Elliptic-Curve Diffie-Hellman Key Exchange for the SSH Transport Level Protocol
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Abstract

This document describes new key exchange algorithms based on Elliptic Curve Cryptography (ECC) for the Secure Shell (SSH) protocol. In particular, it specifies the use of Elliptic Curve Diffie-Hellman (ECDH) key agreement and ECDH with cofactor multiplication key agreement in the SSH Transport Layer protocol.

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in RFC 2119 [1].
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1. Introduction

Elliptic Curve Cryptography (ECC) is emerging as an attractive public-key cryptosystem for mobile/wireless environments. Compared to currently prevalent cryptosystems such as RSA, DSA, and DH, ECC offers equivalent security with smaller key sizes. This is illustrated in the following table, based on [2], which gives approximate comparable key sizes for symmetric- and asymmetric-key cryptosystems based on the best known algorithms for attacking them.

\[
\begin{array}{|c|c|c|}
\hline
\text{Symmetric} & \text{ECC} & \text{DH/DSA/RSA} \\
\hline
80 & 163 & 1024 \\
128 & 283 & 3072 \\
192 & 409 & 7680 \\
256 & 571 & 15360 \\
\hline
\end{array}
\]

Figure 1: Comparable key sizes (in bits)

Smaller key sizes result in power, bandwidth, and computational savings that make ECC especially attractive for constrained environments.

This document describes additions to SSH to support the use of the Elliptic Curve Diffie-Hellman (ECDH) key agreement scheme to establish a shared key, either with or without cofactor multiplication.

Implementation of this specification requires familiarity with both SSH [3][4] and ECC [5][6][7].
2. ECDH Parameter and Key Exchange

2.1 Description

The first stage of the key exchange mechanism is the exchange of elliptic curve domain parameters. These parameters define a finite field (either GF(p), a field of integers modulo a large prime p, or GF(2^m), the field of binary polynomials of degree m or less), an elliptic curve over that finite field, a point on that curve, and the order and cofactor of the subgroup generated by scalar-point multiplication by that point.

Random elliptic curve domain parameters can be generated upon each request. However, this is costly and may result in the generation of parameters the security of which is untested. As a result, there are a number of so-called named elliptic curve domain parameters defined by various standards organizations [8][9][10][11].

In the following: C is the client, S is the server; curves is a list of supported named curves and generic identifiers; min is the minimal size in bits of acceptable generic elliptic curve domain parameters, or 0; pref is the preferred size in bits of acceptable generic elliptic curve domain parameters, or 0; max is the maximal size in bits of acceptable generic elliptic curve domain parameters, or 0; curve is a named curve or generic identifier; prime is a prime defining a prime field; irr is an irreducible polynomial defining a binary field; a is the curve parameter a; b is the curve parameter b; x is the x-coordinate of the generator; y is the y-coordinate of the generator; order is the order of the generator; cofactor is the cofactor of the generator; seed is the the binary string used as a seed for random generation of the elliptic curve domain parameters, or ""; c_x is the x-coordinate of the client’s public key; c_y is the y-coordinate of the client’s public key; s_x is the x-coordinate of the server’s public key; s_y is the y-coordinate of the server’s public key; and K is the shared secret.

1. C sends "curves", a list of preferred named elliptic curve domain parameters and, optionally, a range of bit sizes "min || pref || max" over which generic elliptic curve domain parameters are acceptable.

2. S selects the first curve in the list of preferred curves that it supports. If S selects a named curve, S returns the name as "curve". If S selects a set of generic elliptic curve domain parameters, then S creates or selects a set of elliptic curve domain parameters in the requested range, if S supports a curve in that range; S sends the elliptic curve domain parameters to C: either "prime || a || b || x || y || order || cofactor || seed"
for a prime curve or "irr || a || b || x || y || order ||
cofactor || seed" for a binary curve.

3. If S sends a set of generic elliptic curve domain parameters,
then C MAY verify that the curve was generated at random, using
for example the verification algorithms defined in section A.16.8
of [6]. If C decides to accept the parameters, then C generates
an elliptic curve public-key / private-key pair using the
selected elliptic curve domain parameters and sends the public-
key value "c_x || c_y" to S.

4. S MAY validate C’s public-key value using for example algorithm
A.16.10 of [6]. S generates an elliptic curve public-key /
private-key pair using the selected elliptic curve domain
parameters; the public-key value is "s_x || s_y". S uses C’s
public-key value to compute the shared secret K using the key
derivation function KDF. S computes the hash H of all values
transmitted in the key exchange concatenated with K, and the
signature s on H using its private host key. S sends "K_S || s_x
|| s_y || s", where K_S is S’s public host key.

5. C MAY validate S’s public-key value using for example algorithm
A.16.10 of [6]. C verifies that K_S really is the host key for S
(e.g., using certificates or a local database). C is also
allowed to accept the key without verification; however, doing so
will render the protocol insecure against active attacks (but may
be desirable for practical reasons in the short term in many
environments). C uses S’s public-key value to compute the shared
secret using the key derivation function KDF and verifies the
signature s on H.

When selecting a set of generic elliptic curve domain parameters, the
server SHOULD choose the smallest domain parameters it knows that are
not smaller than the size the client requested. If the server does
not know any domain parameters that are not smaller than the client
request, then it MUST return the largest domain parameters it knows.
In all cases, the size of the returned domain parameters SHOULD be at
least 112 bits, and preferably at least 160 bits. Note that size of
domain parameters is measured as the size in bits of the order of the
generator.

2.2 Implementation

This key exchange algorithm is implemented with the following
messages. The hash algorithm for computing the exchange hash is
defined by the method name, and is called HASH. The key derivation
function for computing the shared secret is defined by the method
name, and is called KDF. The public key algorithm for signing is
negotiated with the KEXINIT messages.

1. The client sends the SSH_MSG_KEX_ECDH_REQUEST (Section 3.1) message. The value of curves is an ordered list of preferred elliptic curve domain parameters. In addition to the standardized named curves, there are two options for generic curves: generic-gfp and generic-gf2m. If curves contains either generic-gfp or generic-gf2m, the client MUST specify a range of acceptable curve sizes using the min, pref, and max values; otherwise, the values min, pref, and max MUST be 0. The following inequalities MUST be satisfied: min <= pref <= max.

2. The server responds with one of the following messages:
   * SSH_MSG_KEX_ECDH_CURVE_NAMED (Section 3.2)
   * SSH_MSG_KEX_ECDH_CURVE_GENERIC_GFP (Section 3.3)
   * SSH_MSG_KEX_ECDH_CURVE_GENERIC_GF2M (Section 3.4)

3. If the server responds with SSH_MSG_KEX_ECDH_CURVE_NAMED (Section 3.2), then the value of curve MUST be an element of the list curves, and MUST NOT be either generic-gfp or generic-gf2m.

4. If the server responds with either the SSH_MSG_KEX_ECDH_CURVE GENERIC_GFP (Section 3.3) or SSH_MSG_KEX_ECDH_CURVE_GENERIC_GF2M (Section 3.4) message, then generic-gfp or generic-gf2m, respectively, MUST be in the list curves, and the size in bits of the order of the generator MUST be in the range min . . . max inclusively, unless the server does not support any curves in that range, in which case the server MUST return the largest curve below that range that it supports.

5. The client sends the SSH_MSG_KEX_ECDH_INIT (Section 3.5) message.

6. The server responds with the SSH_MSG_KEX_ECDH_REPLY (Section 3.6) message.
3. Key Exchange Messages

The following message formats are defined in this document. The messages are used as described in Section 2.

3.1 SSH_MSG_KEX_ECDH_REQUEST

byte SSH_MSG_KEX_ECDH_REQUEST
name-list curves, a list of supported named curves and generic identifiers
uint32 min, minimal size in bits of acceptable generic elliptic curve domain parameters, or 0
uint32 pref, preferred size in bits of acceptable generic elliptic curve domain parameters, or 0
uint32 max, maximal size in bits of acceptable generic elliptic curve domain parameters, or 0

3.2 SSH_MSG_KEX_ECDH_CURVE_NAMED

byte SSH_MSG_KEX_ECDH_CURVE_NAMED
string curve, a named curve or generic identifier

The value of curve MUST NOT be either generic-gfp or generic-gf2m.

3.3 SSH_MSG_KEX_ECDH_CURVE_GENERIC_GFP

byte SSH_MSG_KEX_ECDH_CURVE_GENERIC_GFP
mpint prime, the prime defining the field
mpint a, the curve parameter a
mpint b, the curve parameter b
mpint x, the x-coordinate of the generator
mpint y, the y-coordinate of the generator
mpint order, the order of the generator
uint32 cofactor, the cofactor of the generator
string seed, the binary string used as a seed for random generation of the elliptic curve domain parameters
3.4 SSH_MSG_KEX_ECDH_CURVE_GENERIC_GF2M

byte SSH_MSG_KEX_ECDH_CURVE_GENERIC_GF2M
mpint irr, the irreducible polynomial defining the field
mpint a, the curve parameter a
mpint b, the curve parameter b
mpint x, the x-coordinate of the generator
mpint y, the y-coordinate of the generator
mpint order, the order of the generator
uint32 cofactor, the cofactor of the generator
string seed, the binary string used as a seed for random
    generation of the elliptic curve domain
    parameters

3.5 SSH_MSG_KEX_ECDH_INIT

byte SSH_MSG_KEX_ECDH_INIT
mpint c_x, the x-coordinate of the client’s public key
mpint c_y, the y-coordinate of the client’s public key

3.6 SSH_MSG_KEX_ECDH_REPLY

byte SSH_MSG_KEX_ECDH_REPLY
string K_S, server public host key and certificates
mpint s_x, the x-coordinate of the server’s public key
mpint s_y, the y-coordinate of the server’s public key
string s, the signature of H

The hash H is computed as the HASH hash of the concatenation of the
following. Values marked with * are included in the concatenation
only if the values are from messages that were actually transmitted.

For example, if the message SSH_MSG_KEX_ECDH_CURVE_NAMED (Section
3.2) is sent, then the only value marked with a * that will be
included in the concatenation below is the value curve.
string V_C, the client’s version string (CR and NL excluded)
string V_S, the server’s version string (CR and NL excluded)
string I_C, the payload of the client’s SSH_MSG_KEXINIT
string I_S, the payload of the server’s SSH_MSG_KEXINIT
string K_S, the host key
name-list curves, a list of supported named curves and generic identifiers
uint32 min, minimal size in bits of acceptable generic elliptic curve domain parameters, or 0
uint32 pref, preferred size in bits of acceptable generic elliptic curve domain parameters, or 0
uint32 max, maximal size in bits of acceptable generic elliptic curve domain parameters, or 0
string curve*, a named curve or generic identifier
mpint prime*, the prime defining the field
mpint irr*, the irreducible polynomial defining the field
mpint a*, the curve parameter a
mpint b*, the curve parameter b
mpint x*, the x-coordinate of the generator
mpint y*, the y-coordinate of the generator
mpint order*, the order of the generator
uint32 cofactor*, the cofactor of the generator
string seed*, the binary string used as a seed for random generation of the elliptic curve domain parameters
mpint c_x, the x-coordinate of the client’s public key
mpint c_y, the y-coordinate of the client’s public key
mpint s_x, the x-coordinate of the server’s public key
mpint s_y, the y-coordinate of the server’s public key
mpint K, the shared secret

3.7 Named Elliptic Curve Domain Parameters

The naming scheme for named elliptic curve domain parameters follows the naming conventions defined in Section 5 of [3].

Names that do not contain an at-sign (@) are reserved to be defined by IETF consensus (RFCs). Valid names of this form are listed in the following sections.

Anyone can define additional named elliptic curve domain parameters by using names in the format name@domainname, e.g. "our-curve@example.com". The format of the part preceding the at-sign is not specified. The part following the at-sign MUST be a valid fully qualified internet domain name controlled by the person or organization defining the curve name. It is up to each domain how it manages its local namespace.
3.7.1 Generic curve parameters

The following identifiers are used to indicate the use of an arbitrary generic curve over either GF(p) or GF(2^m).

\begin{verbatim}
  generic-gfp  generic-gf2m
\end{verbatim}

3.7.2 NIST-recommended curves

The following curves are defined in [8]. It is RECOMMENDED that an implementation support at least some of these curves.

\begin{verbatim}
  nistp192  nistp224  nistp256  nistp384  nistp521
  nistk163  nistb163  nistk233  nistb233  nistk283
  nistb283  nistk409  nistb409  nistk571  nistb571
\end{verbatim}

3.7.3 SEC-recommended curves

The following curves are defined in [9].

\begin{verbatim}
  secp112r1  secp112r2  secp128r1  secp128r2  secp160k1
  secp160r1  secp160r2  secp192k1  secp192r1  secp224k1
  secp224r1  secp256k1  secp256r1  secp384r1  secp521r1
  sect113r1  sect113r2  sect131r1  sect131r2  sect163k1
  sect163r1  sect163r2  sect193r1  sect193r2  sect233k1
  sect233r1  sect239k1  sect283k1  sect283r1  sect409k1
  sect409r1  sect571k1  sect571r1
\end{verbatim}

3.7.4 ANSI-recommended curves

The following curves are defined in [10].

\begin{verbatim}
  prime192v1  prime192v2  prime192v3  prime239v1  prime239v2
  prime239v3  prime256v1
  c2pnb163v1  c2pnb163v2  c2pnb163v3  c2pnb208v1  c2tnb239v1
  c2tnb191v2  c2tnb191v3  c2tnb208v1  c2tnb239v1  c2tnb239v2
  c2tnb239v3  c2pnw272v1  c2pnb304v1  c2tnb359v1  c2pnb368v1
  c2tnb431r1
\end{verbatim}

3.7.5 WTLS-recommended curves

The following curves are defined in [11].

\begin{verbatim}
  wtls1  wtls3  wtls4  wtls5  wtls6  wtls7  wtls8
  wtls9  wtls10  wtls11  wtls12
\end{verbatim}
3.8 Summary of Message Numbers

The following message numbers have been defined in this document:

---------------------------------------------------------------------
#define SSH_MSG_KEX_ECDH_REQUEST             30
#define SSH_MSG_KEX_ECDH_CURVE_NAMED         31
#define SSH_MSG_KEX_ECDH_CURVE_GENERIC_GFP   32
#define SSH_MSG_KEX_ECDH_CURVE_GENERIC_GF2M  33
#define SSH_MSG_KEX_ECDH_INIT                34
#define SSH_MSG_KEX_ECDH_REPLY               35
---------------------------------------------------------------------

Figure 14: Summary of Message Numbers

The numbers 30-49 are key exchange-specific and may be redefined by other key exchange methods.
4. ECDH Key Exchange Methods

4.1 ecdh-exchange-sha1

The "ecdh-exchange-sha1" method specifies Elliptic Curve Diffie-Hellman Parameter and Key Exchange with SHA-1 as HASH and ECDH without cofactor multiplication as KDF. The SHA-1 hash algorithm is defined in [12].

In ECDH without cofactor multiplication, the shared secret is generated as follows. Let \( k \) be the private key, and \( P \) be the generator. Then the shared secret \( K \) is the \( x \)-coordinate of the affine representation of the point \( Q = k \cdot P \).

4.2 ecdhc-exchange-sha1

The "ecdhc-exchange-sha1" method specifies Elliptic Curve Diffie-Hellman Parameter and Key Exchange with SHA-1 as HASH and ECDH with cofactor multiplication as KDF. The SHA-1 hash algorithm is defined in [12].

In ECDH with cofactor multiplication, the shared secret is generated as follows. Let \( k \) be the private key, \( P \) be the generator, and \( h \) be the cofactor. Then the shared secret \( K \) is the \( x \)-coordinate of the affine representation of the point \( Q = (k \cdot h) \cdot P \).
5. Security Considerations

The Elliptic Curve Diffie-Hellman key agreement algorithm is defined in [6] and [7]. The appropriate security considerations of those documents apply.

The key exchange methods defined in Section 4 rely on the SHA-1 hash algorithm as defined in [12]. The appropriate security considerations of that document apply.

Server implementations that generate random elliptic curve domain parameters SHOULD generate those parameters verifiably at random, using for example the algorithms defined in section A.16.7 of [6]. Client implementations SHOULD verify that generic parameters have been generated randomly, using for example the verification algorithms defined in section A.16.8 of [6].

Since ECDH allows for elliptic curves of arbitrary sizes and thus arbitrary security strength, it is important that the size of elliptic curve be chosen to match the security strength of other elements of the SSH handshake. In particular, host key sizes and bulk encryption algorithms must be chosen appropriately. Information regarding estimated equivalence of key sizes is available in [2].

For most applications, it should be sufficient to use an existing named curve as recommended in Section 3.7.
6. Intellectual Property Rights

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