

Faster generic IND-CCA2 secure KEM using “encrypt-then-MAC”

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Abstract. The modular Fujisaki-Okamoto (FO) transformation takes public-key encryption with weaker security and constructs a key encapsulation mechanism (KEM) with indistinguishability under adaptive chosen ciphertext attacks. While the modular FO transform enjoys tight security bound and quantum resistance, it also suffers from computational inefficiency and vulnerabilities to side-channel attacks due to using de-randomization and re-encryption for providing ciphertext integrity. In this work, we propose an alternative KEM construction that achieves ciphertext integrity using a message authentication code (MAC) and instantiate a concrete instance using Kyber. Our experimental results showed that where the encryption routine incurs heavy computational cost, replacing re-encryption with MAC provides substantial performance improvements at comparable security level.

Keywords: Key encapsulation mechanism, post-quantum cryptography, lattice cryptography, Fujisaki-Okamoto transformation

1 Introduction

A key encapsulation mechanism (KEM) [Sho01] is a cryptographic primitive that allows two parties to establish a shared secret over an insecure channel. The desired security standard for a KEM is called indistinguishability under adaptive chosen-ciphertext attack (IND-CCA2). Intuitively speaking, IND-CCA2 security requires that no efficient adversary can distinguish a pseudorandom shared secret from truly random noise, even with access to a decapsulation oracle throughout the attack. However, building a provably IND-CCA2 KEM is tremendously difficult. Early attempts without formal proof, such as RSA encryption defined in PKCS#1 v1.5 [Kal98], were later shown to be vulnerable to practical chosen-ciphertext attack [Ble98]. In recent decades, the most viable approach has been to start with cryptographic primitives possessing weaker security properties, such as a public-key encryption (PKE) scheme with one-way security under chosen-plaintext attack (OW-CPA), then add steps to ensure ciphertext non-malleability [BDPR98]. Some of the earliest proposals for generic IND-CCA2 secure constructions include OAEP [BR94], Fujisaki-Okamoto transformation [FO99][FO13], REACT [OP01b], and GEM [CHJ+02].

On the other hand, chosen-ciphertext security is a solve problem in symmetric cryptography. It is well understood that, by combining an IND-CPA secure symmetric encryption scheme with an existentially unforgeable message authentication code (MAC) in a pattern called “encrypt-then-MAC” [Kra01], one can build an authenticated encryption scheme [BN00] that achieves IND-CCA2 security. While this technique cannot be directly applied in the context of public-key cryptography due to the lack of a shared symmetric key between the two communicating parties, the concept of authenticating ciphertext using a MAC still has strong merits. Abdalla, Rogaway, and Bellare proposed DHIES (also known as “Hashed ElGamal”)[ABR99][ABR01], a hybrid public-key encryption (HPKE) scheme whose IND-CCA2 security reduces to the Gap Diffie-Hellman assumption [OP01a] under the random oracle model. The technique behind DHIES is to derive both the shared secret and a symmetric MAC key by hashing a random PKE plaintext, encrypt the PKE

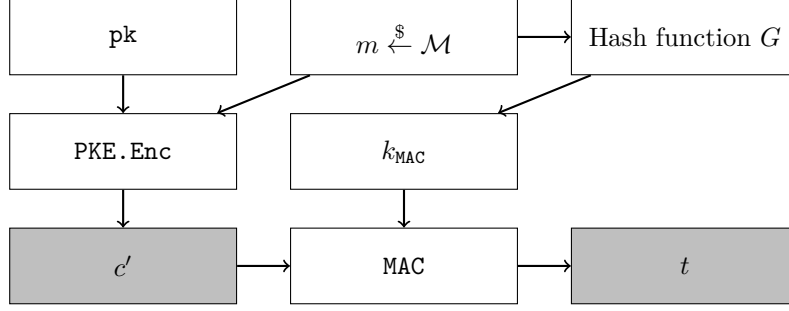


Figure 1: Combining PKE with MAC using “encrypt-then-MAC” to encapsulate a shared secret. The returned values are colored grey

44 plaintext, then authenticate the PKE ciphertext using the previously derived MAC key.
 45 Where the Gap Diffie-Hellman assumption holds and the MAC is existentially unforgeable,
 46 no efficient adversary can recover the decryption of an unknown ciphertext even with
 47 access to a decryption oracle because it cannot produce a valid tag for such unknown
 48 ciphertext.

49 1.1 Our contribution

50 In this paper, we propose a generic IND-CCA2 secure KEM using techniques adapted
 51 from DHIES. We call our proposed scheme the “encrypt-then-MAC” transformation
 52 due to the conceptual similarity to the namesake symmetric encryption technique for
 53 achieving authenticated encryption. A summary of the data flow in the “encrypt-then-MAC”
 54 transformation can be found in figure 1.

55 Our scheme mainly differs from DHIES in its versatility. Whereas the IND-CCA2
 56 security of DHIES reduces specifically to the Gap Diffie-Hellman assumption, the chosen-
 57 ciphertext security of the “encrypt-then-MAC” KEM reduces more generally to the
 58 OW-PCA security [OP01b] of the input scheme (we will show in section 3 that the Gap
 59 Diffie-Hellman assumption implies a special case of OW-PCA security). In addition,
 60 we propose that because each call to encapsulation samples a fresh PKE plaintext, the
 61 “encrypt-then-MAC” KEM can be instantiated with one-time secure MAC such as Poly1305,
 62 which greatly improves the computational efficiency of the scheme.

63 1.1.1 Performance improvements

64 In section 4, we compare the computational performance in a variety of scenarios between
 65 “encrypt-then-MAC” KEM to the modular Fujisaki-Okamoto transformation [HHK17a]. A
 66 major advantage of the “encrypt-then-MAC” construction is the low performance overhead
 67 added to the underlying PKE scheme. We instantiated the “encrypt-then-MAC” KEM
 68 with the underlying PKE routines of ML-KEM and compared its performance to ML-KEM,
 69 which uses the Fujisaki-Okamoto transformation. The Fujisaki-Okamoto transformation
 70 uses *de-randomization* and *re-encryption* to achieve chosen ciphertext security, which
 71 result in substantial performance penalty. When combined with the Poly1305 message
 72 authenticator, our construction ML-KEM⁺ achieves on average 72%-80% reduction of
 73 CPU cycles needed for decapsulation while only incurring 2%-7% increase of CPU cycles
 74 for encapsulation when compared to ML-KEM.

Table 1: ML-KEM⁺ is instantiated with Poly1305

	ML-KEM 512	ML-KEM ⁺ 512	ML-KEM 768	ML-KEM ⁺ 768	ML-KEM 1024	ML-KEM ⁺ 1024
Encap (ccl/tick)	91467	93157 (+1.8%)	136405	146405 (+7.3%)	199185	205763 (+3.3%)
Decap (ccl/tick)	121185	33733 (-72.2%)	186445	43315 (-76.8%)	246245	51375 (-79.1%)
CT size (bytes)	768	784 (+2.1%)	1088	1104 (+1.5%)	1568	1584 (+1.0%)

We also implemented and measured the round trip time of key exchange protocols with various modes of authentication. When compared to ML-KEM, ML-KEM⁺ achieves 24%-28% reduction of round trip time in unauthenticated key exchange (KE), 29%-35% reduction in unilaterally authenticated key exchange (UAKE), and 35%-48% reduction in mutually authenticated key exchange (AKE).

Table 2: Key exchange round-trip times

	ML-KEM 512	ML-KEM ⁺ 512	ML-KEM 768	ML-KEM ⁺ 768	ML-KEM 1024	ML-KEM ⁺ 1024
KE RTT (μ s)	92	70 (-23.9%)	135	99 (-26.7%)	193	138 (-28.5%)
UAKE RTT (μ s)	145	103 (-29.0%)	215	144 (-33.0%)	310	202 (-34.8%)
AKE RTT (μ s)	220	133 (-39.5%)	294	190 (-35.4%)	512	266 (-48.0%)

1.2 Related works

Optimal Asymmetric Encryption Padding (OAEP) [BR94][BDPR98] is a generic PKE construction whose IND-CCA2 security reduces to the one-wayness of the input trapdoor permutation under the random oracle model. OAEP enjoys tight security reduction and minimal performance overhead, but its requirement for a trapdoor permutation is difficult to satisfy. To this day, RSA remains the only practical candidate to instantiate OAEP with [Sho02][FOPS01], and RSA-OAEP saw widespread adoption in Internet communication protocols after its standardization in PKCS#1 v2 [MKJR16].

Originally proposed by Eiichiro Fujisaki and Tatsuaki Okamoto, the Fujisaki-Okamoto transformation [FO99][FO13] is a hybrid PKE whose security reduces non-tightly to the OW-CPA security of the input PKE. Later works by Hofheinz, Hovelmann, and Kiltz [HHK17a][HHM22] made systematic improvements to the original proposal by providing a modular KEM construction whose security tightly reduces to the IND-CPA security of the input PKE. In addition, the authors made extensive security analysis with respect to decryption failure (a non-trivial security flaws in many lattice-based cryptosystems) and provided a non-tight security reduction in the quantum random oracle model (QROM), which made the modular Fujisaki-Okamoto KEM suitable for post-quantum cryptography.

The modular Fujisaki-Okamoto KEM transformation is remarkably successful. It was adopted by many submissions to NIST’s post-quantum cryptography competition, including Kyber [BDK⁺18], Saber [DKRV18], FrodoKEM [BCD⁺16], and classic McEliece [ABC⁺20] among others. When Kyber was standardized by NIST in FIPS 203 “Module-lattice key-encapsulation mechanism” (ML-KEM) [oST24], it kept the Fujisaki-Okamoto transformation in its KEM construction. However, the Fujisaki-Okamoto transformation is not perfect. It uses *de-randomization* and *re-encryption* to achieve *rigidity* [BP18] which then ensures ciphertext integrity. This brings two problems:

- **computational inefficiency:** where the PKE’s encryption routine is substantially more expensive than the decryption routine, using re-encryption causes the decapsulation routine in the output KEM to become computationally expensive

- **side-channel vulnerability:** running the input PKE’s encryption routine in the output KEM’s decapsulation routine introduces risk of side-channel vulnerabilities not found in the input PKE’s decryption routine alone. In fact, many practical attacks [UXT⁺22][RRCB19] exploit re-encryption to decrypt ciphertext or recover secret keys. Countermeasures such as masking have been proposed to address these side channels, but they inevitably carry substantial performance penalty.

2 Preliminaries

2.1 Public-key encryption scheme

Syntax. A public-key encryption scheme $\text{PKE}(\text{KeyGen}, \text{Enc}, \text{Dec})$ is a collection of three routines defined over some plaintext space \mathcal{M} and some ciphertext space \mathcal{C} . $(\text{pk}, \text{sk}) \xleftarrow{\$} \text{KeyGen}()$ is a randomized routine that returns a keypair. The encryption routine $\text{Enc} : (\text{pk}, m) \mapsto c$ encrypts the input plaintext under the input public key. The decryption routine $\text{Dec} : (\text{sk}, c) \mapsto m$ decrypts the input ciphertext under the input secret key. Where the encryption routine is randomized, we denote the randomness by $r \in \mathcal{R}$, where \mathcal{R} is called the coin space. The decryption routine is assumed to always be deterministic. Some decryption routines can detect malformed ciphertext and output the rejection symbol \perp accordingly.

Correctness. Following the definition in [DNR04] and [HHK17b], a PKE is δ -correct if:

$$E \left[\max_{m \in \mathcal{M}} P \left[\text{Dec}(\text{sk}, c) \neq m \mid c \xleftarrow{\$} \text{Enc}(\text{pk}, m) \right] \right] \leq \delta$$

Where the expectation is taken with respect to the probability distribution of all possible keypairs $(\text{pk}, \text{sk}) \xleftarrow{\$} \text{PKE}.\text{KeyGen}()$. For many lattice-based cryptosystems, including ML-KEM, decryption failures could leak information about the secret key, although the probability of a decryption failure is low enough that classical adversaries cannot exploit decryption failure more than they can defeat the underlying lattice problem. On the other hand, a quantum adversary may be able to exploit decryption failure in reasonable runtime by efficiently searching through all possible inputs using Grover’s search algorithm. For that, ML-KEM made slight modifications in its KEM construction to prevent quantum adversary from precomputing large lookup table. We refer readers to [ABD⁺19] and [BDK⁺18] for the details.

Security. We discuss the security of a PKE using the sequence of games described in [Sho04]. Specifically, we first define the OW-ATK as they pertain to a public key encryption scheme. In later section we will define the IND-CCA game as it pertains to a key encapsulation mechanism.

The OW-ATK game

- 1: $(\text{pk}, \text{sk}) \xleftarrow{\$} \text{KeyGen}(1^\lambda)$
- 2: $m^* \xleftarrow{\$} \mathcal{M}$
- 3: $c^* \xleftarrow{\$} \text{Enc}(\text{pk}, m^*)$
- 4: $\hat{m} \xleftarrow{\$} \mathcal{A}^{\text{OW-ATK}}(1^\lambda, \text{pk}, c^*)$
- 5: **return** $\llbracket m^* = \hat{m} \rrbracket$

$\text{PCO}(m \in \mathcal{M}, c \in \mathcal{C})$

- 1: **return** $\llbracket \text{Dec}(\text{sk}, c) = m \rrbracket$
-

Figure 2: One-way security game of PKE (left) and plaintext-checking oracle (right)

141 In the OW-ATK game (see figure 2), an adversary's goal is to recover the decryption of a
 142 randomly generated ciphertext. A challenger randomly samples a keypair and a challenge
 143 plaintext m^* , encrypts the challenge plaintext $c^* \xleftarrow{\$} \text{Enc}(\text{pk}, m^*)$, then gives pk and c^*
 144 to the adversary A . The adversary A , with access to some oracle \mathcal{O}_{ATK} , outputs a guess
 145 decryption \hat{m} . A wins the game if its guess \hat{m} is equal to the challenge plaintext m^* . The
 146 advantage $\text{Adv}_{\text{OW-ATK}}$ of an adversary in this game is the probability that it wins the game:

$$\text{Adv}_{\text{OW-ATK}}(A) = P \left[A(\text{pk}, c^*) = m^* \mid (\text{pk}, \text{sk}) \xleftarrow{\$} \text{KeyGen}(); m^* \xleftarrow{\$} \mathcal{M}; c^* \xleftarrow{\$} \text{Enc}(\text{pk}, m^*) \right]$$

147 The capabilities of the oracle \mathcal{O}_{ATK} depends on the choice of security goal ATK. Particu-
 148 larly relevant to our result is security against plaintext-checking attack (PCA), for which
 149 the adversary has access to a plaintext-checking oracle (PCO) (see figure 2). A PCO takes
 150 as input a plaintext-ciphertext pair (m, c) and returns **True** if m is the decryption of c or
 151 **False** otherwise.

152 2.2 Key encapsulation mechanism (KEM)

153 A key encapsulation mechanism is a collection of three routines (**KeyGen**, **Encap**, **Decap**)
 154 defined over some ciphertext space \mathcal{C} and some key space \mathcal{K} . The key generation routine
 155 takes the security parameter 1^λ and outputs a keypair $(\text{pk}, \text{sk}) \xleftarrow{\$} \text{KeyGen}(1^\lambda)$. **Encap**(pk)
 156 is a probabilistic routine that takes a public key pk and outputs a pair of values (c, K)
 157 where $c \in \mathcal{C}$ is the ciphertext (also called encapsulation) and $K \in \mathcal{K}$ is the shared secret
 158 (also called session key). **Decap**(sk, c) is a deterministic routine that takes the secret key
 159 sk and the encapsulation c and returns the shared secret K if the ciphertext is valid. Some
 160 KEM constructions use explicit rejection, where if c is invalid then **Decap** will return a
 161 rejection symbol \perp ; other KEM constructions use implicit rejection, where if c is invalid
 162 then **Decap** will return a fake session key that depends on the ciphertext and some other
 163 secret values.

164 The IND-CCA security of a KEM is defined by an adversarial game in which an
 165 adversary's goal is to distinguish pseudorandom shared secret (generated by running the
 166 **Encap** routine) and a truly random value.

KEM-IND-CCA2 game

- 1: $(\text{pk}, \text{sk}) \xleftarrow{\$} \text{KeyGen}(1^\lambda)$
- 2: $(c^*, K_0) \xleftarrow{\$} \text{Encap}(\text{pk})$
- 3: $K_1 \xleftarrow{\$} \mathcal{K}$
- 4: $b \xleftarrow{\$} \{0, 1\}$
- 5: $\hat{b} \xleftarrow{\$} A^{\mathcal{O}_{\text{Decap}}}(1^\lambda, \text{pk}, c^*, K_b)$
- 6: **return** $\llbracket \hat{b} = b \rrbracket$

$\mathcal{O}_{\text{Decap}}(c)$

- 1: **return** **Decap**(sk, c)
-

Figure 3: IND-CCA2 game for KEM (left) and decapsulation oracle (right)

167 The decapsulation oracle $\mathcal{O}^{\text{Decap}}$ takes a ciphertext c and returns the output of the
 168 **Decap** routine using the secret key. The advantage $\epsilon_{\text{IND-CCA}}$ of an IND-CCA adversary
 169 $\mathcal{A}_{\text{IND-CCA}}$ is defined by

$$\text{Adv}_{\text{IND-CCA}}(A) = \left| P[A^{\mathcal{O}_{\text{Decap}}}(1^\lambda, \text{pk}, c^*, K_b) = b] - \frac{1}{2} \right|$$

2.3 Message authentication code (MAC)

A message authentication code **MAC** is a collection of routines (**Sign**, **Verify**) defined over some key space \mathcal{K} , some message space \mathcal{M} , and some tag space \mathcal{T} . The signing routine **Sign**(k, m) takes the secret key $k \in \mathcal{K}$ and some message, and outputs a tag t . The verification routine **Verify**(k, m, t) takes the triplet of secret key, message, and tag, and outputs 1 if the message-tag pair is valid under the secret key, or 0 otherwise. Many MAC constructions are deterministic. For these constructions it is simpler to denote the signing routine by $t \leftarrow \text{MAC}(k, m)$ and perform verification using a simple comparison.

The security of a MAC is defined in an adversarial game in which an adversary, with access to some signing oracle $\mathcal{O}_{\text{sign}}(m)$, tries to forge a new valid message-tag pair that has never been queried before. The existential unforgeability under chosen message attack (EUF-CMA) game is shown below:

EUF-CMA game

- 1: $k^* \xleftarrow{\$} \mathcal{K}$
 - 2: $(\hat{m}, \hat{t}) \xleftarrow{\$} \mathcal{A}^{\mathcal{O}_{\text{sign}}()}$
 - 3: **return** $\llbracket \text{Verify}(k^*, \hat{m}, \hat{t}) \wedge (\hat{m}, \hat{t}) \notin \mathcal{O}_{\text{sign}} \rrbracket$
-

Figure 4: The existential forgery game

The advantage $\text{Adv}_{\text{EUF-CMA}}$ of the existential forgery adversary is the probability that it wins the EUF-CMA game.

3 The “encrypt-then-MAC” transformation

Let \mathcal{B}^* denote the set of finite bit strings. Let $\text{PKE}(\text{KeyGen}, \text{Enc}, \text{Dec})$ be a public-key encryption scheme defined over message space \mathcal{M} and ciphertext space \mathcal{C} . Let $\text{MAC} : \mathcal{K}_{\text{MAC}} \times \mathcal{B}^* \rightarrow \mathcal{T}$ be a deterministic message authentication code that takes a key $k \in \mathcal{K}_{\text{MAC}}$, some message $m \in \mathcal{B}^*$, and outputs a digest $t \in \mathcal{T}$. Let $G : \mathcal{M} \rightarrow \mathcal{K}_{\text{MAC}}$ be a hash function that maps from PKE’s plaintext space to MAC’s key space. Let $H : \mathcal{B}^* \rightarrow \mathcal{K}_{\text{KEM}}$ be a hash function that maps bit strings into the set of possible shared secrets. The “encrypt-then-MAC” transformation $\text{EtM}[\text{PKE}, \text{MAC}, G, H]$ constructs a key encapsulation mechanism $\text{KEM}_{\text{EtM}}(\text{KeyGen}_{\text{KEM}}, \text{Encap}, \text{Decap})$, whose routines are described in figure 5.

$\text{KEM}_{\text{EtM}}.\text{KeyGen}()$	$\text{KEM}_{\text{EtM}}.\text{Decap}(\text{sk}, c)$
1: $(\text{pk}, \text{sk}') \xleftarrow{\$} \text{PKE}.\text{KeyGen}()$ 2: $z \xleftarrow{\$} \mathcal{M}$ 3: $\text{sk} \leftarrow \text{sk}' \ z$ 4: return (pk, sk)	1: $(c', t) \leftarrow c$ 2: $(\text{sk}', z) \leftarrow \text{sk}$ 3: $\hat{m} \leftarrow \text{PKE}.\text{Dec}(\text{sk}', c')$ 4: $\hat{k} \leftarrow G(\hat{m})$ 5: if $\text{MAC}(\hat{k}, c') \neq t$ then 6: $K \leftarrow H(z, c')$ 7: else 8: $K \leftarrow H(\hat{m}, c')$ 9: end if 10: return K
$\text{KEM}_{\text{EtM}}.\text{Encap}(\text{pk})$	
1: $m \xleftarrow{\$} \mathcal{M}$ 2: $k \leftarrow G(m)$ 3: $c' \xleftarrow{\$} \text{PKE}.\text{Enc}(\text{pk}, m)$ 4: $t \leftarrow \text{MAC}(k, c')$ 5: $K \leftarrow H(m, c')$ 6: $c \leftarrow c' \ t$ 7: return (c, K)	

Figure 5: KEM_{EtM} routines

193 The key generation routine of KEM_{EtM} is largely identical to that of the PKE, only a
194 secret value z is sampled as the implicit rejection symbol. In the encapsulation routine,
195 a MAC key is derived from the randomly sampled plaintext $k \leftarrow G(m)$, then used
196 to sign the unauthenticated ciphertext c' . Because the encryption routine might be
197 randomized, the session key is derived from both the message and the ciphertext. Finally,
198 the unauthenticated ciphertext c' and the tag t combine into the authenticated ciphertext
199 c that would be transmitted to the peer. In the decapsulation routine, the decryption \hat{m}
200 of the unauthenticated ciphertext is used to re-derive the MAC key \hat{k} , which is then used
201 to re-compute the tag \hat{t} . The ciphertext is considered valid if and only if the recomputed
202 tag is identical to the input tag.

203 For an adversary A to produce a valid tag t for some unauthenticated ciphertext
204 c' under the symmetric key $k \leftarrow G(\text{Dec}(\text{sk}', c'))$ implies that A must either know the
205 symmetric key k or produce a forgery. Under the random oracle model, A also cannot
206 know k without knowing its preimage $\text{Dec}(\text{sk}', c')$, so A must either have produced c'
207 honestly, or have broken the one-way security of PKE. This means that the decapsulation
208 oracle will not give out information on decryptions that the adversary does not already
209 know.

$\text{PCO}(m, c)$
1: $k \leftarrow G(m)$ 2: $t \leftarrow \text{MAC}(k, c)$ 3: return $\llbracket \mathcal{O}^{\text{Decap}}((c, t)) = H(m, c) \rrbracket$

Figure 6: Every decapsulation oracle can be converted into a plaintext-checking oracle

210 However, a decapsulation oracle can still give out some information: for a known
211 plaintext m , all possible encryptions $c' \xleftarrow{\$} \text{Enc}(\text{pk}, m)$ can be correctly signed, while
212 ciphertexts that don't decrypt back to m cannot be correctly signed. This means that a
213 decapsulation oracle can be converted into a plaintext-checking oracle (see figure 6), so

every chosen-ciphertext attack against the KEM can be converted into a plaintext-checking attack against the underlying PKE.

On the other hand, if the underlying PKE is one-way secure against plaintext-checking attack that makes q plaintext-checking queries, then “encrypt-then-MAC” KEM is semantically secure under chosen ciphertext attacks making the same number of decapsulation queries:

Theorem 1. *For every IND-CCA2 adversary A against KEM_{ETM} that makes q decapsulation queries, there exists an OW-PCA adversary B who makes at least q plaintext-checking queries against the underlying PKE, and an one-time existential forgery adversary C against the underlying MAC such that*

$$\text{Adv}_{\text{IND-CCA2}}(A) \leq q \cdot \text{Adv}_{\text{OT-MAC}}(C) + 2 \cdot \text{Adv}_{\text{OW-PCA}}(B)$$

Theorem 1 naturally flows into an equivalence relationship between the security of the KEM and the security of the PKE:

Lemma 1. *KEM_{ETM} is IND-CCA2 secure if and only if the input PKE is OW-PCA secure*

3.1 Proof of theorem 1

We will prove theorem 1 using a sequence of game. A summary of the the sequence of games can be found in figure 7 and 8. From a high level we made three incremental modifications to the IND-CCA2 game for KEM_{ETM} : replace true decapsulation with simulated decapsulation, replace the pseudorandom MAC key $k^* \leftarrow G(m^*)$ with a truly random MAC key $k^* \xleftarrow{\$} \mathcal{K}_{\text{MAC}}$, and finally replace pseudorandom shared secret $K_0 \leftarrow H(m^*, c')$ with a truly random shared secret $K_0 \xleftarrow{\$} \mathcal{K}_{\text{KEM}}$. A OW-PCA adversary can then simulate the modified IND-CCA2 game for the KEM adversary, and the advantage of the OW-PCA adversary is associated with the probability of certain behaviors of the KEM adversary.

Proof. *Game 0* is the standard IND-CCA2 game for KEMs. The decapsulation oracle $\mathcal{O}^{\text{Decap}}$ executes the decapsulation routine using the challenge keypair and return the results faithfully. The queries made to the hash oracles $\mathcal{O}^G, \mathcal{O}^H$ are recorded to their respective tapes $\mathcal{L}^G, \mathcal{L}^H$.

Game 1 is identical to game 0 except that the true decapsulation oracle $\mathcal{O}^{\text{Decap}}$ is replaced with a simulated oracle $\mathcal{O}_1^{\text{Decap}}$. Instead of directly decrypting c' as in the decapsulation routine, the simulated oracle searches through the tape \mathcal{L}^G to find a matching query (\tilde{m}, \tilde{k}) such that \tilde{m} is the decryption of c' . The simulated oracle then uses \tilde{k} to validate the tag t against c' .

If the simulated oracle accepts the queried ciphertext as valid, then there is a matching query that also validates the tag, which means that the queried ciphertext is honestly generated. Therefore, the true oracle must also accept the queried ciphertext. On the other hand, if the true oracle rejects the queried ciphertext (and output the implicit rejection $H(z, c')$), then the tag is simply invalid under the MAC key $k = G(\text{Dec}(\text{sk}', c'))$. Therefore, there could not have been a matching query that also validates the tag, and the simulated oracle must also rejects the queried ciphertext.

This means that from the adversary A 's perspective, game 1 and game 0 differ only when the true oracle accepts while the simulated oracle rejects, which means that t is a valid tag for c' under $k = G(\text{Dec}(\text{sk}', c'))$, but k has never been queried. Under the random oracle model, such k is a uniformly random sample of \mathcal{K}_{MAC} that the adversary does not know, so for A to produce a valid tag is to produce a forgery against the MAC under an unknown and uniformly random key. Furthermore, the security game does not include a signing oracle, so this is a zero-time forgery. While zero-time forgery is not a standard

IND-CCA2 game for KEM_{EtM}	$\mathcal{O}^{\text{Decap}}(c)$
1: $(\text{pk}, \text{sk}) \xleftarrow{\$} \text{KEM}_{\text{EtM}}.\text{KeyGen}()$ 2: $m^* \xleftarrow{\$} \mathcal{M}$ 3: $c' \xleftarrow{\$} \text{PKE}.\text{Enc}(\text{pk}, m^*)$ 4: $k^* \leftarrow G(m^*)$ \triangleright Game 0-1 5: $k^* \xleftarrow{\$} \mathcal{K}_{\text{MAC}}$ \triangleright Game 2-3 6: $t \leftarrow \text{MAC}(k^*, c')$ 7: $c^* \leftarrow c' t$ 8: $K_0 \leftarrow H(m^*, c')$ \triangleright Game 0-2 9: $K_0 \xleftarrow{\$} \mathcal{K}_{\text{KEM}}$ \triangleright Game 3 10: $K_1 \xleftarrow{\$} \mathcal{K}_{\text{KEM}}$ 11: $b \xleftarrow{\$} \{0, 1\}$ 12: $\hat{b} \leftarrow A^{\mathcal{O}^{\text{Decap}}}(\text{pk}, c^*, K_b)$ \triangleright Game 0 13: $\hat{b} \leftarrow A^{\mathcal{O}_1^{\text{Decap}}}(\text{pk}, c^*, K_b)$ \triangleright Game 1-3 14: return $\llbracket \hat{b} = b \rrbracket$	1: $(c', t) \leftarrow c$ 2: $\hat{m} = \text{Dec}(\text{sk}', c')$ 3: $\hat{k} \leftarrow G(\hat{m})$ 4: if $\text{MAC}(\hat{k}, c') = t$ then 5: $K \leftarrow H(\hat{m}, c')$ 6: else 7: $K \leftarrow H(z, c')$ 8: end if 9: return K
$\mathcal{O}^G(m)$	$\mathcal{O}_1^{\text{Decap}}(c)$
1: if $\exists(\tilde{m}, \tilde{k}) \in \mathcal{L}^G : \tilde{m} = m$ then 2: return \tilde{k} 3: end if 4: $k \xleftarrow{\$} \mathcal{K}_{\text{MAC}}$ 5: $\mathcal{L}^G \leftarrow \mathcal{L}^G \cup \{(m, k)\}$ 6: return k	1: $(c', t) \leftarrow c$ 2: if $\exists(\tilde{m}, \tilde{k}) \in \mathcal{L}^G : \tilde{m} = \text{Dec}(\text{sk}', c') \wedge \text{MAC}(\tilde{k}, c') = t$ then 3: $K \leftarrow H(\tilde{m}, c')$ 4: else 5: $K \leftarrow H(z, c')$ 6: end if 7: return K
$\mathcal{O}^H(m, c)$	$\mathcal{O}^H(m, c)$
	1: if $\exists(\tilde{m}, \tilde{c}, \tilde{K}) \in \mathcal{L}^H : \tilde{m} = m \wedge \tilde{c} = c$ then 2: return \tilde{K} 3: end if 4: $K \xleftarrow{\$} \mathcal{K}_{\text{KEM}}$ 5: $\mathcal{L}^H \leftarrow \mathcal{L}^H \cup \{(m, c, K)\}$ 6: return K

Figure 7: Sequence of games

259 security definition for a MAC, we can bound it by the advantage of a one-time forgery
260 adversary C :

$$P \left[\mathcal{O}^{\text{Decap}}(c) \neq \mathcal{O}_1^{\text{Decap}}(c) \right] \leq \text{Adv}_{\text{OT-MAC}}(C)$$

261 Across all q decapsulation queries, the probability that at least one query is a forgery
262 is thus at most $q \cdot P \left[\mathcal{O}^{\text{Decap}}(c) \neq \mathcal{O}_1^{\text{Decap}}(c) \right]$. By the difference lemma:

$$\text{Adv}_{G_0}(A) - \text{Adv}_{G_1}(A) \leq q \cdot \text{Adv}_{\text{OT-MAC}}(C)$$

263 *Game 2* is identical to game 1, except that the challenger samples a uniformly random
264 MAC key $k^* \xleftarrow{\$} \mathcal{K}_{\text{MAC}}$ instead of deriving it from m^* . From A 's perspective the two games
265 are indistinguishable, unless A queries G with the value of m^* . Denote the probability
266 that A queries G with m^* by $P[\text{QUERY } G]$, then:

$$\text{Adv}_{G_1}(A) - \text{Adv}_{G_2}(A) \leq P[\text{QUERY } G]$$

267 *Game 3* is identical to game 2, except that the challenger samples a uniformly random
 268 shared secret $K_0 \xleftarrow{\$} \mathcal{K}_{\text{KEM}}$ instead of deriving it from m^* and c' . From A 's perspective the
 269 two games are indistinguishable, unless A queries H with (m^*, \cdot) . Denote the probability
 270 that A queries H with (m^*, \cdot) by $P[\text{QUERY } H]$, then:

$$\text{Adv}_{G_2}(A) - \text{Adv}_{G_3}(A) \leq P[\text{QUERY } H]$$

271 Since in game 3, both K_0 and K_1 are uniformly random and independent of all other
 272 variables, no adversary can have any advantage: $\text{Adv}_{G_3}(A) = 0$.

$B(\text{pk}, c'^*)$	$\mathcal{O}_B^{\text{Decap}}(c)$
1: $z \xleftarrow{\$} \mathcal{M}$ 2: $k \xleftarrow{\$} \mathcal{K}_{\text{MAC}}$ 3: $t \leftarrow \text{MAC}(k, c'^*)$ 4: $c^* \leftarrow (c'^*, t)$ 5: $K \xleftarrow{\$} \mathcal{K}_{\text{KEM}}$ 6: $\hat{b} \leftarrow A^{\mathcal{O}_B^{\text{Decap}}, \mathcal{O}_B^G, \mathcal{O}_B^H}(\text{pk}, c^*, K)$ 7: if $\text{ABORT}(m)$ then 8: return m 9: end if	1: $(c', t) \leftarrow c$ 2: if $\exists(\tilde{m}, \tilde{k}) \in \mathcal{L}^G : \text{PCO}(c', \tilde{m}) = 1 \wedge \text{MAC}(k, c') = t$ then 3: $K \leftarrow H(\tilde{m}, c')$ 4: else 5: $K \leftarrow H(z, c')$ 6: end if 7: return K
$\mathcal{O}_B^H(m, c)$	$\mathcal{O}_B^G(m)$
if $\text{PCO}(m, c'^*) = 1$ then $\text{ABORT}(m)$ end if if $\exists(\tilde{m}, \tilde{c}, \tilde{K}) \in \mathcal{L}^H : \tilde{m} = m \wedge \tilde{c} = c$ then return \tilde{K} end if $K \xleftarrow{\$} \mathcal{K}_{\text{KEM}}$ $\mathcal{L}^H \leftarrow \mathcal{L}^H \cup \{(m, c, K)\}$ return K	1: if $\text{PCO}(m, c'^*) = 1$ then 2: $\text{ABORT}(m)$ 3: end if 4: if $\exists(\tilde{m}, \tilde{k}) \in \mathcal{L}^G : \tilde{m} = m$ then 5: return \tilde{k} 6: end if 7: $k \xleftarrow{\$} \mathcal{K}_{\text{MAC}}$ 8: $\mathcal{L}^G \leftarrow \mathcal{L}^G \cup \{(m, k)\}$ 9: return k

Figure 8: OW-PCA adversary B simulates game 3 for IND-CCA2 adversary A

273 We will bound $P[\text{QUERY } G]$ and $P[\text{QUERY } H]$ by constructing a OW-PCA adversary B
 274 against the underlying PKE that uses A as a sub-routine. B 's behaviors are summarized
 275 in figure 8.

276 B simulates game 3 for A : receiving the public key pk and challenge encryption c'^* , B
 277 samples random MAC key and session key to produce the challenge encapsulation, then
 278 feeds it to A . When simulating the decapsulation oracle, B uses the plaintext-checking
 279 oracle to look for matching queries in \mathcal{L}^G . When simulating the hash oracles, B uses the
 280 plaintext-checking oracle to detect when $m^* = \text{Dec}(\text{sk}', c'^*)$ has been queried. When m^*
 281 is queried, B terminates A and returns m^* to win the OW-PCA game. In other words:

$$\begin{aligned} P[\text{QUERY } G] &\leq \text{Adv}_{\text{OW-PCA}}(B) \\ P[\text{QUERY } H] &\leq \text{Adv}_{\text{OW-PCA}}(B) \end{aligned}$$

282 Combining all equations above produce the desired security bound. \square

4 Implementation

ML-KEM is an IND-CCA2 secure key encapsulation mechanism standardized by NIST in FIPS 203. The IND-CCA2 security of ML-KEM is achieved in two steps. First, ML-KEM constructs an IND-CPA secure public key encryption scheme K-PKE(KeyGen, Enc, Dec) whose security is based on the conjectured intractability of the module learning with error (MLWE) problems against both classical and quantum adversaries. Then, the U_m^L variant of the Fujisaki-Okamoto transformation [HHK17b] is used to construct the KEM MLKEM(KeyGen, Encap, Decap) by calling K-PKE(KeyGen, Enc, Dec) as sub-routines. Because K-PKE.Enc includes substantially more arithmetics than K-PKE.Dec, by using *re-encryption* and *de-randomization*, ML-KEM's decapsulation routine incurs significant computational cost.

We implemented the “encrypt-then-MAC” KEM construction using K-PKE as the input PKE and compared its performance against ML-KEM under a variety of scenarios. The experimental data showed that while the “encrypt-then-MAC” construction adds a small amount of computational overhead to the encapsulation routine and a small increase in ciphertext size when compared with ML-KEM, it boasts enormous runtime savings in the decapsulation routine, which makes it particularly suitable for deployment in constrained environment. See appendix 6.1 for comparison with Kyber's third round submission to NIST's PQC competition.

We refer readers to [oST24] for the details of the K-PKE routines. The “encrypt-then-MAC” KEM routines are described in figure 9 below.

ML-KEM ⁺ .KeyGen()	ML-KEM ⁺ .Decap(sk, c)
<ol style="list-style-type: none"> 1: $z \xleftarrow{\\$} \{0, 1\}^{256}$ 2: $(pk, sk') \xleftarrow{\\$} \text{K-PKE.KeyGen}()$ 3: $h \leftarrow H(pk)$ 4: $sk \leftarrow (sk' pk h z)$ 5: return (pk, sk) 	<p>Require: Secret key $sk = (sk' pk h z)$</p> <p>Require: Ciphertext $c = (c' t)$</p> <ol style="list-style-type: none"> 1: $(sk', pk, h, z) \leftarrow sk$ 2: $(c', t) \leftarrow c$ 3: $\hat{m} \leftarrow \text{K-PKE.Dec}(sk', c')$ 4: $(\bar{K}, \hat{r}, \hat{k}) \leftarrow \text{XOF}(\hat{m} h)$ 5: $\hat{t} \leftarrow \text{MAC}(\hat{k}, c')$ 6: if $\hat{t} = t$ then 7: $K \leftarrow \text{KDF}(\bar{K} t)$ 8: else 9: $K \leftarrow \text{KDF}(z t)$ 10: end if 11: return K
ML-KEM ⁺ .Encap(pk)	
<p>Require: Public key pk</p> <ol style="list-style-type: none"> 1: $m \xleftarrow{\\$} \{0, 1\}^{256}$ 2: $(\bar{K}, r, k) \leftarrow \text{XOF}(m H(pk))$ 3: $c' \leftarrow \text{K-PKE.Enc}(pk, m, r)$ 4: $t \leftarrow \text{MAC}(k, c')$ 5: $K \leftarrow \text{KDF}(\bar{K} c')$ 6: $c \leftarrow (c', t)$ 7: return (c, K) 	

Figure 9: ML-KEM⁺ routines

Our implementation extended from the reference implementation by the PQCrystals team (<https://github.com/pq-crystals/kyber>). All C code is compiled with GCC 11.4.1 and OpenSSL 3.0.8. All binaries are executed on an AWS c7a.medium instance with an AMD EPYC 9R14 CPU at 3.7 GHz and 1 GB of RAM.

4.1 Choosing a message authenticator

For the ML-KEM⁺ implementation, we instantiated MAC with a selection that covered a wide range of MAC designs, including Poly1305 [Ber05], GMAC [MV04], CMAC [IK03][BR05], and KMAC [Gro13].

Poly1305 and GMAC are both Carter-Wegman style authenticators [WC81] that compute the tag using finite field arithmetic. Generically speaking, Carter-Wegman MAC is parameterized by some finite field \mathbb{F} and the maximal message length $L > 0$. Each symmetric key $k = (k_1, k_2) \xleftarrow{\$} \mathbb{F}^2$ is a pair of uniformly random field elements, and the message is parsed into tuples of field elements up to length L : $m = (m_1, m_2, \dots, m_l) \in \mathbb{F}^{\leq L}$. The tag t is computed by evaluating a polynomial whose coefficients are the message blocks and whose indeterminate is the key:

$$\text{MAC}((k_1, k_2), m) = H_{\text{xpoly}}(k_1, m) + k_2 \quad (1)$$

Where H_{xpoly} is given by:

$$H_{\text{xpoly}}(k_1, m) = k_1^{l+1} + k_1^l \cdot m_1 + k_1^{l-1} \cdot m_2 + \dots + k_1 \cdot m_l$$

The authenticator formulated in equation 1 is a one-time MAC. To make the construction many-time secure, a non-repeating nonce r and a PRF is needed:

$$\text{MAC}((k_1, k_2), m, r) = H_{\text{xpoly}}(k_1, m) \oplus \text{PRF}(k_2, r)$$

Specifically, Poly1305 operates in the prime field \mathbb{F}_q where $q = 2^{130} - 5$ whereas GMAC operates in the binary field $\mathbb{F}_{2^{128}}$. In OpenSSL’s implementation, standalone Poly1305 is a one-time secure MAC, whereas GMAC uses a nonce and AES as the PRF and is thus many-time secure (in OpenSSL GMAC is AES-256-GCM except all data is fed into the “associated data” section and thus not encrypted).

CMAC is based on the CBC-MAC with the block cipher instantiated from AES-256. To compute a CMAC tag, the message is first broke into 128-bit blocks with appropriate padding. Each block is first XOR’d with the previous block’s output, then encrypted under AES using the symmetric key. The final output is XOR’d with a sub key derived from the symmetric key, before being encrypted for one last time.

KMAC is defined in [Gro13] to be based on the family of sponge functions with Keccak permutation as the underlying function. We chose KMAC-256, which uses Shake256 as the underlying extendable output functions. KMAC allows variable-length key and tag, but we chose the 256 bits for key length and 128 bits for tag size for consistency with other authenticators.

To isolate the performance characteristics of each authenticator in our instantiation of ML-KEM⁺, we measured the CPU cycles needed for each authenticator to compute a tag on random inputs whose sizes correspond to the ciphertext sizes of ML-KEM. The measurements are summarized in table 3.

From our testing, we found Poly1305 to exhibit the best performance characteristics. However, there are additional security considerations that may require the use of other less efficient MAC instances. For example, it is possible for an adversary with large computing infrastructure or quantum computers to pre-compute a large lookup table mapping symmetric key to the source plaintext. Upon receiving a ciphertext, the adversary can then search through the lookup table for a matching key, which would’ve revealed the corresponding decryption. We partially mitigated such attack by deriving the symmetric key from both the public key and the plaintext, but in case of a long-term keypair, the adversary might still be able to compute a large lookup table AFTER obtaining the long-term public key. Further mitigation could include using larger-size keys, which can be accomplished either by using a Carter-Wegman MAC that operates on a larger finite field or using a MAC with a variable key-length such as KMAC.

Table 3: CPU cycles needed to compute tag on various input sizes

Input size: 768 bytes			Input size: 1088 bytes			Input size: 1568 bytes		
MAC	Median	Average	MAC	Median	Average	MAC	Median	Average
Poly1305	909	2823	Poly1305	961	2704	Poly1305	1065	1809
GMAC	3899	4859	GMAC	3899	4827	GMAC	4055	5026
CMAC	6291	6373	CMAC	7305	7588	CMAC	8735	8772
KMAC	6373	7791	KMAC	9697	9928	KMAC	11647	12186

4.2 KEM performance

Compared to the U_m^\perp variant of Fujisaki-Okamoto transformed used in ML-KEM, the “encrypt-then-MAC” transformation the following trade-off when given the same input sub-routines:

- Both encapsulation and decapsulation add a small amount of overhead for needing to hash both the PKE plaintext and the PKE ciphertext when deriving the shared secret, where as the U_m^\perp transformation only needs to hash the PKE plaintext.
- The encapsulation routine adds a small amount of run-time overhead for computing the authenticator
- The decapsulation routine enjoys substantial runtime speedup because *re-encryption* is replaced with computing an authenticator
- Ciphertext size increases by the size of an authenticator

Since K-PKE.Enc carries significantly more computational complexity than K-PKE.Dec or any MAC we chose, the performance advantage of the “encrypt-then-MAC” transformation over the U_m^\perp transformation is dominated by the runtime saving gained from replacing *re-encryption* with MAC. A comparison between ML-KEM and variations of the ML-KEM⁺ can be found in table 4

Table 4: CPU cycles of each KEM routine

128-bit security		KEM variant		Encap cycles/tick		Decap cycles/tick	
size parameters (bytes)				Median	Average	Median	Average
pk size	800	ML-KEM-512		91467	92065	121185	121650
sk size	1632	Kyber512		97811	98090	119937	120299
ct size	768	ML-KEM ⁺ -512 w/ Poly1305		93157	93626	33733	33908
KeyGen cycles/tick		ML-KEM ⁺ -512 w/ GMAC		97369	97766	37725	37831
Median	75945	ML-KEM ⁺ -512 w/ CMAC		99739	99959	40117	39943
Average	76171	ML-KEM ⁺ -512 w/ KMAC		101009	101313	40741	40916

192-bit security		KEM variant		Encap cycles/tick		Decap cycles/tick	
size parameters (bytes)				Median	Average	Median	Average
pk size	1184	ML-KEM-768		136405	147400	186445	187529
sk size	2400	Kyber768		153061	153670	182129	182755
ct size	1088	ML-KEM ⁺ -768 w/ Poly1305		146405	146860	43315	43463
KeyGen cycles/tick		ML-KEM ⁺ -768 w/ GMAC		149525	150128	46513	46706
Median	129895	ML-KEM ⁺ -768 w/ CMAC		153139	153735	49841	50074
Average	130650	ML-KEM ⁺ -768 w/ KMAC		155219	155848	52415	52611

256-bit security		KEM variant		Encap cycles/tick		Decap cycles/tick	
size parameters (bytes)				Median	Average	Median	Average
pk size	1568	ML-KEM-1024		199185	199903	246245	247320
sk size	3168	Kyber1024		222351	223260	258231	259067
ct size	1568	ML-KEM ⁺ -1024 w/ Poly1305		205763	206499	51375	51562
KeyGen cycles/tick		ML-KEM ⁺ -1024 w/ GMAC		208805	209681	54573	54780
Median	194921	ML-KEM ⁺ -1024 w/ CMAC		213667	214483	59175	59408
Average	195465	ML-KEM ⁺ -1024 w/ KMAC		216761	217468	62269	62516

4.3 Key exchange protocols

A common application of key encapsulation mechanism is key exchange protocols, where two parties establish a shared secret using a public channel. [BDK⁺18] described three key exchange protocols: unauthenticated key exchange (KE), unilaterally authenticated key exchange (UAKE), and mutually authenticated key exchange (AKE). We instantiated an implementation for each of the three key exchange protocols using different variations of the “encrypt-then-MAC” KEM and compared round trip time with implementations instantiated using ML-KEM.

For clarity, we denote the party who sends the first message to be the client and the other party to be the server. Round trip time (RTT) is defined to be the time interval between the moment before the client starts generating ephemeral keypairs and the moment after the client derives the final session key. All experiments are run on a pair of AWS c7a.medium instances both located in the **us-west-2** region. For each experiment, a total of 10,000 rounds of key exchange are performed, with the median and average round trip time (measured in microsecond) recorded.

4.3.1 Unauthenticated key exchange (KE)

In unauthenticated key exchange, a single pair of ephemeral keypair $(\mathbf{pk}_e, \mathbf{sk}_e) \xleftarrow{\$} \text{KeyGen}()$ is generated by the client. The client transmits the ephemeral public key \mathbf{pk}_e to the server, who runs the encapsulation routine $(c_e, K_e) \xleftarrow{\$} \text{Encap}(\mathbf{pk}_e)$ and transmits the ciphertext c_e back to the client. The client finally decapsulates the ciphertext to recover the shared secret $K_e \leftarrow \text{Decap}(\mathbf{sk}_e, c_e)$. The key exchange routines are summarized in figure 10.

Note that in our implementation, a key derivation function (KDF) is applied to the ephemeral shared secret to derive the final session key. This step is added to maintain consistency with other authenticated key exchange protocols, where the final session key is derived from multiple shared secrets. The key derivation function is instantiated using Shake256, and the final session key is 256 bits in length.

$\text{KE}_C()$	$\text{KE}_S()$
1: $(\mathbf{pk}_e, \mathbf{sk}_e) \xleftarrow{\$} \text{KeyGen}()$	1: $\mathbf{pk}_e \leftarrow \text{read}()$
2: $\text{send}(\mathbf{pk}_e)$	2: $(c_e, K_e) \xleftarrow{\$} \text{Encap}(\mathbf{pk}_e)$
3: $c_e \leftarrow \text{read}()$	3: $\text{send}(c_e)$
4: $K_e \leftarrow \text{Decap}(\mathbf{sk}_e, c_e)$	4: $K \leftarrow \text{KDF}(K_e)$
5: $K \leftarrow \text{KDF}(K)$	5: $\text{return } K$
6: $\text{return } K$	

Figure 10: Unauthenticated key exchange (KE) routines

The RTT comparison is summarized in table 5

Table 5: KE RTT comparison

KEM variant	Client TX bytes	Server TX bytes	RTT time (μs)	
			Median	Average
ML-KEM-512	800	768	92	97
ML-KEM-512 ⁺ w/ Poly1305	800	784	70	72
ML-KEM-512 ⁺ w/ GMAC	800	784	73	76
ML-KEM-512 ⁺ w/ CMAC	800	784	75	79
ML-KEM-512 ⁺ w/ KMAC	800	784	76	78

KEM variant	Client TX bytes	Server TX bytes	RTT time (μs)	
			Median	Average
ML-KEM-768	1184	1088	135	140
ML-KEM-768 ⁺ w/ Poly1305	1184	1104	99	104
ML-KEM-768 ⁺ w/ GMAC	1184	1104	101	105
ML-KEM-768 ⁺ w/ CMAC	1184	1104	103	109
ML-KEM-768 ⁺ w/ KMAC	1184	1104	103	107

KEM variant	Client TX bytes	Server TX bytes	RTT time (μs)	
			Median	Average
ML-KEM-1024	1568	1568	193	199
ML-KEM-1024 ⁺ w/ Poly1305	1568	1584	138	141
ML-KEM-1024 ⁺ w/ GMAC	1568	1584	140	145
ML-KEM-1024 ⁺ w/ CMAC	1568	1584	143	148
ML-KEM-1024 ⁺ w/ KMAC	1568	1584	144	149

4.3.2 Unilaterally authenticated key exchange (UAKE)

In unilaterally authenticated key exchange, the authenticating party proves its identity to the other party by demonstrating possession of a secret key that corresponds to a published long-term public key. In this implementation, the client possesses the long-term public key \mathbf{pk}_S of the server, and the server authenticates itself by demonstrating possession of the corresponding long-term secret key \mathbf{sk}_S . UAKE routines are summarized in figure 11.

In addition to the long-term key, the client will also generate an ephemeral keypair as it does in an unauthenticated key exchange, and the session key is derived by applying the KDF to the concatenation of both the ephemeral shared secret and the shared secret encapsulated under server’s long-term key. This helps the key exchange to achieve weak forward secrecy (citation needed).

Using KEM for authentication is especially interesting within the context of post-quantum cryptography: post-quantum KEM schemes usually enjoy better performance characteristics than post-quantum signature schemes with faster runtime, smaller memory footprint, and smaller communication sizes. KEMTLS was proposed in 2020 as an alternative to existing TLS handshake protocols, and many experimental implementations have demonstrated the performance advantage. (citation needed).

$\text{UAKE}_c(\text{pk}_S)$	$\text{UAKE}_s(\text{sk}_S)$
Require: Server's long-term pk_S	Require: Server's long-term sk_S
1: $(\text{pk}_e, \text{sk}_e) \xleftarrow{\$} \text{KeyGen}()$	1: $(\text{pk}_e, c_S) \leftarrow \text{read}()$
2: $(c_S, K_S) \xleftarrow{\$} \text{Encap}(\text{pk}_S)$	2: $K_S \leftarrow \text{Decap}(\text{sk}_S, c_S)$
3: send (pk_e, c_S)	3: $(c_e, K_e) \xleftarrow{\$} \text{Encap}(\text{pk}_e)$
4: $c_e \leftarrow \text{read}()$	4: send (c_e)
5: $K_e \leftarrow \text{Decap}(\text{sk}_e, c_e)$	5: $K \leftarrow \text{KDF}(K_e \ K_S)$
6: $K \leftarrow \text{KDF}(K_e \ K_S)$	6: return K
7: return K	

Figure 11: Unilaterally authenticated key exchange (UAKE) routines

Table 6: UAKE RTT comparison

KEM variant	Client TX bytes	Server TX bytes	RTT time (μs)	
			Median	Average
ML-KEM-512	1568	768	145	151
ML-KEM-512 ⁺ w/ Poly1305	1584	784	103	106
ML-KEM-512 ⁺ w/ GMAC	1584	784	106	110
ML-KEM-512 ⁺ w/ CMAC	1584	784	108	112
ML-KEM-512 ⁺ w/ KMAC	1584	784	109	113

KEM variant	Client TX bytes	Server TX bytes	RTT time (μs)	
			Median	Average
ML-KEM-768	2272	1088	215	222
ML-KEM-768 ⁺ w/ Poly1305	2288	1104	144	150
ML-KEM-768 ⁺ w/ GMAC	2288	1104	149	156
ML-KEM-768 ⁺ w/ CMAC	2288	1104	153	160
ML-KEM-768 ⁺ w/ KMAC	2288	1104	154	159

KEM variant	Client TX bytes	Server TX bytes	RTT time (μs)	
			Median	Average
ML-KEM-1024	3136	1568	310	318
ML-KEM-1024 ⁺ w/ Poly1305	3152	1584	202	209
ML-KEM-1024 ⁺ w/ GMAC	3152	1584	212	228
ML-KEM-1024 ⁺ w/ CMAC	3152	1584	212	218
ML-KEM-1024 ⁺ w/ KMAC	3152	1584	213	220

4.3.3 Mutually authenticated key exchange (AKE)

Mutually authenticated key exchange is largely identical to unilaterally authenticated key exchange, except for that client authentication is required. This means that client possesses server's long-term public key and its own long-term secret key, while the server possesses client's long-term public key and its own long-term secret key. The session key is derived by applying KDF onto the concatenation of shared secrets produced under the ephemeral keypair, server's long-term keypair, and client's long-term keypair, in this order.

AKE_C(pk_S, sk_C)	AKE_S(sk_S, pk_C)
Require: Server's long-term pk _S	Require: Server's long-term sk _S
Require: Client's long-term sk _C	Require: Client's long-term pk _C
1: (pk _e , sk _e) $\xleftarrow{\$}$ KeyGen()	1: (pk _e , c _S) \leftarrow read()
2: (c _S , K _S) $\xleftarrow{\$}$ Encap(pk _S)	2: K _S \leftarrow Decap(sk _S , c _S)
3: send(pk _e , c _S)	3: (c _e , K _e) $\xleftarrow{\$}$ Encap(pk _e)
4: (c _e , c _C) \leftarrow read()	4: (c _C , K _C) $\xleftarrow{\$}$ Encap(pk _C)
5: K _e \leftarrow Decap(sk _e , c _e)	5: send(c _e , c _C)
6: K _C \leftarrow Decap(sk _e , c _C)	6: K \leftarrow KDF(K _e K _S K _C)
7: K \leftarrow KDF(K _e K _S K _C)	7: return K
8: return K	

Figure 12: Mutually authenticated key exchange (AKE) routines

Table 7: AKE RTT comparison

KEM variant	Client TX bytes	Server TX bytes	RTT time (μ s)	
			Median	Average
ML-KEM-512	1568	1536	220	213
ML-KEM-512 ⁺ w/ Poly1305	1584	1568	133	138
ML-KEM-512 ⁺ w/ GMAC	1584	1568	139	143
ML-KEM-512 ⁺ w/ CMAC	1584	1568	143	148
ML-KEM-512 ⁺ w/ KMAC	1584	1568	145	151

KEM variant	Client TX bytes	Server TX bytes	RTT time (μ s)	
			Median	Average
ML-KEM-768	2272	2176	294	301
ML-KEM-768 ⁺ w/ Poly1305	2288	2208	190	196
ML-KEM-768 ⁺ w/ GMAC	2288	2208	197	210
ML-KEM-768 ⁺ w/ CMAC	2288	2208	202	208
ML-KEM-768 ⁺ w/ KMAC	2288	2208	204	210

KEM variant	Client TX bytes	Server TX bytes	RTT time (μ s)	
			Median	Average
ML-KEM-1024	3136	3136	512	511
ML-KEM-1024 ⁺ w/ Poly1305	3152	3168	266	273
ML-KEM-1024 ⁺ w/ GMAC	3152	3168	273	282
ML-KEM-1024 ⁺ w/ CMAC	3152	3168	280	287
ML-KEM-1024 ⁺ w/ KMAC	3152	3168	282	288

5 Conclusions and future works

The “encrypt-then-MAC” transformation is a generic KEM construction that achieves IND-CCA2 security under the random oracle model if the input PKE is OW-PCA secure. Compared to the Fujisaki-Okamoto transformation, our construction replaced *de-randomization* and *re-encryption* with a message authenticator. At the cost of some minimal increase in communication size and encapsulation runtime, our construction achieves significant efficiency gains in the decapsulation routine. In practical key exchange protocols, our construction saves between 35-45% in round trip time.

Other suitable post-quantum instantiation. In section 4, we instantiated the “encrypt-then-MAC” KEM transformation with the PKE subroutines of ML-KEM. Unfortunately, ML-KEM is vulnerable to plaintext checking attacks that can recover complete

secret key if the keypair is reused [BDH⁺19]. In fact, as Chris Peikert pointed out, because of the search-decision equivalence of LWE problems, almost all LWE-based cryptosystems will be vulnerable to plaintext-checking attacks [Pei14]. This naturally raises the question of finding other post-quantum primitives to instantiate “encrypt-then-MAC” with, such as other lattice-based cryptosystems not based on LWE, code-based cryptosystems and isogeny-based cryptosystems.

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6 Appendix

6.1 Performance comparison between ML-KEM⁺ and Kyber

ML-KEM directly evolved from CRYSTALS-Kyber’s third round submission to NIST’s post quantum cryptography competition. While their IND-CPA subroutines (see figure

13) are identical, ML-KEM deviated from Kyber by choosing a different variant of the Fujisaki-Okamoto transformation.

K-PKE.KeyGen()	K-PKE.Enc(pk, m)	K-PKE.Dec(sk, c)
1: $A \xleftarrow{\$} R_q^{k \times k}$ 2: $\mathbf{s} \xleftarrow{\$} \mathcal{X}_{\eta_1}^k$ 3: $\mathbf{e} \xleftarrow{\$} \mathcal{X}_{\eta_1}^k$ 4: $\mathbf{t} \leftarrow A\mathbf{s} + \mathbf{e}$ 5: $\mathbf{pk} \leftarrow (A, \mathbf{t})$ 6: $\mathbf{sk} \leftarrow \mathbf{s}$ 7: return (pk, sk)	Ensure: $\mathbf{pk} = (A, \mathbf{t})$ Ensure: $m \in R_2$ 1: $\mathbf{r} \xleftarrow{\$} \mathcal{X}_{\eta_1}^k$ 2: $\mathbf{e}_1 \xleftarrow{\$} \mathcal{X}_{\eta_2}^k$ 3: $e_2 \xleftarrow{\$} \mathcal{X}_{\eta_2}$ 4: $\mathbf{c}_1 \leftarrow A\mathbf{r} + \mathbf{e}_1$ 5: $c_2 \leftarrow \mathbf{t}^\top \mathbf{r} + e_2 + m \cdot \lfloor \frac{q}{2} \rfloor$ 6: return (\mathbf{c}_1, c_2)	Ensure: $c = (c_1, c_2)$ Ensure: $\mathbf{sk} = \mathbf{s}$ 1: $\hat{m} \leftarrow c_2 - \mathbf{c}_1^\top \cdot \mathbf{s}$ 2: $\hat{m} \leftarrow \text{Round}(\hat{m})$ 3: return \hat{m}

Figure 13: K-PKE routines are identical between Kyber and ML-KEM

CRYSTALS-Kyber uses the $U^\mathcal{L}$ variant, where the shared secret is derived from both the plaintext and the ciphertext. On the other hand, because by using *re-encryption* and *de-randomization*, the PKE is already made *rigid*, the CRYSTALS-Kyber team decided to use the $U_m^\mathcal{L}$ variant, where the shared secret is derived from the plaintext alone.

KEM.KeyGen()	KEM.Decap(sk, c)
1: $z \xleftarrow{\$} \{0, 1\}^{256}$ 2: $(\mathbf{pk}, \mathbf{sk}') \xleftarrow{\$} \text{PKE.KeyGen}()$ 3: $\mathbf{sk} \leftarrow (\mathbf{sk}' \parallel \mathbf{pk} \parallel H(\mathbf{pk}) \parallel z)$ 4: return (pk, sk)	Ensure: $\mathbf{sk} = (\mathbf{sk}' \parallel \mathbf{pk} \parallel H(\mathbf{pk}) \parallel z)$ 1: $\hat{m} \leftarrow \text{PKE.Dec}(\mathbf{sk}', c)$ 2: $(\bar{K}, \hat{r}) \leftarrow G(\hat{m} \parallel H(\mathbf{pk}))$ 3: if $\text{PKE.Enc}(\mathbf{pk}, \hat{m}, \hat{r}) = c$ then 4: $K \leftarrow \text{KDF}(\bar{K}, H(c))$ $\triangleright U^\mathcal{L}$ 5: $K \leftarrow \bar{K}$ $\triangleright U_m^\mathcal{L}$ 6: else 7: $K \leftarrow \text{KDF}(z \parallel H(c))$ 8: end if 9: return K
KEM.Encap(pk)	
1: $m \xleftarrow{\$} \{0, 1\}^{256}$ 2: $(\bar{K}, r) \leftarrow G(m \parallel H(\mathbf{pk}))$ 3: $c \leftarrow \text{PKE.Enc}(\mathbf{pk}, m, r)$ 4: $K \leftarrow \text{KDF}(\bar{K} \parallel H(c))$ $\triangleright U^\mathcal{L}$ 5: $K \leftarrow \bar{K}$ $\triangleright U_m^\mathcal{L}$ 6: return (c, K)	

Figure 14: Kyber uses $U^\mathcal{L}$ variant. ML-KEM uses $U_m^\mathcal{L}$ variant.

The reason for ML-KEM to use a different variant of the Fujisaki-Okamoto transformation is two-fold. The first reason is performance: using the $U_m^\mathcal{L}$ transformation saves the need to hash the ciphertext, and since Kyber/ML-KEM’s performance is mainly bottlenecked by the symmetric components, omitting the hash leads to significant runtime savings (up to 17% in AVX-2 optimized implementations). The second reason is the simplified security proof and tighter security bounds of the $U_m^\mathcal{L}$ variant compared to the $U^\mathcal{L}$ variant. We will omit the details of the security proof and refer readers to [HHK17b].

In section 4, we mainly compared ML-KEM⁺ with ML-KEM, but the we would like to point out that, because Kyber uses the $U^\mathcal{L}$ variant and needs to hash the ciphertext for deriving the shared secret, the performance advantage of ML-KEM⁺ over Kyber will be even greater.