $(R_{\mathsf{key}}, \mathsf{nonce}_{AB}, c_{AB}, \mathsf{aad}_{AB})$, $\mathsf{rk}_{A\to B}$

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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