

Internet Engineering Task Force (IETF)
Request for Comments: 6989
Updates: [5996](#)
Category: Standards Track
ISSN: 2070-1721

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July 2013

Additional Diffie-Hellman Tests
for the Internet Key Exchange Protocol Version 2 (IKEv2)

Abstract

This document adds a small number of mandatory tests required for the secure operation of the Internet Key Exchange Protocol version 2 (IKEv2) with elliptic curve groups. No change is required to IKE implementations that use modular exponential groups, other than a few rarely used so-called Digital Signature Algorithm (DSA) groups. This document updates the IKEv2 protocol, [RFC 5996](#).

Status of This Memo

This is an Internet Standards Track document.

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1. Introduction

IKEv2 [RFC5996] consists of the establishment of a shared secret using the Diffie-Hellman (DH) protocol, followed by authentication of the two peers. Existing implementations typically use modular exponential (MODP) DH groups, such as those defined in [RFC3526].

IKEv2 does not require that any tests be performed by a peer receiving a public Diffie-Hellman key from the other peer. This is fine for the common case of MODP groups. For other DH groups, when peers reuse DH values across multiple IKE sessions, the lack of tests by the recipient results in a potential vulnerability (see [Section 4.1](#) for more details). In particular, this is true for Elliptic Curve (EC) groups, whose use is becoming ever more popular. This document defines such tests for several types of DH groups.

In addition, this document describes another potential attack related to the reuse of DH keys: a timing attack. This additional material is taken from [RFC2412].

This document updates [RFC5996] by adding security requirements that apply to many of the protocol's implementations.

1.1. Conventions Used in This Document

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 [RFC2119].

2. Group Membership Tests

This section describes the tests that need to be performed by IKE peers receiving a Key Exchange (KE) payload. The tests are RECOMMENDED for all implementations but only REQUIRED for those that reuse DH private keys (as defined in [RFC5996], Section 2.12). The tests apply to the recipient of a KE payload and describe how it should check the received payload. They are listed here according to the DH group being used.

2.1. Sophie Germain Prime MODP Groups

These are currently the most commonly used groups; all these groups have the property that $(p-1)/2$ is also prime; this section applies to any such MODP group. Each recipient MUST verify that the peer's public value r is in the legal range ($1 < r < p-1$). According to [Menezes], Section 2.2, even with this check there remains the possibility of leaking a single bit of the secret exponent when DH keys are reused; this amount of leakage is insignificant.

See Section 5 for the specific groups covered by this section.

2.2. MODP Groups with Small Subgroups

[RFC5114] defines modular exponential groups with small subgroups; these are modular exponential groups with comparatively small subgroups, and all have $(p-1)/2$ composite. Section 2.1 of [Menezes] describes some informational leakage from a small-subgroup attack on these groups if the DH private value is reused.

This leakage can be prevented if the recipient performs a test on the peer's public value; however, this test is expensive (approximately as expensive as what reusing DH private values saves). In addition, the NIST standard ([NIST-800-56A], Section 5.6.2.4) requires that test; hence, anyone needing to conform to that standard will need to implement the test anyway.

Because of the above, the IKE implementation MUST choose between one of the following two options:

- o It MUST check both that the peer's public value is in range ($1 < r < p-1$) and that $r^q = 1 \bmod p$ (where q is the size of the subgroup, as listed in the RFC defining the group). DH private values MAY then be reused. This option is appropriate if conformance to [NIST-800-56A] is required.
- o It MUST NOT reuse DH private values (that is, the DH private value for each DH exchange MUST be generated from a fresh output of a cryptographically secure random number generator), and it MUST check that the peer's public value is in range ($1 < r < p-1$). This option is more appropriate if conformance to [NIST-800-56A] is not required.

See Section 5 for the specific groups covered by this section.

2.3. Elliptic Curve Groups

IKEv2 can be used with elliptic curve groups defined over a field $GF(p)$ [RFC5903] [RFC5114]. According to [Menezes], Section 2.3, there is some informational leakage possible. A receiving peer MUST check that its peer's public value is valid; that is, the x and y parameters from the peer's public value satisfy the curve equation, $y^2 = x^3 + ax + b \bmod p$ (where for groups 19, 20, and 21, $a = -3 \bmod p$), and all other values of a , b , and p for the group are listed in the RFC defining the group).

We note that an additional check to ensure that the public value is not the point at infinity is not needed, because IKE (see Section 7 of [RFC5903]) does not allow for encoding this value.

See Section 5 for the specific groups covered by this section.

2.4. Transition

Existing implementations of IKEv2 with Elliptic Curve Diffie-Hellman (ECDH) groups may be modified to include the tests described in the current document, even if they do not reuse DH keys. The tests can be considered as sanity checks and will prevent the code having to handle inputs that it may not have been designed to handle.

ECDH implementations that do reuse DH keys MUST be enhanced to include the above tests.

2.5. Protocol Behavior

The recipient of a DH public key that fails one of the above tests must assume that the sender is either truly malicious or has a bug in its implementation. The behavior defined below attempts to balance resistance to attackers that are trying to disrupt the IKE exchange, against the need to help a badly implemented peer by providing useful error indications.

If this error happens during the IKE_SA_INIT exchange, then the recipient **MUST** drop the message that contains an invalid KE payload and **MUST NOT** use that message when creating the IKE security association (SA).

If the implementation employs the DoS-resistant behavior proposed in [Section 2.4 of \[RFC5996\]](#), it may simply ignore the erroneous request or response message, and continue waiting for a later message containing a legitimate KE payload.

If DoS-resistant behavior is not implemented and the invalid KE payload was in the IKE_SA_INIT request, the implementation **MAY** send an INVALID_SYNTAX error notification back and remove the in-progress IKE SA; if the invalid KE payload was in the IKE_SA_INIT response, then the implementation **MAY** simply delete the half-created IKE SA and re-initiate the exchange.

If the invalid KE payload is received during the CREATE_CHILD_SA exchange (or any other exchange after the IKE SA has been established) and the invalid KE payload is in the request message, the Responder **MUST** reply with an INVALID_SYNTAX error notification and drop the IKE SA. If the invalid KE payload is in a response, the Initiator getting this reply **MUST** immediately delete the IKE SA by sending an IKE SA Delete notification as a new exchange. In this case, the sender evidently has an implementation bug, and dropping the IKE SA makes it easier to detect.

3. Side-Channel Attacks

In addition to the small-subgroup attack, there is also a potential timing attack on IKE peers when they are reusing Diffie-Hellman secret values. This is a side-channel attack, which means that it may or may not be a vulnerability in certain cases, depending on implementation details and the threat model.

The remainder of this section is quoted from [\[RFC2412\]](#), [Section 5](#), with a few minor clarifications. This attack still applies to IKEv2 implementations, and both to MODP groups and ECDH groups. We also note that more efficient countermeasures are available for EC groups represented in projective form, but these are outside the scope of the current document.

Timing attacks that are capable of recovering the exponent value used in Diffie-Hellman calculations have been described by Paul Kocher [\[Kocher\]](#). In order to nullify the attack, implementors must take pains to obscure the sequence of operations involved in carrying out modular exponentiations.

One potential method to foil these timing attacks is to use a "blinding factor". In this method, a group element, r , is chosen at random, and its multiplicative inverse modulo p is computed, which we'll call r_{inv} . r_{inv} can be computed by the Extended Euclidean Method, using r and p as inputs. When an exponent x is chosen, the value r_{inv}^x is also calculated. Then, when calculating $(g^y)^x$, the implementation will calculate this sequence:

$$\begin{aligned} A &= r * g^y \\ B &= A^x = (r * g^y)^x = (r^x)(g^{xy}) \\ C &= B * r_{\text{inv}}^x = (r^x)(r^{-1x})(g^{xy}) = g^{xy} \end{aligned}$$

The blinding factor is only necessary if the exponent x is used more than 100 times.

4. Security Considerations

This entire document is concerned with the IKEv2 security protocol and the need to harden it in some cases.

4.1. DH Key Reuse and Multiple Peers

This section describes one variant of the attack prevented by the tests defined above.

Suppose that IKE peer Alice maintains IKE security associations with peers Bob and Eve. Alice uses the same secret ECDH key for both SAs, which is allowed with some restrictions. If Alice does not implement these tests, Eve will be able to send a malformed public key, which would allow her to efficiently determine Alice's private key (as described in Section 2 of [\[Menezes\]](#)). Since the key is shared, Eve will be able to obtain Alice's shared IKE SA key with Bob.

4.2. DH Key Reuse: Variants

Private DH keys can be reused in different ways, with subtly different security implications. For example:

1. DH keys are reused for multiple connections (IKE SAs) to the same peer and for connections to different peers.
2. DH keys are reused for multiple connections to the same peer (e.g., when the peer is identified by its IP address) but not for different peers.
3. DH keys are reused only when they had not been used to complete an exchange, e.g., when the peer replies with an `INVALID_KEY_PAYLOAD` notification.

Both the small-subgroup attack and the timing attack described in this document apply at least to options #1 and #2.

4.3. Groups Not Covered by This RFC

There are a number of group types that are not specifically addressed by this RFC. A document that defines such a group **MUST** describe the tests required by that group.

One specific type of group would be an even-characteristic elliptic curve group. Now, these curves have cofactors greater than 1; this leads to a possibility of some information leakage. There are several ways to address this information leakage, such as performing a test analogous to the test in [Section 2.2](#) or adjusting the ECDH operation to avoid this leakage (such as Elliptic Curve Cryptography Cofactor Diffie-Hellman (ECC CDH), where the shared secret really is $hxyG$). Because the appropriate test depends on how the group is defined, we cannot document it in advance.

4.4. Behavior upon Test Failure

The behavior recommended in [Section 2.5](#) is in line with generic error treatment during the `IKE_SA_INIT` exchange, per [Section 2.21.1 of \[RFC5996\]](#). The sender is not required to send back an error notification, and the recipient cannot depend on this notification because it is unauthenticated and may in fact have been sent by an attacker trying to launch a DoS attack on the connection. Thus, the notification is only useful to debug implementation errors.

On the other hand, the error notification is secure in the sense that no secret information is leaked. All IKEv2 Diffie-Hellman groups are publicly known, and none of the tests defined here depend on any private key. In fact, the tests can all be performed by an eavesdropper.

The situation when the failure occurs in the CREATE_CHILD_SA exchange is different, since everything is protected by an IKE SA. The peers are authenticated, and error notifications can be relied on. See [Section 2.21.3 of \[RFC5996\]](#) for more details on error handling in this case.

5. IANA Considerations

IANA has added a column named "Recipient Tests" to the Transform Type 4 - Diffie-Hellman Group Transform IDs registry for IKEv2 [[IANA-IKEv2-Registry](#)].

This column has been initially populated as follows.

Number	Recipient Tests
1, 2, 5, 14, 15, 16, 17, 18	RFC 6989, Section 2.1
22, 23, 24	RFC 6989, Section 2.2
19, 20, 21, 25, 26, 27, 28, 29, 30	RFC 6989, Section 2.3

Groups 27-30 are defined in [[RFC6954](#)].

Future documents that define new DH groups for IKEv2 are REQUIRED to provide this information for each new group, possibly by referring to the current document.

6. Acknowledgements

We would like to thank Dan Harkins, who initially raised this issue on the IPsec mailing list. Thanks to Tero Kivinen and Rene Struik for their useful comments. Much of the text in [Section 3](#) is taken from [[RFC2412](#)], and we would like to thank its author, Hilarie Orman.

The document was originally prepared using the lyx2rfc tool, created by Nico Williams.

7. References

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