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Post-quantum Hybrid Key Exchange with ML-KEM in the Internet Key  
Exchange Protocol Version 2 (IKEv2)  
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## Abstract

NIST recently standardized ML-KEM, a new key encapsulation mechanism, which can be used for quantum-resistant key establishment. This draft specifies how to use ML-KEM as an additional key exchange in IKEv2 along with traditional key exchanges. This Post-Quantum Traditional Hybrid Key Encapsulation Mechanism approach allows for negotiating IKE and Child SA keys which are safe against cryptanalytically-relevant quantum computers and theoretical weaknesses in ML-KEM.

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## 1. Introduction

A Cryptanalytically-relevant Quantum Computer (CRQC), if it became a reality, could threaten today's public key establishment algorithms. Someone storing encrypted communications that use (Elliptic Curve) Diffie-Hellman ((EC)DH) to establish keys could decrypt these communications in the future after a CRQC became available to them. Such communications include Internet Key Exchange Protocol Version 2 (IKEv2).

To address this concern, the Mixing Preshared Keys in IKEv2 specification [RFC8784] introduced Post-quantum Preshared Keys as a temporary option for stirring a pre-shared key of adequate entropy in the derived Child SA encryption keys in order to provide quantum-resistance. This specification can be used in conjunction with PPK as defined in [RFC8784].

Since then, NIST has been working on a public project [NIST-PQ] for standardizing quantum-resistant algorithms which include key encapsulation and signatures. At the end of Round 3, they picked Kyber as the first Key Encapsulation Mechanism (KEM) for standardization [I-D.draft-cfrg-schwabe-kyber-04]. Kyber was then standardized as Module-Lattice-based Key-Encapsulation Mechanism (ML-KEM) in 2024 [FIPS203].

As post-quantum public keys and ciphertexts may make UDP packet sizes larger than common network Maximum Transport Units (MTU), the Intermediate Exchange in IKEv2 document [RFC9242] defined how to do additional large message exchanges by using new `IKE_INTERMEDIATE` messages. `IKE_INTERMEDIATE` messages can only be used after `IKE_SA_INIT`. The Multiple Key Exchanges in IKEv2 specification [RFC9370] defined how to do up to seven additional key exchanges by using `IKE_INTERMEDIATE` or `IKE_FOLLOWUP_KEY` messages and by deriving new `SKEYSEED` and `KEYMAT` key materials. These messages can be fragmented at the IKEv2 layer before causing IP fragmentation [RFC7383]. If a post-quantum KEM does not fit inside `IKE_SA_INIT` without causing IP fragmentation, then it should be used after `IKE_SA_INIT` in an `IKE_INTERMEDIATE` or `IKE_FOLLOWUP_KEY` message as an additional key establishment algorithm.

This document describes how ML-KEM can be used as a quantum-resistant KEM in IKEv2 in an `IKE_SA_INIT` key exchange, or in one additional `IKE_INTERMEDIATE` or `IKE_FOLLOWUP_KEY` key exchange after an initial `IKE_SA_INIT` or `CREATE_CHILD_SA` respectively. This approach of combining a quantum-resistant with a traditional algorithm, is commonly called Post-Quantum Traditional (PQ/T) Hybrid [I-D.ietf-pquip-pqt-hybrid-terminology-04] key exchange and combines the security of a well-established algorithm with relatively new quantum-resistant algorithms. The result is a new Child SA key or an IKE or Child SA rekey with keying material which is safe against a CRQC. Another use of a PQ/T Hybrid key exchange in IKEv2 is for someone that wants to exchange keys using the high security parameter of ML-KEM. As these may not fit in common network packet payload sizes, they will need to be sent in a `IKE_FOLLOWUP_KEY` or `CREATE_CHILD_SA` key exchange which can be fragmented. This specification is a profile of the Multiple Key Exchanges in IKEv2 specification [RFC9370] and registers new algorithm identifiers for ML-KEM key exchanges in IKEv2.

### 1.1. KEMs

In the context of the NIST Post-Quantum Cryptography Standardization Project [NIST-PQ], key exchange algorithms are formulated as KEMs, which consist of three steps:

- \* `'KeyGen() -> (pk, sk)'`: A probabilistic key generation algorithm, which generates a public / encapsulation key `'pk'` and a private / decapsulation key `'sk'`. The resulting `pk` is sent to the responder in the `KEi` payload.

- \* 'Encaps(pk) -> (ct, ss)': A probabilistic encapsulation algorithm, which takes as input a public key 'pk' (from the KEi) and outputs a ciphertext 'ct' and shared secret 'ss'. The 'ct' is sent back to initiator in the KEr payload.
- \* 'Decaps(sk, ct) -> ss': A decapsulation algorithm, which takes as input a secret key 'sk' and ciphertext 'ct' (from the KEr) and outputs a shared secret 'ss', or in some rare cases a distinguished error value.

## 1.2. ML-KEM

ML-KEM is a standardized lattice-based key encapsulation mechanism [FIPS203]. It uses Module Learning with Errors as its underlying primitive which is a structured lattices variant that offers good performance and relatively small and balanced key and ciphertext sizes. ML-KEM was standardized with three parameters, ML-KEM-512, ML-KEM-768, and ML-KEM-1024. These were mapped by NIST to the three security levels defined in the NIST PQC Project, Level 1, 3, and 5. These levels correspond to the hardness of breaking AES-128, AES-192 and AES-256 respectively.

ML-KEM-512, ML-KEM-768 and ML-KEM-1024 key exchanges will not have material performance impact on IKEv2/IPsec tunnels which usually stay up for long periods of time and transfer sizable amounts of data. Since the ML-KEM-768 and ML-KEM-1024 public key and ciphertext sizes can exceed the typical network MTU, these key exchanges could require two or three network IP packets from both the initiator and the responder.

## 1.3. Conventions and Definitions

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 [RFC2119] [RFC8174] when, and only when, they appear in all capitals, as shown here.

## 2. ML-KEM in IKEv2

### 2.1. ML-KEM in IKE\_INTERMEDIATE or CREATE\_CHILD\_SA messages

ML-KEM key exchanges can be negotiated in IKE\_INTERMEDIATE or IKE\_FOLLOWUP\_KEY messages as defined in the Multiple Key Exchanges in IKEv2 specification [RFC9370]. We summarize them here for completeness.

Section 2.2.2 of [RFC9370] specifies that  $KE_i(0)$ ,  $KE_r(0)$  are regular key exchange messages in the first `IKE_SA_INIT` exchange which end up generating a set of keying material,  $SK_d$ ,  $SK_a[i/r]$ , and  $SK_e[i/r]$ . The peers then perform an `IKE_INTERMEDIATE` exchange, carrying new Key Exchange payloads. These are protected with the  $SK_e[i/r]$  and  $SK_a[i/r]$  keys which were derived from the `IKE_SA_INIT` as per Section 3.3.1 of the Intermediate Exchange in IKEv2 document [RFC9242]. The initiator generates an ML-KEM keypair ( $sk$ ,  $pk$ ) using `KeyGen()`, and sends the public key ( $pk$ ) to the responder inside a  $KE_i(1)$  payload. The responder will encapsulate a shared secret  $ss$  using `Encaps(pk)` and the resulting ciphertext ( $ct$ ) is sent to initiator using the  $KE_r(1)$ . After the initiator receives  $KE_r(1)$ , it will decapsulate it using `Decaps(sk, ct)`. Both `Encaps` and `Decaps` return the shared secret ( $ss$ ) and both peers have a common shared secret  $SK(1)$  at the end of this  $KE(1)$  exchange. The ML-KEM shared secret is stirred into new keying material  $SK_d$ ,  $SK_a[i/r]$ , and  $SK_e[i/r]$  as defined in Section 2.2.2 of the Multiple Key Exchanges in IKEv2 document [RFC9370]. Afterwards the peers continue to the `IKE_AUTH` exchange phase as defined in Section 3.3.2 of the Intermediate Exchange in IKEv2 specification [RFC9242].

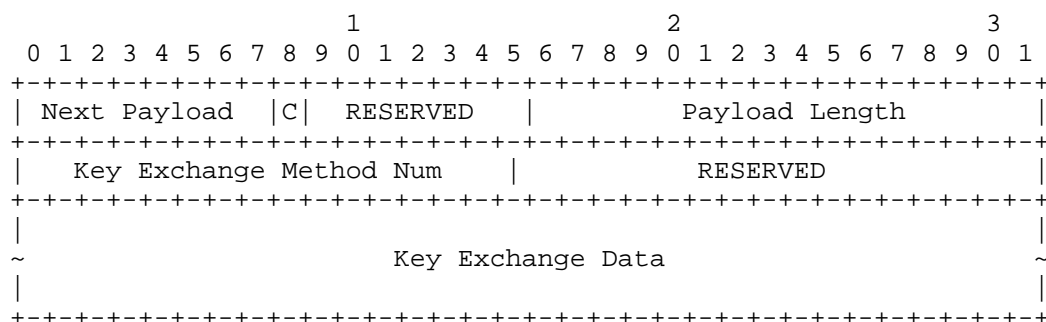
ML-KEM can also be used to create or rekey a Child SA or rekey the IKE SA by using a `IKE_FOLLOWUP_KEY` message after a `CREATE_CHILD_SA` message. After the ML-KEM additional key exchange  $KE(1)$  has taken place using and `IKE_FOLLOWUP_KEY` exchange, the IKE or Child SA are rekeyed by stirring the new ML-KEM shared secret  $SK(1)$  in `SKEYSEED` and `KEYMAT` as specified in Section 2.2.4 of [RFC9370].

ML-KEM-768 and ML-KEM-1024 public keys and ciphertexts may make UDP packet sizes larger than typical network MTUs (1500 bytes). Thus, `IKE_INTERMEDIATE` or `IKE_FOLLOWUP_KEY` messages carrying ML-KEM public keys and ciphertexts may be IKEv2 fragmented as per the IKEv2 Message Fragmentation specification [RFC7383].

Although, this document focuses on using ML-KEM as the second key exchange in a PQ/T Hybrid KEM [I-D.ietf-pquip-pqt-hybrid-terminology-04] scenario, ML-KEM-512 and ML-KEM-768 Key Exchange Method identifiers TBD35 and TBD36 respectively MAY be used in `IKE_SA_INIT` as a quantum-resistant-only key exchange. The encapsulation key and ciphertext sizes for these ML-KEM parameters may not push the UDP packet to size larger than typical network MTUs of 1500 bytes. ML-KEM-1024 Key Exchange Method identifier TBD37 SHOULD NOT be used in `IKE_SA_INIT` messages which could exceed typical network MTUs and cannot be IKEv2 fragmented.

## 2.2. Key Exchange Payload

The KE payload is shown below and the fields inside it has meaning as defined in Section 3.4 of the IKEv2 standard [RFC7296]:



The Key Exchange Data from the initiator to the responder contains the public key (pk) from the KeyGen() operation encoded as a raw byte array (i.e., output of ByteEncode) as defined in Section 7.1 of Module-Lattice-Based KEM standard [FIPS203].

The Key Exchange Data from the responder to the initiator contains the ciphertext (ct) from the Encaps operation encoded as a raw byte array.

Table 1 shows the Payload Length, Key Exchange Method Num identifier and the Key Exchange Data Size in octets for Key Exchange Payloads from the initiator and the responder for the ML-KEM variants specified in this document.

KEM	Payload Length (initiator / responder)	Key Exchange Method Num	Data Size in Octets (initiator / responder)
ML-KEM-512	808 / 776	TBD35	800 / 768
ML-KEM-768	1192 / 1096	TBD36	1184 / 1088
ML-KEM-1024	1576 / 1576	TBD37	1568 / 1568

Table 1: Key Exchange Payload Fields

### 2.3. Recipient Tests

Receiving and handling of malformed ML-KEM public keys or ciphertexts SHOULD follow the input validation described in the Module-Lattice-Based KEM standard [FIPS203].

Responders SHOULD perform the checks specified in section 7.2 of the Module-Lattice-Based KEM standard [FIPS203] before the Encaps(pk) operation. If the checks fail, the responder SHOULD send a Notify payload of type INVALID\_SYNTAX as a response to the request from initiator.

Initiators SHOULD perform the Ciphertext type check specified in section 7.3 of the Module-Lattice-Based KEM standard [FIPS203] before the Decaps(sk, ct) operation. If the check fails, the initiator MUST reject the ciphertext and MUST fail the exchange. In this case, the initiator MAY send a Notify payload of type INVALID\_SYNTAX to the responder as a separate INFORMATIONAL exchange, usually with no other payloads. This is an exception for the general rule of not starting new exchanges based on errors in responses.

Note that during decapsulation, ML-KEM uses implicit rejection which leads the decapsulating entity to implicitly reject the decapsulated shared secret by setting it to a hash of the ciphertext together with a random value stored in the ML-KEM secret when the re-encrypted shared secret does not match the original one.

### 3. Security Considerations

All security considerations from [RFC9242] and [RFC9370] apply to the ML-KEM exchanges described in this specification.

The main security property for KEMs standardized by NIST is indistinguishability under adaptive chosen ciphertext attacks (IND-CCA2), which means that shared secret values should be indistinguishable from random strings even given the ability to have arbitrary ciphertexts decapsulated. IND-CCA2 corresponds to security against an active attacker, and the public key / secret key pair can be treated as a long-term key or reused. A weaker security notion is indistinguishability under chosen plaintext attacks (IND-CPA), which means that the shared secret values should be indistinguishable from random strings given a copy of the public key. IND-CPA roughly corresponds to security against a passive attacker, and sometimes corresponds to one-time key exchange. Generating an ephemeral key exchange keypair for ECDH and ML-KEM is REQUIRED per connection by this specification, as is common practice for (EC)DH keys today.

The ML-KEM public key generated by the initiator and the ciphertext generated by the responder use randomness (usually a seed) which MUST be independent of any other random seed used in the IKEv2 negotiation. For example, at the initiator, the ML-KEM and (EC)DH keypairs used in a PQ/T Hybrid key exchange should not be generated from the same seed.

SKEYSEED and KEYMAT in this specification are generated from PQ/T Hybrid key exchanges by using shared secrets, nonces, and SPIs with a pseudorandom function as defined in [RFC9370]. As discussed in [PQ-PROOF2], such PQ/T Hybrid key derivations are IND-CPA, but not proven to be IND-CCA2 secure although the keys could be reused if the nonces are never reused.

IKEv2 is susceptible to downgrade attacks where an active man-in-the-middle could force the peers to negotiate the weakest key exchange method supported by both. In particular, if both peers support some sequence of key exchanges that involve only classical algorithms, an active, on-path attacker with a CRQC may be able to convince the peers to use it even if they both support ML-KEM as well. Note that to achieve such a downgrade, the adversary needs to break classical (EC)DH IKE\_SA\_INIT ephemeral exchanges while the negotiation is still taking place and completely control the flow to delay or drop legitimate IKEv2 messages. IKEv2 downgrades is a known issue [DOWN-RES] caused by the way IKEv2 authenticates messages only in one direction of the exchange; [PQIKEV2-FA] concluded that IKE\_INTERMEDIATE [RFC9370] does not introduce additional attacks with respect to IKEv2's original security model.

The simplest way to prevent such active attacks is to disable support for classical-only sequences of key exchanges whenever possible. If the responder knows out-of-band that initiators support ML-KEM, then it SHOULD reject any proposal that doesn't include ML-KEM in the IKE\_SA\_INIT or IKE\_INTERMEDIATE. Likewise, if the initiator knows out-of-band that a responder supports ML-KEM, it SHOULD abort the negotiation if the responder selects a proposal that doesn't include ML-KEM. A long-term solution for the downgrade issue in IKEv2 is proposed in [I-D.smyslov-ipsecme-ikev2-downgrade-prevention].

As an alternative, [RFC9370] supports Childless IKE SAs which can be followed by a new Child SA after doing more key exchanges. To ensure that data is encrypted over a quantum-resistant IPsec Child SA, the peers could enforce a policy which first establishes a Childless IKE SA [RFC6023] (or a Child SA which does not encrypt any data) with a classical key exchange without an IKE\_INTERMEDIATE exchange. Subsequently the peers can rekey the initial IKE SA and derive a new Child SA (or rekey the existing Child SA that did not encrypt any data) with additional key exchanges using a CREATE\_CHILD\_SA exchange

followed by IKE\_FOLLOWUP\_KE messages that negotiate (and stir in the SKEYSEED and/or KEYMAT) an ML-KEM shared secret. Section 2.2.5.1 of [RFC9370] discusses the details of such scenarios. This approach could be enforced only for certain, known out-of-band, peer identities that support ML-KEM which are known to the initiator or responder during the CREATE\_CHILD\_SA exchange that follows IKE\_AUTH. It has the disadvantage that an adversary with a CRQC that could decrypt the IKE\_SA\_INIT exchange has access to all the information exchanged over the initial IKE SA or Child SA before the rekey. This information includes the identities of the peers, configuration parameters, and all negotiated SA information (including traffic selectors), but not the information and data encrypted after the CREATE\_CHILD\_SA (and IKE\_FOLLOWUP\_KE with ML-KEM)

#### 4. IANA Considerations

IANA is requested to assign three values for the names "mlkem-512", "mlkem-768", and "mlkem-1024" in the IKEv2 "Transform Type 4 - Key Exchange Method Transform IDs" and has listed this document as the reference. The Recipient Tests field should also point to this document:

Number	Name	Status	Recipient Tests	Reference
TBD35	ml-kem-512		[TBD, this draft, Section 2.3],	[TBD, this draft]
TBD36	ml-kem-768		[TBD, this draft, Section 2.3],	[TBD, this draft]
TBD37	ml-kem-1024		[TBD, this draft, Section 2.3],	[TBD, this draft]
38-1023	Unassigned			

Table 2: Updates to the IANA "Transform Type 4 - Key Exchange Method Transform IDs" table

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