FIDO ECDAA Algorithm

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The English version of this specification is the only normative version. Non-normative translations may also be available.

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Abstract

The FIDO Basic Attestation scheme uses attestation "group" keys shared across a set of authenticators with identical characteristics in order to preserve privacy by avoiding the introduction of global correlation handles. If such an attestation key is extracted from one single authenticator, it is possible to create a "fake" authenticator using the same key and hence indistinguishable from the original authenticators by the relying party. Removing trust for registering new authenticators with the related key would affect the entire set of authenticators sharing the same "group" key. Depending on the number of authenticators, this risk might be unacceptable high.

This is especially relevant when the attestation key is primarily protected against malware attacks as opposed to targeted physical attacks.

An alternative approach to "group" keys is the use of individual keys combined with a Privacy-CA [TPMv1-2-Part1]. Translated to FIDO, this approach would require one Privacy-CA interaction for each Uauth key. This means relatively high load and high availability requirements for the Privacy-CA. Additionally the Privacy-CA aggregates sensitive information (i.e. knowing the relying parties the user interacts with). This might make the Privacy-CA an interesting attack target.

Another alternative is the Direct Anonymous Attestation [BriCamChe2004-DAA]. Direct Anonymous Attestation is a cryptographic scheme combining privacy with security. It uses the authenticator specific secret once to communicate with a single DAA Issuer and uses the resulting DAA credential in the DAA-Sign protocol with each relying party. The DAA scheme has been adopted by the Trusted Computing Group for TPM v1.2 [TPMv1-2-Part1].

In this document, we specify the use of an improved DAA scheme based on elliptic curves and bilinear pairings largely compatible with [CheLi2013-ECDAA] called ECDAA. This scheme provides significantly
improved performance compared with the original DAA and basic building blocks for its implementation are part of the TPMv2 specification [TPMv2-Part1].

Our improvements over [CheLi2013-ECDA] mainly consist of security fixes (see [ANZ-2013] and [XYZF-2014]) when splitting the sign operation into two parts.

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1. Notation

Type names, attribute names and element names are written as code.

String literals are enclosed in """, e.g. “ED256”.

In formulas we use “|” to denote byte wise concatenation operations.

\[ X = P^x \] denotes scalar multiplication (with scalar x) of a (elliptic) curve point P.

RAND(x) denotes generation of a random number between 0 and x-1.

RAND(G) denotes generation of a random number belonging to Group G.

Specific terminology used in this document is defined in [FIDO Glossary].

The type BigNumber denotes an arbitrary length integer value.

The type ECPoint denotes an elliptic curve point with its affine coordinates x and y.

The type ECPoint2 denotes a point on the sextic twist of a BN elliptic curve over \( \mathbb{F}(q^2) \). The ECPoint2 has two affine coordinates each having two components of type BigNumber.

1.1 Conformance

As well as sections marked as non-normative, all authoring guidelines, diagrams, examples, and notes in this specification are non-normative. Everything else in this specification is normative.

The key words must, must not, required, should, should not, recommended, may, and optional in this specification are to be interpreted as described in [RFC2119].

2. Overview

This section is non-normative.

FIDO uses the concept of attestation to provide a cryptographic proof of the authenticator [FIDO Glossary] model to the relying party. When the authenticator is registered to the relying party (RP), it generates a new authentication key pair and includes the public key in the attestation message (also known as key registration data object, KRD). When using the ECDAA algorithm, the KRD object is signed using 3.5 ECDAA-Sign.

For privacy reasons, the authentication key pair is dedicated to one RP (to an application identifier ApplID [FIDO Glossary] to be more specific). Consequently the attestation method needs to provide the same level of unlinkability. This is the reason why the FIDO ECDAA Algorithm doesn't use a basename (bsn) often found in other direct anonymous attestation algorithms, e.g. [BriCamChe2004-DAA] or [BFGSW-2011].

The authenticator encapsulates all user verification operations and cryptographic functions. An authenticator specific module (ASM) [FIDO Glossary] is used to provide a standardized communication interface for authenticators. The authenticator might be implemented in separate hardware or trusted execution environments. The ASM is assumed to run in the normal operating system (e.g. Android, Windows, ...).

2.1 Scope

This document describes the FIDO ECDAA attestation algorithm in detail.

2.2 Architecture Overview
ECDAA attestation defines **global system parameters** and **issuer specific parameters**. Both parameter sets need to be installed on the host, in the authenticator and in the FIDO Server. The ECDAA method consists of two steps:

- **ECDAA-Join** to be performed before the first FIDO Registration
  - \( n = \text{GetNonceFromECDAAIssuer()} \)
  - \((Q, c_1, s_1) = \text{EcdaaJoin1}(X, Y, n)\)
  - \((A, B, C, D, s_2, c_2) = \text{EcdaaIssuerJoin}(Q, c_1, s_1)\)
  - \(\text{EcdaaJoin2}(A, B, C, D, c_2, s_2) \) // store \( \text{cre} = (A, B, C, D) \)
- and the pair of **ECDAA-Sign** performed by the authenticator and **ECDAA-Verify** performed by the FIDO Server as part of the FIDO Registration.
  - Client: Attestation = \( (\text{signature}, \text{KRD}) = \text{EcdaaSign(AppID)} \)
  - Server: success=\( \text{EcdaaVerify}(\text{signature}, \text{KRD}, \text{AppID}) \)

The technical implementation details of the ECDAA-Join step are out-of-scope for FIDO. In this document we normatively specify the general algorithm to the extent required for interoperability and we outline examples of some possible implementations for this step.

The ECDAA-Sign and ECDAA-Verify steps and the encoding of the related ECDAA Signature are normatively specified in this document. The generation and encoding of the KRD object is defined in other FIDO specifications.

The algorithm and terminology are inspired by [BFGSW-2011]. The algorithm was modified in order to fix security weaknesses (e.g. as mentioned by [ANZ-2013] and [XYZF-2014]). Our algorithm proposes an improved task split for the sign operation while still being compatible to TPMv2 (without fixing the TPMv2 weaknesses in such case).

# 3. FIDO ECDAA Attestation

*This section is normative.*

## 3.1 Object Encodings

We need to convert **BigNumber** and **ECPoint** objects to byte strings using the following encoding functions:

### 3.1.1 Encoding **BigNumber** values as byte strings (BigNumberToB)

We use the I2OSP algorithm as defined in [RFC3447] for converting big numbers to byte arrays. The bytes from the big endian encoded (non-negative) number \( n \) will be copied right-aligned into the buffer area \( b \). The unused bytes will be set to 0. Negative values will not occur due to the construction of the algorithms.

**EXAMPLE 1:** Converting \( \text{BigNumber} n \) to byte string \( b \)

\[
\begin{array}{cccccccc}
0 & 0 & n0 & n1 & n2 & n3 & n4 & n5 \\
\end{array}
\]

The algorithm implemented in Java looks like this:

**EXAMPLE 2:** Algorithm for converting \( \text{BigNumber} \) to byte strings

```java
ByteArray BigNumberToB(
    BigNumber inVal, // IN: number to convert
    int size         // IN: size of the output.
) {
    ByteArray buffer = new ByteArray(size);
    int oversize = size - inVal.length;
    if (oversize < 0)
        return null;
    for (int i=oversize; i > 0; i--)
        buffer[i] = 0;
    ByteCopy( inVal.bytes, &buffer[oversize], inVal.length);
    return buffer;
}
```

### 3.1.2 Encoding **ECPoint** values as byte strings (ECPointToB)

3.1.2 Encoding **ECPoint** values as byte strings (ECPointToB)
We use the ANSI X9.62 Point-to-Octet-String [ECDSA-ANSI] conversion using the expanded format, i.e. the format where the compression byte (i.e. 0x04 for expanded) is followed by the encoding of the affine x coordinate, followed by the encoding of the affine y coordinate.

**EXAMPLE 3:** Converting ECPoint P to byte string

\[
(x, y) = \text{ECPointGetAffineCoordinates}(P) \\
\text{len} = G1.\text{byteLength} \\
\text{byte string} = 0x04 \mid \text{BigIntegerToB}(x, \text{len}) \mid \text{BigIntegerToB}(y, \text{len})
\]

3.1.3 Encoding ECPoint2 values as byte strings (ECPoint2ToB)

The type ECPoint2 denotes a point on the sextic twist of a BN elliptic curve over \(\mathbb{F}(q^2)\), see section 4.1 Supported Curves for ECDAA. Each ECPoint2 is represented by a pair \((a, b)\) of elements of \(\mathbb{F}(q)\).

The group zero element is always encoded (using the encoding rules as described below) as a an element having all components set to zero (i.e. \(cx.a=0, cx.b=0, cy.a=0, cy.b=0\)).

We always assume normalized (non-zero) ECPoint2 values (i.e. \(cz = 1\)) before encoding them. Non-zero values are encoded using the expanded format (i.e. 0x04 for expanded) followed by the \(cx\) followed by the \(cy\) value. This leads to the concatenation of 0x04 followed by the first element \((cx.a)\) and second element \((cx.b)\) of the pair of \(cx\) followed by the first element \((cy.a)\) and second element \((cy.b)\) of the pair of \(cy\). All individual numbers are padded to the same length (i.e. the maximum byte length of all relevant 4 numbers).

**EXAMPLE 4:** Converting ECPoint2 P2 to byte string

\[
(cx, cy) = \text{ECPointGetAffineCoordinates}(P2) \\
\text{len} = G2.\text{byteLength} \\
\text{byte string} = 0x04 \mid \text{BigIntegerToB}(cx.a, \text{len}) \mid \text{BigIntegerToB}(cx.b, \text{len}) \\
\mid \text{BigIntegerToB}(cy.a, \text{len}) \mid \text{BigIntegerToB}(cy.b, \text{len})
\]

3.2 Global ECDAA System Parameters

1. Groups \(G_1, G_2\) and \(G_T\) of sufficiently large prime order \(p\)
2. Two generators \(P_1\) and \(P_2\), such that \(G_1 = \langle P_1 \rangle\) and \(G_2 = \langle P_2 \rangle\)
3. A bilinear pairing \(e: G_1 \times G_2 \rightarrow G_T\). We propose the use of "ate" pairing (see [BarNae-2006]). For example source code on this topic, see [BNPairings].
4. Hash function \(H\) with \(H: \{0,1\}^* \rightarrow Z_p\).
5. \((G_1, P_1, p, H)\) are installed in all authenticators implementing FIDO ECDAA attestation.

**Definition of \(G_1, G_2, G_T, Pairings\) and hash function\(H**

See section 4.1 Supported Curves for ECDAA.

3.3 Issuer Specific ECDAA Parameters

Issuer Parameters pari

1. Randomly generated issuer private key \(isk = (x, y)\) with \([x, y = RAND(p)]\).
2. Issuer public key \((X, Y)\), with \(X = P_2^x\) and \(Y = P_2^y\).
3. A proof that the issuer key was correctly computed
   1. BigInteger \(r_x = RAND(p)\)
   2. BigInteger \(r_y = RAND(p)\)
   3. ECPoint2 \(U_x = P_2^{r_x}\)
   4. ECPoint2 \(U_y = P_2^{r_y}\)
   5. BigInteger \(c = H(U_x \mid U_y \mid P_2 \mid X \mid Y)\)
6. BigInteger \( s_x = r_x + c \cdot x \pmod{p} \)
7. BigInteger \( s_y = r_y + c \cdot y \pmod{p} \)
4. \( ipk = X, Y, c, s_x, s_y \)

Whenever a party uses ipk for the first time, it must first verify that it was correctly generated:

\[
H(P_x \cdot X^{-c} | P_y \cdot Y^{-c} | P_2 | X | Y) = c
\]

**NOTE**

\[
P_x \cdot X^{-c} = P_x^{r_x + cx} \cdot P_2^{-cx} = P_x^{r_x} = U_x
\]

\[
P_y \cdot Y^{-c} = P_y^{r_y + cy} \cdot P_2^{-cy} = P_y^{r_y} = U_y
\]

The ECDAA-Issuer public key ipk must be dedicated to a single authenticator model.

### 3.4 ECDAA-Join

**NOTE**

One ECDAA-Join operation is required once in the lifetime of an authenticator prior to the first registration of a credential.

In order to use ECDAA, the authenticator must first receive ECDAA credentials from an ECDAA-Issuer. This is done by the ECDAA-Join operation. This operation needs to be performed a single time (before the first credential registration can take place). After the ECDAA-Join, the authenticator will use the ECDAA-Sign operation as part of each FIDO Registration. The ECDAA-Issuer is not involved in this step. ECDAA plays no role in FIDO Authentication / Transaction Confirmation operations.

In order to use ECDAA, (at least) one ECDAA-Issuer is needed. The approach specified in this document easily scales to multiple ECDAA-Issuers, e.g. one per authenticator vendor. FIDO lets the authenticator vendor choose any ECDAA-Issuer (similar to his current freedom for selecting any PKI infrastructure/service provider to issuing attestation certificates required for FIDO Basic Attestation).

- All ECDAA-Join operations (of the related authenticators) are performed with one of the ECDAA-Issuer entities.
- Each ECDAA-Issuer has a set of public parameters, i.e. ECDAA public key material. The related Attestation Trust Anchor is contained in the metadata of each authenticator model identified by its AAGUID.

There are two different implementation options relevant for the authenticator Vendors (the authenticator vendor can freely choose them):

1. In-Factory ECDAA-Join
2. Remote ECDAA-Join and

In the first case, physical proximity is used to locally establish the trust between the ECDAA-Issuer and the authenticator (e.g. using a key provisioning station in a production line). There is no requirement for the ECDAA-Issuer to operate an online web service.

In the second case, some credential is required to remotely establish the trust between the ECDAA-Issuer and the authenticator. As this operation is performed once and only with a single ECDAA-Issuer, privacy is preserved and an authenticator specific credential can and should be used.

Not all ECDAA authenticators might be able to add their authenticator model IDs (e.g. AAGUID) to the registration assertion (e.g. TPMS). In all cases, the ECDAA-Issuer will be able to derive the exact authenticator model from either the credential or the physically proximate authenticator. So the ECDAA-Issuer root key must be dedicated to a single authenticator model.
3.4.1 ECDAA-Join Algorithm

This section is normative.

NOTE
If this join is not in-factory, the value Q must be authenticated by the authenticator. Upon receiving this value, the issuer must verify that this authenticator did not join before.

1. The authenticator asks the issuer for a nonce.
2. The issuer chooses a nonce BigInteger \( n = RAND(p) \) and sends \( n \) via the ASM to the authenticator.
3. The authenticator chooses and stores the ECDAA private key BigInteger \( sk = RAND(p) \)
4. The authenticator computes its ECDAA public key ECPoint \( Q = P_1^{sk} \)
5. The authenticator proves knowledge of \( sk \) as follows
   1. BigInteger \( r_1 = RAND(p) \)
   2. ECPoint \( U_1 = P_1^{r_1} \)
   3. BigInteger \( c_1 = H(U_1|P_1|Q|n) \)
   4. BigInteger \( s_1 = r_1 + c_1 \cdot sk \)
6. The authenticator sends \( Q, c_1, s_1 \) via the ASM to the issuer
7. The issuer verifies that the authenticator is "authentic" and that \( Q \) was indeed generated by the authenticator. In the case of an in-factory Join, this might be trivial; in the case of a remote Join this typically requires the use of other cryptographic methods. Since ECDAA-Join is a one-time operation, unlinkability is not a concern for that.
8. The issuer verifies that \( Q \in G_1 \) and verifies \( H(P_1^{r_1} \cdot Q^{-c_1}|P_1|Q|n) = c_1 \) (check proof-of-possession of private key).

NOTE
\[ P_1^{r_1} \cdot Q^{-c_1} = P_1^{r_1} + c_1sk \cdot Q^{-c_1} = P_1^{r_1} + c_1sk \cdot P_1^{-c_1}sk = P_1^{r_1} = U_1 \]

9. The issuer creates credential \((A, B, C, D)\) as follows
   1. BigInteger \( l_J = RAND(p) \)
   2. ECPoint \( A = P_1^{l_J} \)
   3. ECPoint \( B = A^y \)
   4. ECPoint \( C = A^x \cdot Q^{y l_J} \)
   5. ECPoint \( D = Q^{l_J y} \)
10. The issuer proves that it computed this credential correctly:
    1. BigInteger \( r_2 = RAND(p) \)
    2. ECPoint \( U_2 = P_1^{r_2} \)
    3. ECPoint \( V_2 = Q^{r_2} \)
    4. BigInteger \( c_2 = H(U_2|V_2|P_1|B|Q|D) \)
    5. BigInteger \( s_2 = r_2 + c_2 \cdot l_J \cdot y \)
11. The issuer sends \( A, B, C, D, c_2, s_2 \) to the authenticator.
12. The authenticator checks that \( A, B, C, D \in G_1 \) and \( A \neq 1_{G_1} \)
The authenticator checks \( H(P_{1}^{s_{2}} \cdot B^{-c_{2}} | Q_{2}^{s_{2}} \cdot D^{-c_{2}} | P_{1} | B | Q | D) = c_{2} \)

\[ P_{1}^{s_{2}} \cdot B^{-c_{2}} = P_{1}^{s_{2}} \cdot P_{1}^{s_{2}lJy} \cdot B^{-c_{2}} = U_{2} \cdot B^{c_{2}} \cdot B^{-c_{2}} = U_{2} \]
\[ Q_{2}^{s_{2}} \cdot D^{-c_{2}} = Q_{2}^{s_{2}} \cdot Q_{2}^{s_{2}lJy} \cdot D^{-c_{2}} = V_{2} \cdot D^{c_{2}} \cdot D^{-c_{2}} = V_{2} \]

The authenticator checks \( e(A, Y) = e(B, P_{2}) \)

\[ e(A, Y) = e(P_{1}^{lJy}, P_{2}^{lJy}); \ e(B, P_{2}) = e(A^{y}, P_{2}) = e(P_{1}^{lJy}, P_{2}) \]

and the authenticator checks \( e(C, P_{2}) = e(A \cdot D, X) \)

\[ e(C, P_{2}) = e(A^{x} \cdot Q_{x}^{y}lJ, P_{2}^{lJy}); \ e(A \cdot D, X) = e(A \cdot Q_{x}^{y}lJ, P_{2}^{lJy}) \]

The authenticator stores credential \( A, B, C, D \)

### 3.4.2 ECDAA-Join Split between Authenticator and ASM

*This section is non-normative.*

If this join is not in-factory, the value \( Q \) must be authenticated by the authenticator. Upon receiving this value, the issuer must verify that this authenticator did not join before.

1. The ASM asks the issuer for a nonce.
2. The issuer chooses a nonce BigInteger \( n = RAND(p) \) and sends \( n \) to the ASM.
3. The ASM forwards \( n \) to the authenticator.
4. The authenticator chooses and stores the private key BigInteger \( sk = RAND(p) \).
5. The authenticator computes its ECDAA public key ECPoint \( Q = P_{1}^{sk} \).
6. The authenticator proves knowledge of \( sk \) as follows
   1. BigInteger \( r_{1} = RAND(p) \)
   2. ECPoint \( U_{1} = P_{1}^{r_{1}} \)
   3. BigInteger \( c_{1} = H(U_{1} | P_{1} | Q | n) \)
   4. BigInteger \( s_{1} = r_{1} + c_{1} \cdot sk \)
7. The authenticator sends \( Q, c_{1}, s_{1} \) to the ASM, who forwards it to the issuer.
8. The issuer verifies that the authenticator is "authentic" and that \( Q \) was indeed generated by the
authenticator. In the case of an in-factory Join, this might be trivial; in the case of a remote Join this typically requires the use of other cryptographic methods. Since ECDAA-Join is a one-time operation, unlinkability is not a concern for that.

9. The issuer verifies that \( Q \in G_1 \) and verifies \( H(P_1^{P_i} \cdot Q^{-c_1} | P_1 | Q | n) = c_1 \).

10. The issuer creates credential \( (A, B, C, D) \) as follows
   1. \( \text{BigInteger} \ l_J = RAND(p) \)
   2. \( \text{ECPoint} \ A = P_1^{l_J} \)
   3. \( \text{ECPoint} \ B = A^y \)
   4. \( \text{ECPoint} \ C = A^x \cdot Q^{y_J} \)
   5. \( \text{ECPoint} \ D = Q^{l_J y} \)

11. The issuer proves that it computed this credential correctly:
   1. \( \text{BigInteger} \ r_2 = RAND(p) \)
   2. \( \text{ECPoint} \ U_2 = P_1^{r_2} \)
   3. \( \text{ECPoint} \ V_2 = Q^{r_2} \)
   4. \( \text{BigInteger} \ c_2 = H(U_2 | V_2 | P_1 | B | Q | D) \)
   5. \( \text{BigInteger} \ s_2 = r_2 + c_2 \cdot l_J \cdot y \)

12. The issuer sends \( A, B, C, D, c_2, s_2 \) to the ASM. The issuer authenticates \( B, D, c_2, s_2 \) such that the authenticator can verify they were created by the issuer.

13. The ASM checks that \( A, B, C, D \in G_1 \) and \( A \neq 1_{G_1} \).

14. The ASM checks \( H(P_1^{r_2} \cdot B^{-c_2} | Q^{r_2} \cdot D^{-c_2} | P_1 | B | Q | D) = c_2 \).

15. The ASM checks \( e(A, Y) = e(B, P_2) \).

16. and the ASM checks that \( e(C, P_2) = e(A \cdot D, X) \).

17. The ASM stores \( A, B, C, D \) and sends \( B, D, c_2, s_2 \) to the authenticator.

18. The authenticator checks \( B, D \in G_1 \) and \( B \neq 1_{G_1} \) and verifies that \( B, D, c_2, s_2 \) were sent by the issuer.

19. The authenticator checks \( H(P_1^{s_2} \cdot B^{-c_2} | Q^{s_2} \cdot D^{-c_2} | P_1 | B | Q | D) = c_2 \).

20. The authenticator stores \( B, D \) and ignores further join requests.

**NOTE**

These values belong to the ECDAA secret key \( sk \). They should persist even in the case of a factory reset.

### 3.4.3 ECDAA-Join Split between TPM and ASM

*This section is non-normative.*

**NOTE**

The Endorsement key credential (EK-C) and TPM2_ActivateCredentials are used for supporting the remote Join.
This description is based on the principles described in [TPMv2-Part1] section 24 and [Arthur-Challener-2015], page 109 ("Activating a Credential").

1. The ASM asks the ECDAA Issuer for a nonce.
2. The ECDAA Issue chooses a nonce BigInteger \( n = \text{RAND}(p) \) and sends \( n \) to the ASM.
3. The ASM
   1. instructs the TPM to create a restricted key by calling TPM2_Create, giving the public key template TPMT_PUBLIC [TPMv2-Part2] (including the public key \( Q \) in field \( \text{unique} \)) to the ASM.
   2. retrieves TPM Endorsement Key Certificate (EK-C) from the TPM
   3. calls TPM2_Commit(keyhandle, P1, s2, y2) where keyhandle is the handle of the restricted key generated before (see above), P1 is set to \( P_1 \), and s2 and y2 are left empty. This call returns K, L, E, and \( \text{ctr} \); where K and L will be empty.
4. computes BigInteger \( c_1 = H(E|P_1|Q|n) \)
5. call TPM2_Sign\( (c_1, \text{ctr}) \), returning \( s_1 \).
6. sends EK-C, TPMT_PUBLIC (including \( Q \) in field \( \text{unique} \)), \( c_1, s_1 \) to the ECDAA Issuer.
4. The ECDAA Issuer
   1. verifies EK-C and its certificate chain. As a result the ECDAA Issuer knows the TPM model related to EK-C.
   2. verifies that this EK-C was not used in a (successful) Join before
   3. Verifies that the objectAttributes in TPMT_PUBLIC [TPMv2-Part2] matches the following flags:
      \( \text{fixedTPM} = 1; \text{fixedParent} = 1; \text{sensitiveDataOrigin} = 1; \text{encryptedDuplication} = 0; \text{restricted} = 1; \text{decrypt} = 0; \text{sign} = 1. \)
4. examines the public key Q, i.e. it verifies that \( Q \in G_1 \)
5. checks \( H(P_1^c_1 \cdot Q^{-c_1} | P_1 | Q | n) = c_1 \)
6. generates the ECDAA credential\( (A, B, C, D) \) as follows
   1. BigInteger \( l_J = \text{RAND}(p) \)
   2. ECPoint \( A = P_1^l_J \)
   3. ECPoint \( B = A^y \)
   4. ECPoint \( C = A^x \cdot Q^{y \cdot l_J} \)
   5. ECPoint \( D = Q^{l_J \cdot y} \)
7. proves that it computed this credential correctly:
   1. BigInteger \( r_2 = \text{RAND}(p) \)
   2. ECPoint \( U_2 = P_1^r_2 \)
   3. ECPoint \( V_2 = Q^r_2 \)
   4. BigInteger \( c_2 = H(U_2 | V_2 | P_1 | B | Q | D) \)
   5. BigInteger \( s_2 = r_2 + c_2 \cdot l_J \cdot y \)
8. generates a secret (derived from a seed) and wraps the credential\( A, B, C, D \) using that secret.
9. encrypts the seed using the public key included in EK-C.
10. uses seed and name in KDFa (see [TPMv2-Part2] section 24.4) to derive HMAC and symmetric encryption key. Wrap the secret in symmetric encryption key and protect it with the HMAC key.

**NOTE**

The parameter name in KDFa is derived from TPMT_PUBLIC, see [TPMv2-Part1], section 16.

11. sends the credential proof\( c_2, s_2 \) and the wrapped object including the credential from previous
5. The ASM instructs the TPM (by calling TPM2_ActivateCredential) to
   1. decrypt the seed using the TPM Endorsement key
   2. compute the name (for the ECDAA attestation key)
   3. use the seed in KDFa (with name) to derive the HMAC key and the symmetric encryption key.
   4. use the symmetric encryption key to unwrap the secret.

6. The ASM
   1. unwraps the credential $A, B, C, D$ using the secret received from the TPM.
   2. checks that $A, B, C, D \in G_1$ and $A \neq 1_{G_1}$
   3. checks $H(P_1^{2c_1} \cdot B^{-c_2} \cdot Q_2^{2} \cdot D^{-c_2} \cdot P_1 \cdot B \cdot Q \cdot D) = c_2$
   4. checks $e(A, Y) = e(B, P_2)$ and $e(C, P_2) = e(A \cdot D, X)$
   5. stores $A, B, C, D$

3.5 ECDAA-Sign

NOTE

One ECDAA-Sign operation is required for the client-side environment whenever a new credential is being registered at a relying party.

3.5.1 ECDAA-Sign Algorithm

This section is normative.

$(\text{signature, KRD}) = \text{EcdaaSign(String AppID)}$

Parameters

- $p$: System parameter prime order of group $G_1$ (global constant)
- AppID: FIDO AppID (i.e. https-URL of TrustedFacets object)

Algorithm outline

1. KRD = BuildAndEncodeKRD(); // all traditional Registration tasks are here
2. BigNumber $l = \text{RAND}(p)$
3. ECPoint $R = A^l$;
4. ECPoint $S = B^l$;
5. ECPoint $T = C^l$;
6. ECPoint $W = D^l$;
7. BigInteger $r = \text{RAND}(p)$
8. ECPoint $U = S^r$
9. BigInteger $c = H(U \| S \| W \| \text{AppID} \| H(KRD))$
10. BigInteger $s = r + c \cdot sk \pmod{p}$
11. signature = $(c, s, R, S, T, W)$
12. return (signature, KRD)

3.5.2 ECDAA-Sign Split between Authenticator and ASM

This section is non-normative.
Algorithm outline

1. The ASM randomizes the credential
   1. BigNumber $l = RAND(p)$
   2. ECPoint $R = A^l$
   3. ECPoint $S = B^l$
   4. ECPoint $T = C^l$
   5. ECPoint $W = D^l$
2. The ASM sends $l, AppID$ to the authenticator
3. The authenticator performs the following tasks
   1. KRD = BuildAndEncodeKRD(); // all traditional Registration tasks are here
   2. ECPoint $S’ = B^l$
   3. ECPoint $W’ = D^l$
   4. BigInteger $r = RAND(p)$
   5. ECPoint $U = S’$
   6. BigInteger $c = H(U | S’ | W’ | AppID | H(KRD))$
   7. BigInteger $s = r + c \cdot sk \pmod{p}$
   8. Send $c, s, KRD$ to the ASM
4. The ASM sets signature = $(c, s, R, S, T, W)$ and outputs $(signature, KRD)$

3.5.3 ECDAA-Sign Split between TPM and ASM

This section is non-normative.

NOTE

This split requires both the authenticator and ASM to be honest to achieve anonymity. Only the authenticator must be trusted for unforgeability. The communication between ASM and authenticator must be secure.

NOTE

This algorithm is for the special case of a TPMv2 as authenticator. This case requires both the TPM and ASM to be honest for anonymity and unforgeability (see [XYZF-2014]).
3.6 ECDAA-Verify Operation

This section is normative.

NOTE
One ECDAA-Verify operation is required for the FIDO Server as part of each FIDO Registration.

boolean EcdaaVerify(signature, AppID, KRD, ModelName)

Parameters

- \( p \): System parameter prime order of group \( G_1 \) (global constant)
- \( P_2 \): System parameter generator of group \( G_2 \) (global constant)
- signature: \((c, s, R, S, T, W)\)
- AppID: FIDO AppID
- KRD: Attestation Data object as defined in other specifications.
- ModelName: the claimed FIDO authenticator model (i.e. either AAID or AAGUID)

Algorithm outline

1. Based on the claimed ModelName, look up \( X, Y \) from trusted source
2. Check that \( R, S, T, W \in G_1, R \neq 1_{G_1}, \text{ and } S \neq 1_{G_1} \)
3. \( H(S^{s} \cdot W^{-c} | S | W | AppID | H(KRD)) = c \); fail if not equal
4. \( e(R, Y) = e(S, P_2) \); fail if not equal
5. \( e(T, P_2) = e(R \cdot W, X) \); fail if not equal

NOTE

\[ B = A^y = P_1^y \]
\[ D = Q_{k,j}^y = P_{1}^{sk,l,j} = B^k \]
\[ S = B^l \text{ and } W = D^l \]
\[ U = S^r \]
\[ S^{s} \cdot W^{-c} = S^{r+c} \cdot W^{-c} = U \cdot S^{csk} \cdot W^{-c} = U \cdot B^{lcsk} \cdot D^{-lc} = U \cdot B^{lcsk} \cdot B^{-lcsk} = U \]

\[ e(R, Y) = e(A^l, P_2^v); e(S, P_2) = e(B^l, P_2) = e(A^l, P_2) \]

\[ e(T, P_2) = e(R \cdot W, X) \]
(all sk' on RogueList) do if $W = S^k$ fail;

// perform all other processing steps for new credential registration

8. return true;

### 4. FIDO ECDAA Object Formats and Algorithm Details

This section is normative.

#### 4.1 Supported Curves for ECDAA

**Definition of G1**

G1 is an elliptic curve group $E : y^2 = x^3 + ax + b$ over $F(q)$ with $a = 0$.

**Definition of G2**

G2 is the p-torsion subgroup of $E'(F_{q^2})$ where $E'$ is a sextic twist of $E$. With $E' : y'^2 = x'^3 + b'$.

An element of $F(q^2)$ is represented by a pair $(a,b)$ where $a + bX$ is an element of $F(q)[X]/< X^2 + 1 >$. We use angle brackets $< Y >$ to signify the ideal generated by the enclosed value.

**Definition of GT**

GT is an order-p subgroup of $F_{q^{12}}$.

**Pairings**

We propose the use of Ate pairings as they are efficient (more efficient than Tate pairings) on Barreto-Naehrig curves [DevScoDah2007].

**Supported BN curves**

We use pairing-friendly Barreto-Naehrig [BarNae-2006] [ISO15946-5] elliptic curves. The curves $\text{TPM\_ECC\_BN\_P256}$ and $\text{TPM\_ECC\_BN\_P638}$ curves are defined in [TPMv2-Part4].

BN curves have a Modulus $q = 36 \cdot u^4 + 36 \cdot u^3 + 24 \cdot u^2 + 6 \cdot u + 1$ [ISO15946-5] and a related order of the group $p = 36 \cdot u^4 + 36 \cdot u^3 + 18 \cdot u^2 + 6 \cdot u + 1$ [ISO15946-5].

- $\text{TPM\_ECC\_BN\_P256}$ is a curve of form $E(F(q))$, where $q$ is the field modulus [TPMv2-Part4] [BarNae-2006]. This curve is identical to the P256 curve defined in [ISO15946-5] section C.3.5.
  - The values have been generated using $u=-7 530 851 732 716 300 289$.
  - Modulus $q = 115 792 089 237 314 936 872 688 561 244 471 742 058 375 878 355 761 205 198 700 409 522 629 646 518 163$
  - Group order $p = 115 792 089 237 314 936 872 688 561 244 471 742 058 035 595 988 840 268 584 488 757 999 429 535 617 037$
p and q have length of 256 bit each.

\( b = 3 \)

\( P \_256 = (x=1, y=2) \)

\( b' = (a=3, b=3) \)

\( P \_256 = (x, y), \) with

\[
P \_256.x = (a=114\ 909\ 019\ 869\ 825\ 495\ 805\ 605\ 623\ 913\ 174\ 726\ 536\ 241\ 706\ 071\ 648\ 811)
\]

\[
P \_256.y = (a=35\ 574\ 363\ 727\ 580\ 634\ 541\ 303\ 789\ 372\ 416\ 298\ 017\ 450\ 764\ 517\ 685\ 681\ 349\ 061\ 506\ 360\ 354\ 665\ 554\ 452\ 649\ 749\ 368)
\]

\[
TPM\_ECC\_BN\_P638 \ [TPMv2-Part4]\ uses
\]

The values have been generated using \( u=365\ 375\ 408\ 992\ 443\ 362\ 629\ 982\ 744\ 420\ 548\ 242\ 302\ 862\ 098\ 433 \)

Modulus \( q = 641\ 593\ 209\ 463\ 000\ 238\ 256 \)

The related order of the group is \( p = 641\ 593\ 209\ 463\ 000\ 238\ 256 \)

\( p \) and \( q \) have length of 638 bit each.

\( b = 257 \)

\( P \_638 = (x=641\ 593\ 209\ 463\ 000\ 238\ 256 \)

\[
P \_638.x = (a=192\ 492\ 098\ 325\ 059\ 629\ 927\ 844\ 609\ 092\ 536\ 807\ 849\ 769\ 208\ 589)
\]

\[
P \_638.y = (a=622\ 964\ 952\ 935\ 200\ 827\ 531\ 506\ 751\ 874\ 197\ 454\ 618\ 413\ 255)
\]

\[
ECC\_BN\_DSD\_P256 \ [DevScoDah2007]\ section 3 uses
\]

The values have been generated using \( u=6\ 917\ 529\ 027\ 641\ 089\ 837 \)

Modulus \( q = 824340166543006797212173535031900388365717811386228921167322412819029493183 \)

The related order of the group is \( p = 82434016654300679721217353503190038836284668564296686430114510052556401373769 \)

\( p \) and \( q \) have length of 256 bit each.

\( b = 3 \)

\( P \_DSD\_P256 = (1, 2) \)

\( b' = (a=3, b=6) \)

\( P \_DSD\_P256 = (x, y), \) with

\[
P \_DSD\_P256.x = (a=73\ 481\ 346\ 555\ 305\ 118\ 071\ 940\ 904\ 527\ 347\ 990\ 526\ 214\ 212)
\]
ECC_BN_ISOP512 [ISO15946-5] section C.3.7 uses

The values have been generated using u=138 919 694 570 098 040 331 481 282 401 523 727

Modulus q = 13 407 807 929 942 597 099 574 024 998 205 830 437 246 153 344 875 909 881 795 845 981 157 516 604 994 291 639 750 834 285 779 043 186 149 750 164 319 950 153 126 044 364 566 323

The related order of the group is p = 13 407 807 929 942 597 099 574 024 998 205 830 437 246 153 344 875 111 580 494 527 427 714 590 099 881 795 845 981 157 516 604 994 291 639 750 834 285 779 043 186 149 750 164 319 950 153 126 044 364 566 323

p and q have length of 512 bit each.

b=3

P1_ISO_P512 = (x=1,y=2)

b′ = (a=3, b=3)

P2_ISO_P512 = (x, y), with

**NOTE**

Spaces are used inside numbers to improve readability.

**Hash Algorithms**

Depending on the curve, we use \( H(x) = \text{SHA256}(x) \mod p \) or \( H(x) = \text{SHA512}(x) \mod p \) as hash algorithm \( H : \{0, 1\}^* \rightarrow \mathbb{Z}_p \).

The argument of the hash function must always be converted to a byte string using the appropriate encoding function specific in section 3.1 Object Encodings, e.g. according to section 3.1.3 Encoding ECPoint2 values as byte strings (ECPoint2ToB) in the case of ECPoint2 points.

**NOTE**

We don't use IEEE P1363.3 section 6.1.1 IHF1-SHA with security parameter t (e.g. t=128 or 256) as it is more complex and not supported by TPMv2.

**4.2 ECDAA Algorithm Names**

We define the following JWS-style algorithm names (see [RFC7515]):

**ED256**

TPM_ECC_BN_P256 curve, using SHA256 as hash algorithm H.

**ED256-2**

ECC_BN_DSD_P256 curve, using SHA256 as hash algorithm H.
4.3 ecdaaSignature object

The fields c and s both have length N. The fields R, S, T, W have equal length (2*N+1 each).

In the case of BN_P256 curve (with key length N=32 bytes), the fields R, S, T, W have length 2*32+1=65 bytes. The fields c and s have length N=32 each.

The ecdaaSignature object is a binary object generated as the concatenation of the binary fields in the order described below (total length of 324 bytes for 256bit curves):

<table>
<thead>
<tr>
<th>Value</th>
<th>Length (in Bytes)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>UINT8[] ECDAA_Signature_c</td>
<td>N</td>
<td>The c value, c=H(U I S I W I KRD I AppID) as returned by AuthnrEcdaaSign encoded as byte string according to BigNumberToB.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Where</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- U = S', with r = RAND(p) computed by the signer.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- KRD is the the entire to-be-signed object (e.g. TAG_UAFV1_KRD in the case of FIDO UAF).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- S = B', with l = RAND(p) computed by the signer and B = A^y computed in the ECDAA-Join</td>
</tr>
<tr>
<td>UINT8[] ECDAA_Signature_s</td>
<td>N</td>
<td>The s value, s=r + c * sk (mod p), as returned by AuthnrEcdaaSign encoded as byte string according to BigNumberToB.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Where</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- r = RAND(p), computed by the signer at FIDO registration (see 3.5.2 ECDAA-Sign Split between Authenticator and ASM)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- p is the group order of G1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- sk: is the authenticator's attestation secret key, see above</td>
</tr>
<tr>
<td>UINT8[] ECDAA_Signature_R</td>
<td>2*N+1</td>
<td>R = A^l; computed by the ASM or the authenticator at FIDO registration; encoded as byte string according to ECPointToB.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Where</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- l = RAND(p), i.e. random number 0≤l≤p. Computed by the ASM or the authenticator at FIDO registration.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- And where R = A^l denotes the scalar multiplication (of scalar l) of a curve point A.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Where A has been provided by the ECDAA-Issuer as part of ECDAA-Join: A = P1J, see 3.4.1 ECDAA-Join Algorithm.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Where P1 and p are system values, injected into the authenticator and lJ is a random number computed by the ECDAA-Issuer on Join.</td>
</tr>
<tr>
<td>UINT8[] ECDAA_Signature_S</td>
<td>2*N+1</td>
<td>S = B^l; computed by the ASM or the authenticator at FIDO registration encoded as byte string according to ECPointToB.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Where B has been provided by the ECDAA-Issuer on Join: B = A^y, see 3.4.1 ECDAA-Join Algorithm.</td>
</tr>
<tr>
<td>Value</td>
<td>Length (in Bytes)</td>
<td>Description</td>
</tr>
<tr>
<td>-----------------------</td>
<td>------------------</td>
<td>-------------</td>
</tr>
</tbody>
</table>
| ECDAA_Signature_T     | 2*N+1            | $T = C^i$; computed by the ASM or the authenticator at FIDO registration encoded as byte string according to ECPointToB. Where:
|                       |                  | - $C = A^x \cdot Q^y$; provided by the ECDAA-Issuer on Join
|                       |                  | - $l_f = RAND(p)$ computed by the ECDAA-Issuer at Join (see 3.4.1 ECDAA-Join Algorithm)
|                       |                  | - $x$ and $y$ are components of the ECDAA-Issuer private key, iskk=(x,y).
|                       |                  | - $Q$ is the authenticator public key |
| ECDAA_Signature_W     | 2*N+1            | $W = D^j$; computed by the ASM or the authenticator at FIDO registration encoded as byte string according to ECPointToB. Where $D = Q^l \cdot y$ is computed by the ECDAA-Issuer at Join (see 3.4.1 ECDAA-Join Algorithm). |

5. Considerations

*This section is non-normative.*

A detailed security analysis of this algorithm can be found in [FIDO-DAA-Security-Proof].

5.1 Algorithms and Key Sizes

The proposed algorithms and key sizes are chosen such that compatibility to TPMv2 is possible.

5.2 Indicating the Authenticator Model

Some authenticators (e.g. TPMv2) do not have the ability to include their model (i.e. vendor ID and model name) in attested messages (i.e. the to-be-signed part of the registration assertion). The TPM’s endorsement key certificate typically contains that information directly or at least it allows the model to be derived from the endorsement key certificate.

In FIDO, the relying party expects the ability to cryptographically verify the authenticator model.

We require the ECDAA-Issuers public key (ipk=(X,Y,c,sx,sy)) to be dedicated to one single authenticator model (e.g. as identified by AAID or AAGUID).

5.3 Revocation

If the private ECDAA attestation key $sk$ of an authenticator has been leaked, it can be revoked by adding its value to a RogueList.

The ECDAA-Verifier (i.e. FIDO Server) check for such revocations. See section 3.6 ECDAA-Verify Operation.

The ECDAA-Issuer is expected to check revocation by other means:

1. if ECDAA-Join is done in-factory, it is assumed that produced devices are known to be uncompromised (at time of production).
2. if a remote ECDAA-Join is performed, the (remote) ECDAA-Issuer already must use a different method to remotely authenticate the authenticator (e.g. using some endorsement key). We expect the ECDAA-Issuer to perform a revocation check based on that information. This is even more flexible as it does not require access to the authenticator ECDAA private key $sk$.

5.4 Pairing Algorithm

The pairing algorithm needs to be used by the ASM as part of the Join process and by the verifier (i.e. FIDO relying party) as part of the verification (i.e. FIDO registration) process.

The result of such a pairing operation is only compared to the result of another pairing operation...
computed by the same entity. As a consequence, it doesn't matter whether the ASM and the verifier use the exact same pairings or not (as long as they both use valid pairings).

5.5 Performance

For performance reasons the calculation of $\text{Sig2} = (R, S, T, W)$ may be performed by the ASM running on the FIDO user device (as opposed to inside the authenticator). See section 3.5.2 ECDAA-Sign Split between Authenticator and ASM.

The cryptographic computations to be performed inside the authenticator are limited to $G_1$. The ECDAA-Issuer has to perform two $G_2$ point multiplications for computing the public key. The Verifier (i.e. FIDO relying party) has to perform $G_1$ operations and two pairing operations.

5.6 Binary Concatentation

We use a simple byte-wise concatenation function for the different parameters, i.e. $H(a,b) = H(a \| b)$.

This approach is as secure as the underlying hash algorithm since the authenticator controls the length of the (fixed-length) values (e.g. $U, S, W$). The AppID is provided externally and has unverified structure and length. However, it is only followed by a fixed length entry - the (system defined) hash of $KRD$. As a consequence, no parts of the AppID would ever be confused with the fixed length value.

5.7 IANA Considerations

This specification registers the algorithm names "ED256", "ED512", and "ED638" defined in section 4. FIDO ECDAA Object Formats and Algorithm Details with the IANA JSON Web Algorithms registry as defined in section "Cryptographic Algorithms for Digital Signatures and MACs" in [RFC7518].

<table>
<thead>
<tr>
<th>Algorithm Name</th>
<th>&quot;ED256&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algorithm Description</td>
<td>FIDO ECDAA algorithm based on TPM_ECC_BN_P256 [TPMv2-Part4] curve using SHA256 hash algorithm.</td>
</tr>
<tr>
<td>Algorithm Usage Location(s)</td>
<td>&quot;alg&quot;, i.e. used with JWS.</td>
</tr>
<tr>
<td>JOSE Implementation Requirements</td>
<td>Optional</td>
</tr>
<tr>
<td>Change Controller</td>
<td>FIDO Alliance, [Contact Us]</td>
</tr>
<tr>
<td>Specification Documents</td>
<td>Sections 3. FIDO ECDAA Attestation and 4. FIDO ECDAA Object Formats and Algorithm Details of [FIDOEcdaaAlgorithm].</td>
</tr>
<tr>
<td>Algorithm Analysis Document(s)</td>
<td>[FIDO-DAA-Security-Proof]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Algorithm Name</th>
<th>&quot;ED512&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algorithm Description</td>
<td>ECDAA algorithm based on ECC_BN_ISOP512 [ISO15946-5] curve using SHA512 algorithm.</td>
</tr>
<tr>
<td>Algorithm Usage Location(s)</td>
<td>&quot;alg&quot;, i.e. used with JWS.</td>
</tr>
<tr>
<td>JOSE Implementation Requirements</td>
<td>Optional</td>
</tr>
<tr>
<td>Change Controller</td>
<td>FIDO Alliance, [Contact Us]</td>
</tr>
<tr>
<td>Specification Documents</td>
<td>Sections 3. FIDO ECDAA Attestation and 4. FIDO ECDAA Object Formats and Algorithm Details of [FIDOEcdaaAlgorithm].</td>
</tr>
<tr>
<td>Algorithm Analysis Document(s)</td>
<td>[FIDO-DAA-Security-Proof]</td>
</tr>
<tr>
<td>Algorithm Name</td>
<td>&quot;ED638&quot;</td>
</tr>
<tr>
<td>----------------</td>
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<tr>
<td>Algorithm Usage Location(s)</td>
<td>&quot;alg&quot;, i.e. used with JWS.</td>
</tr>
<tr>
<td>JOSE Implementation Requirements</td>
<td>Optional</td>
</tr>
<tr>
<td>Change Controller</td>
<td>FIDO Alliance. Contact Us</td>
</tr>
<tr>
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<td>Sections 3. FIDO ECDAA Attestation and 4. FIDO ECDAA Object Formats and Algorithm Details of [FIDOEcdaaAlgorithm].</td>
</tr>
<tr>
<td>Algorithm Analysis Document(s)</td>
<td>[FIDO-DAA-Security-Proof]</td>
</tr>
</tbody>
</table>

### A. References

#### A.1 Normative references

<table>
<thead>
<tr>
<th>Reference</th>
<th>Title</th>
</tr>
</thead>
</table>

#### A.2 Informative references

<table>
<thead>
<tr>
<th>Reference</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>[CheLi2013-ECDAA]</td>
<td>Liqun Chen, HP Laboratories and Jiangtao Li, Intel Corporation, <em>Flexible and Scalable Digital Signatures in TPM 2.0</em>, 2013, URL: <a href="http://dx.doi.org/10.1145/2508859.2516729">http://dx.doi.org/10.1145/2508859.2516729</a></td>
</tr>
</tbody>
</table>
[FIDO Glossary]
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