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Quantum-Safe Hybrid (QSH) Ciphersuite for Transport Layer Security (TLS) version 1.3

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Abstract

This document describes the Quantum-Safe Hybrid ciphersuite, a new cipher suite providing modular design for quantum-safe cryptography to be adopted in the handshake for the Transport Layer Security (TLS) protocol version 1.3. In particular, it specifies the use of the NTRUEncrypt encryption scheme in a TLS handshake.

Status of This Memo

Update from last version: keeping alive till TLS WG review.

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1. Introduction

Quantum computers pose a significant threat to modern cryptography. Two most widely adopted public key cryptosystems, namely, RSA [PKCS1] and Elliptic Curve Cryptography (ECC) [SECG], will be broken by general purpose quantum computers. RSA is adopted in TLS from Version 1.0 and to TLS Version 1.3 [RFC2246], [RFC4346], [RFC5246], [TLS1.3]. ECC is enabled in RFC 4492 [RFC4492] and adopted in TLS version 1.2 [RFC5246] and version 1.3 [TLS1.3]. On the other hand, there exist several quantum-safe cryptosystems, such as the NTRUEncrypt cryptosystem [EESS1], that deliver similar performance, yet are conjectured to be robust against quantum computers.

This document describes a modular design that allows one or many quantum-safe cryptosystems to be adopted in the handshake protocol, applicable to TLS Version 1.3 [TLS1.3]. It uses a hybrid approach that combines a classical handshake mechanism with key encapsulation mechanisms instantiated with quantum-safe encryption schemes. The modular design provides quantum-safe features to TLS 1.3 without any introduction of extra cipher suites. Yet, it allows the flexibility to include new and advanced quantum-safe encryption schemes at present and in the future.

Extensions to TLS 1.2 [RFC5246] and earlier versions can be found in [QSH12].

The remainder of this document is organized as follows. Section 2 provides an overview of the modular design of quantum-safe handshake for TLS 1.3. Section 3 specifies various data structures needed for a quantum safe handshake, their encoding in TLS messages, and the processing of those messages. Section 4 defines new TLS_QSH cipher suites. Section 5 provides specific information for quantum safe encryption schemes. Section 6 discusses security considerations. Section 7 discusses compatibility with other versions of TLS. Section 8 describes IANA considerations for the name spaces created by this document. Section 9 gives acknowledgements.

This is followed by the lists of normative and informative references cited in this document, the authors' contact information, and statements on intellectual property rights and copyrights.

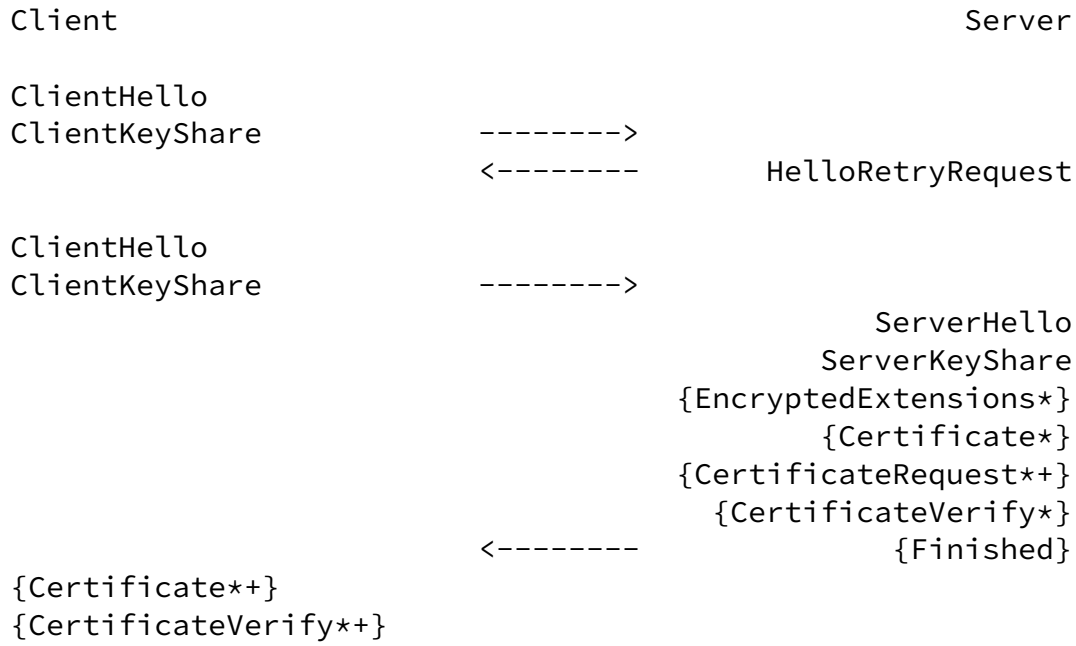
Implementation of this specification requires familiarity with TLS [RFC2246], [RFC4346], [RFC5246], [TLS1.3], TLS extensions [RFC4366], and knowledge of the corresponding quantum-safe cryptosystem.

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 [RFC2119].

Well-known abbreviations and acronyms can be found at RFC Editor Abbreviations List [REAL].

2. Modular design for quantum-safe hybrid handshake

This document introduces a modular approach to including new quantum-safe key exchange algorithms within TLS 1.3, while maintaining the assurance that comes from the use of already established cipher suites. It allows the TLS premaster secret to be agreed using both an established classical cipher suite and a quantum-safe key encapsulation mechanism.



```
{Finished}                  -------->
[Application Data]          <-------->      [Application Data]


      * message is not sent under some conditions
      + message is not sent unless client authentication
        is desired
```

Figure 1: Message flow in a full TLS 1.3 handshake

Figure 1 shows all messages involved in the TLS key establishment protocol (aka full handshake). The addition of quantum-safe cryptography has direct impact only on the ClientHello, the HelloRetryRequest, and the ServerKeyShare messages. In the rest of this document, we describe each quantum-safe key exchange data structure in greater detail in terms of the content and processing of these messages.

The authentication is provided by classical cryptography. The

introduction of quantum-safe encryption schemes delivers forward secrecy against quantum attackers. The additional cryptographic data exchanged between the client and the server is shown in Figure 2 and 3.

Figure 2 illustrates the data flow of a zero round trip quantum-safe handshake for TLS. This handshake is proceeded when 1) the classical key exchange is also zero round trip, and 2) the server supports the QSH schemes from QSHPKList.

```
    Client                                                Server

    ClientHelloExtension
    + qshDataExtension
      (QSHPKList)
    + qshNegotiateExtension
      (QSHSchemeIDList)         -------->
                                                EncryptedExtensions*
                                                  + qshDataExtension
                                                     (QSHCipherList)
                                <--------                 {Finished}
    {Finished}                  -------->
```

```
ClassicSecret|QSHSecret   <-------> ClassicSecret|QSHSecret

      * previously known as SeverKeyShareExtensions
      + additional data
```

Figure 2: Additional cryptographic data for a zero round trip TLS handshake

In the case that the server does not support the QSH schemes from QSHPKList, the server will reply with a HelloRetryRequest, which results into a full handshake.

```
Client                                                  Server

ClientHelloExtensions
+ qshDataExtension
  (QSHPKList)
+ qshNegotiateExtension
  (QSHSchemeIDList)       -------->
                                HelloRetryRequestExtensions
                                    + qshNegotiateExtension
                          <-------- (AcceptQSHSchemeIDList)

ClientHelloExtensions
+ qshDataExtension
```



```
  (QSHPKList)             -------->
                                        EncryptedExtensions*
                                          + qshDataExtension
                                             (QSHCipherList)
                          <--------                {Finished}
{Finished}                -------->

ClassicSecret|QSHSecret   <-------> ClassicSecret|QSHSecret

      * previously known as SeverKeyShareExtensions
      + additional data
```

Figure 3: Additional cryptographic data for a full TLS handshake

As usual, the ClientHello message includes the list of classical cipher suites the client wishes to negotiate (e.g., TLS_ECDH_ECDSA_WITH_NULL_SHA). In addition there will be two potential extension fields, indicating qshData and qshNegotiate extensions.

The ClientHelloExtension field MUST have qshData extension field:

- QSHPKList: a list of distinct public keys for QSH Scheme from the client, each public key for a distinct quantum safe encryption scheme supported by the client.

The ClientHelloExtension field MAY have qshNegotiate extension field:

- QSHSchemeIDList: a list of distinct QSHSchemeIDs from the client, each ID represents a quantum safe encryption scheme/parameter set supported by the client

QSHSchemeIDList must not list the scheme IDs whose public key is already included in the QSHPKList.

If the server supports QSH schemes/parameter sets for the public keys received from QSHPKList, the server will proceed the zero round trip handshake, provided that the zero round trip is also permitted by classical handshake. If not, the server will pick a (list of) QSHSchemeID(s) from the QSHSchemeIDList to form the AcceptQSHSchemeIDList, and request public keys for those schemes in a HelloRetryRequest message. If the server does not support any of the QSH schemes from either QSHPKList or QSHSchemeIDList, the server will abort the handshake.

The extension field of the HelloRetryRequest message MUST have an

qshNegotiate extension field:

- AcceptQSHSchemeIDList: a list of distinct QSHSchemeIDs from the server, each ID represents a quantum safe encryption scheme/parameter set supported/selected by the server

The ServerKeyShare message contains an indication of the classical cipher suite selected, and the ServerKeyShare material appropriate to

that cipher suite. Additionally, the ServerKeyShareExtension (a.k.a. EncryptedExtension) field message MUST contain a qshData extension field listing ciphertexts:

o QSHCipherList:
a list of ciphertests
[Encrypt_QSHPK1(QSHS1)]|[Encrypt_QSHPK2(QSHS2)]|...
where the QSH secret keying material is
QSHSecret = QSHS1|QSHS2|..., and QSHPKi is from
QSHPKList.

The final premaster secret negotiated by the client and the server is the concatenation of the classical premaster secret, QSHSecret, QSHPK1|QSHPK2|... in that order. A 48 bytes fixed length master secret is derived from the premaster secret at the end of the handshake, using a pseudo random function specified by the classical cipher suite (see Section 8.1. RFC 5246 [RFC5246]).

3. Data Structures and Computations

This section specifies the data structures and computations used by TLS_QSH cipher suite specified in Sections 2. The presentation language used here is the same as that used in TLS v1.3 [TLS1.3]. Since this specification extends TLS, these descriptions should be merged with those in the TLS specification and any others that extend TLS. This means that enum types may not specify all possible values, and structures with multiple formats chosen with a select() clause may not indicate all possible cases.

3.1. Data structures for Quantum-safe Crypto Schemes

```
enum {
    ntru_eess443 (0x0101),
    ntru_eess587 (0x0102),
    ntru_eess743 (0x0103),
    reserved     (0x0102..0x01FF),
    lwe_XXX      (0x0201),
    reserved     (0x0202..0x02FF),
    hfe_XXX      (0x0301),
    reserved     (0x0302..0x03FF),
    mcbits_XXX   (0x0401),
```



```
    reserved     (0x0402..0x04FF),
```

```
        reserved     (0x0500..0xFEFF),
        (0xFFFF)
    } QSHSchemeID;
```

ntru_eess443, etc: Indicates parameter set to be used for the NTRUEncrypt encryption scheme. The name of the parameter sets defined here are those specified in [EESS1].

lwe_XXX, etc: Indicates parameters for Learning With Error (LWE) encryption scheme. The name of the parameters defined here are not specified in this document.

hfe_XXX, etc: Indicates parameters for Hidden Field Equotion (HFE) encryption scheme. The name of the parameters defined here are not specified in this document.

mcbits_XXX, etc: Indicates parameters for McEliece encryption scheme instantiated with McBits parameter set. The name of the parameters defined here are not specified in this document.

See Section 5 for specific information for quantum safe scheme.

The QSHSchemes name space is maintained by IANA [IANA]. See Section 8 for information on how new schemes are added.

The server implementation SHOULD support all of the above QSHSchemes, and client implementation SHALL support at least one of them.

```
    struct {
        QSHSchemeID   id<1..2^16-1>
    } QSHIDList;
```

The QSHSchemeIDList and AcceptQSHSchemeIDList are two instances of QSHIDList structure. This structure defines a list of QSHSchemeIDs, each representing a quantum safe encryption scheme.

```
    struct {
        QSHSchemeID   id,
        opaque        pubKey<1..2^16-1>
    } QSHPK;

    struct {
        QSHPK         keys<1..2^24-1>
    } QSHPKList;
```

The structure of public keys send from the client to the server, namely, QSHPK, has two fields: QSHSchemeID specifies the

corresponding quantum safe encryption scheme, and an opaque encodes the actual public key data following the specification of the corresponding quantum safe encryption scheme. Any entity that reserves a new quantum safe encryption scheme identifier MUST specify how the keys and ciphertexts for that scheme are encoded. See Section 5 for definitions of the encodings of the schemes specified in this document.

NOTE: the QSHPK is a opaque of up to (2^24-1) bytes. This may exceed the size limitation of extensions (2^16-1).

The QSHPKList is a list of QSHPKs.

```
struct {
    QSHSchemeID   id,
    opaque        encryptedKey<1..2^16-1>
} QSHCipher;

struct {
    QSHCipher     encryptedKeys<1..2^24-1>
} QSHCipherList;
```

The structure of ciphertext send from the server to the client, namely QSHCipher, has two fields: QSHSchemeID specifies the corresponding quantum safe encryption scheme, and an opaque encodes the actual ciphertext following the specification of the corresponding quantum safe encryption scheme.

The QSHCipherList is a list of ciphertexts.

3.2. Client Hello Extensions

This section specifies a TLS extension that can be included with the ClientHello message as described in RFC 4366 [RFC4366].

NOTE: To support larger QSH quantum-safe cryptosystems it may be necessary to raise the maximum size of an extension to 2^24-1 octets.

When these extensions are sent:

When a client wish to negotiate a handshake using TLS_QSH approach, the extensions MUST be sent along with the first ClientHello message. Follow-up ClientHello message MAY also use these extensions when a zero round trip handshake failed.

Meaning of these extensions:

qshNegotiate extension allows a client to send a QSHSchemeIDList that enumerates QSHSchemeIDs for supported quantum safe cryptosystems. qshData extension allows a client to send a QSHPKList of public keys for quantum-safe encryption schemes.

Note: QSHSchemeID MUST be distinct in QSHSchemeIDList. If qshNegotiate extension and qshData extension are both send within a same ClientHello extension, QSHSchemeIDList must not enumerate QSHschemeIDs whose public keys are already in QSHPKList.

Structure of the extensions:

The general structure of TLS extensions is described in [RFC4366], and this specification adds a new type to ExtensionType.

```
enum {
     qshNegotiate(0x18)
     qshData(0x19)
} ExtensionType;
```

qshNegotiate (Supported TLS_QSH Extension): Indicates the list of QSHSchemeIDs supported by the client. For this extension, the opaque extension_data field MAY contain QSHSchemeIDList and its field can be NULL.

qshData (Supported TLS_QSH Extension): Indicates the list of QSHScheme public keys supported by the client. For this extension, the opaque extension_data field MUST contain QSHPKList and its field is not NULL.

```
struct {
    select (ExtensionType) {
        case qshNegotiate:
            QSHSchemeIDList qshSchemeIDList,
        case qshData:
            QSHPKList       qshPKList,
    }
} ClientHelloExtension;
```

Items in both qshPKList and qshSchemeIDList are ordered according to the client's preferences (favorite choice first).

As an example, a client that only supports ntru_eess439 (0x0101) and ntru_eess593 (0x0102) and prefers to use ntru_eess439 would encode its qshSchemeIDList as follows:

```
04 01 01 01 02
```


An example of a qshNegotiate extension field will therefore look as follows:

```
00 18 | extension length | 00 04 01 01 01 02 | ...
```

Note: the extension type value appearing in these examples is tentative.

Actions of the sender:

If the ClientHello message starts a fresh handshake, a client that proposes TLS_QSH approach in its ClientHello message appends both qshNegotiate and qshData extensions (along with any others), enumerating the supported quantum-safe crypto systems that the client wish to use to negotiate keys with the server.

If the ClientHello message is in response to a HelloRetryRequest, the client appends qshData extension (along with any others), enumerating the QSHScheme public keys supported by the server.

Actions of the receiver:

A server that receives a ClientHello with a TLS_QSH approach MUST check the extension field to use the client's enumerated capabilities to guide its selection of appropriate quantum safe encryption algorithms. The TLS_QSH approach must be negotiated only if the server can successfully complete the handshake while using the listed quantum-safe cryptosystems from the client.

The server will carry out a classic handshake with the client using a classical cipher suite indicated by the ClientHello message. If the server supports QSHSchemes of public keys included in the qshData

extension, the server will include a QSHCipherList in the EncryptedExtension field of ServerKeyShare message; if not, the server will select a (list of) supported QSHScheme(s), indexed by QSHSchemeID(s), and form the AcceptQSHSchemeIDList with its selected schemes. This list will be send back to the client via the extension field of HelloRetryRequest.

If a server does not understand the Extension, does not understand the list of quantum-safe encryption schemes, or is unable to complete the TLS_QSH handshake while restricting itself to the enumerated cryptosystems, it MUST NOT negotiate the use of a TLS_QSH approach. Depending on what other cipher suites are proposed by the client and supported by the server, this may result in a fatal handshake failure alert due to the lack of common cipher suites.

3.3. HelloRetryRequest Extensions

This section specifies a TLS extension that can be included with the HelloRetryRequest message as described in [TLS1.3].

When this extension is sent:

The server will send this message in response to a ClientHello message where the extension fields contains a extension type quantum-safe-hybrid, when it was able to find an acceptable set of QSHSchemes from qshNegotiate but not from qshData. If it cannot find such a match, it will respond with a handshake failure alert.

Meaning of this extension:

This extension allows a server to notify the client the ID(s) for the quantum-safe encryption scheme(s) it chooses from the QSHSchemeIDList.

Structure of this extension:

```
struct {
    select (ExtensionType) {
        case qshNegotiate:
            QSHSchemeIDList acceptQSHSchemeIDList,
    }
} HelloRetryRequestExtension;
```

Actions of the sender:

The server selects a number of QSHSchemeIDs in response to a ClientHelloExtension message. The selection is based on client's preference. The QSHSchemeIDs selected MUST exist in the received QSHSchemeIDList. The server form the acceptQSHSchemeIDList with the list of selected QSHSchemeIDs.

Actions of the receiver:

A client that receives a HelloRetryRequest message containing an extension type qshNegotiate will extract the agreed QSHSchemeIDs and from the acceptQSHSchemeIDList. Those QSHSchemeIDs will be used when the client generates another ClientHello message.

3.4. Server Key Share Extension

[[This may be later on changed into *EncryptedExtensions* let's see how TLS 1.3 will define it]]

NOTE: To support larger QSH quantum-safe cryptosystems it may be necessary to raise the maximum size of an extension to 2^24-1 octets.

When this message is sent:

The server will include this extension field in response to a ClientHello message with extension type qshData.

Meaning of this message:

It is used to send QSH key material (encrypted by one or many of the client's public keys) to the client.

Structure of this message:

The TLS ServerKeyShareExtension field is extended as follows.

```
struct {
    select (ExtensionType) {
        case qshData:
            QSHCipherList     encryptedQSHSecret,
```

```
        }
    } ServerKeyShare;
```

Actions of the sender:

The server extracts client's public keys QSHPK1, ..., QSHPKn from the qshData field in the received Client Hello extensions. For each of the public keys QSHPKi, generates a secret QSHSi. The length in bytes of QSHSi MUST be the lesser of (a) 48, the length of the classical master secret, and (b) the maximum plaintext input length for the corresponding encryption scheme (see Section 5).

The server then encrypts the QSHSi with QSHPKi, and form the encryptedQSHSecret with those ciphertexts.

The QSH keying material is:

```
QSHSecret = QSHS1|QSHS2|...|QSHSk
```

The server will finally form the premaster secret as a concatenation of the classical premaster secret (negotiated via classical exchange, i.e., Key Share messages), QHSSecret, and QSHPK (the public keys that encrypts the message). A 48 bytes fixed length master secret is derived from the premaster secret at the end of the handshake, using a pseudo random function specified by the classical cipher suite (see Section 8.1. RFC 5246 [RFC5246]).

Actions of the receiver:

The client processes the ServerKeyShareExtension

by decrypting each ciphertext in encryptedQSHSecret using the client's secret key and obtaining QSHSecret.

The client will finally form the premaster secret as a concatenation of the classical premaster secret (negotiated via classical exchange, i.e., Key Share messages), QHSSecret, and QSHPK (the public keys that encrypts the message). A 48 bytes fixed length master secret is derived from the premaster secret at the end of the handshake, using a pseudo random function specified by the classical cipher suite (see Section 8.1. RFC 5246 [RFC5246]).

4. Cipher Suites

The TLS_QSH approach does not introduce any additional cipher suite identifiers.

5. Specific information for Quantum Safe Scheme

Selection criteria for qauntum-safe cryptography to be used in this TLS_QSH approach can be found at [QSHPKC]. Also see [PQCRY] for initial recommendations of quantum safe cryptography from EU's PQCRYPTO project.

5.1. NTRUEncrypt

NTRUEncrypt parameter sets are identified by the values ntru_eess443 (0x0101), ntru_eess587 (0x0102), ntru_eess743 (0x0103) assigned in this document.

For each of these parameter sets, the public key and ciphertext are Ring Elements as defined in [EESS1]. The encoded public key and ciphertext are the result of encoding the relevant Ring Element with RE2BSP as defined in [EESS1].

For each parameter set the the maximum plaintext input length in bytes is as follows. This is used when determining the length of the client/server-generated secrets CliSi and SerSi as specified in sections 3.4 and 3.5.

```
eess443  49
eess587  76
eess743  106
```

5.2. LWE

Encoding not defined in this document.

5.3. HFE

Encoding not defined in this document.

5.4. McEliece/McBits

Encoding not defined in this document.

6. Security Considerations

6.1. Security, Authenticity and Forward Secrecy

Security, authenticity and forward secrecy against classical computers are inherent from classical handshake mechanism.

6.2. Quantum Security and Quantum Forward Secrecy

The proposed handshake mechanism provides quantum security and quantum forward secrecy.

Quantum resistant feature of QSHSchemes ensures a quantum attacker will not learn QSH keying material S. A quantum attacker may learn classic handshake information. Given an input X, the leftover hash lemma [LHL] ensures that one can extract Y bits that are almost uniformly distributed, where Y is asymptotic to the min-entropy of X. An adversary who has some partial knowledge about X, will have almost no knowledge about Y. This guarantees the attacker will not learn the final premaster secret so long as S has enough entropy and remains secret. This also guarantees the premaster secret is secure even if the client's and/or the server's long term keys are compromised.

6.3. Quantum Authenticity

The proposed approach relies on the classical cipher suite for authenticity. Thus, an attacker with quantum computing capability will be able to break the authenticity.

7. Compatibility with TLS 1.2 and earlier version

Compatibility with TLS 1.2 and earlier version can be found in [QSH12].

8. IANA Considerations

This document describes a new name spaces for use with the TLS protocol:

- QSHSchemeID

Any additional assignments require IETF Consensus action [RFC2434]. Process for determining whether a public key algorithm is in fact quantum-safe, and therefore entitled to a QSHSchemeId, is not

specified in this document and may be established by the TLS working group as it sees fit. For example, TLS WG may require that algorithms are vetted in some sense by CFRG or have been published in a standard by a recognized international standards body such as IEEE or ANSI X9.

9. Acknowledgements

Funding for the RFC Editor function is provided by the IETF Administrative Support Activity (IASA).

We wish to thank Douglas Stebila, [[[names]]] for helpful discussions.

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