

INTERNET-DRAFT  
Intended Status: Experimental  
Expires: 2016-10-04

J. M. Schanck  
Security Innovation & U. Waterloo  
W. Whyte  
Security Innovation  
Z. Zhang  
Security Innovation  
2016-04-04

Quantum-Safe Hybrid (QSH) Ciphersuite  
for Transport Layer Security (TLS) version 1.3  
[draft-whyte-qsh-tls13-02.txt](#)

## 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

This Internet-Draft is submitted in full conformance with the provisions of [BCP 78](#) and [BCP 79](#).

Internet-Drafts are working documents of the Internet Engineering Task Force (IETF), its areas, and its working groups. Note that other groups may also distribute working documents as Internet-Drafts.

The list of current Internet-Drafts can be accessed at <http://www.ietf.org/1id-abstracts.html>.

The list of Internet-Draft Shadow Directories can be accessed at <http://www.ietf.org/shadow.html>.

Internet-Drafts are draft documents valid for a maximum of six months and may be updated, replaced, or obsoleted by other documents at any time. It is inappropriate to use Internet-Drafts as reference material or to cite them other than as "work in progress."

This Internet-Draft will expire on 2016-10-04.

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

## Table of Contents

<a href="#">1.</a>	Introduction . . . . .	<a href="#">3</a>
<a href="#">2.</a>	Modular design for quantum-safe hybrid handshake . . . . .	<a href="#">4</a>
<a href="#">3.</a>	Data Structures and Computations . . . . .	<a href="#">7</a>
<a href="#">3.1.</a>	Data structures for Quantum-safe Crypto Schemes . . . . .	<a href="#">7</a>
<a href="#">3.2.</a>	Client Hello Extensions . . . . .	<a href="#">9</a>
<a href="#">3.3.</a>	HelloRetryRequest Extensions . . . . .	<a href="#">11</a>
<a href="#">3.4.</a>	Server Key Share Extension . . . . .	<a href="#">12</a>
<a href="#">4.</a>	Cipher Suites . . . . .	<a href="#">14</a>
<a href="#">5.</a>	Specific information for Quantum Safe Scheme . . . . .	<a href="#">14</a>
<a href="#">5.1.</a>	NTRUEncrypt . . . . .	<a href="#">14</a>
<a href="#">5.2.</a>	LWE . . . . .	<a href="#">14</a>
<a href="#">5.3.</a>	HFE . . . . .	<a href="#">14</a>
<a href="#">5.4.</a>	McEliece/McBits . . . . .	<a href="#">15</a>
<a href="#">6.</a>	Security Considerations . . . . .	<a href="#">15</a>
<a href="#">6.1.</a>	Security, Authenticity and Forward Secrecy . . . . .	<a href="#">15</a>
<a href="#">6.2.</a>	Quantum Security and Quantum Forward Secrecy . . . . .	<a href="#">15</a>
<a href="#">6.3.</a>	Quantum Authenticity . . . . .	<a href="#">15</a>
<a href="#">7.</a>	Compatibility with TLS 1.2 and earlier version . . . . .	<a href="#">15</a>
<a href="#">8.</a>	IANA Considerations . . . . .	<a href="#">15</a>
<a href="#">9.</a>	Acknowledgements . . . . .	<a href="#">16</a>
<a href="#">10.</a>	References . . . . .	<a href="#">16</a>
<a href="#">10.1.</a>	Normative References . . . . .	<a href="#">16</a>
<a href="#">10.2.</a>	Informative References . . . . .	<a href="#">17</a>
	Authors' Addresses . . . . .	<a href="#">18</a>
	Copyright Notice . . . . .	<a href="#">18</a>



## 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.

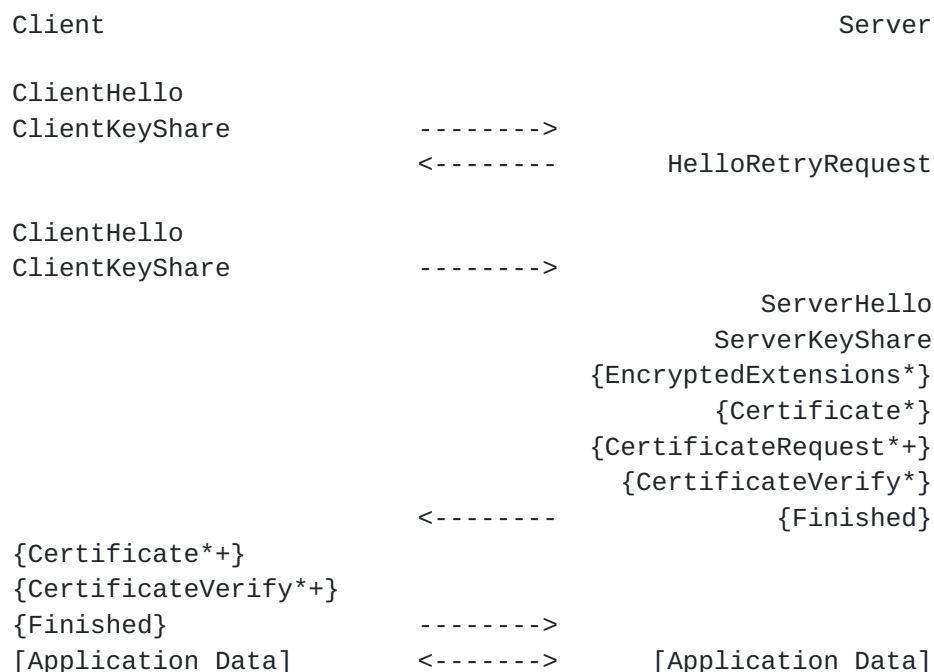
The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in [RFC 2119](#) [[RFC2119](#)].



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.



\* 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.

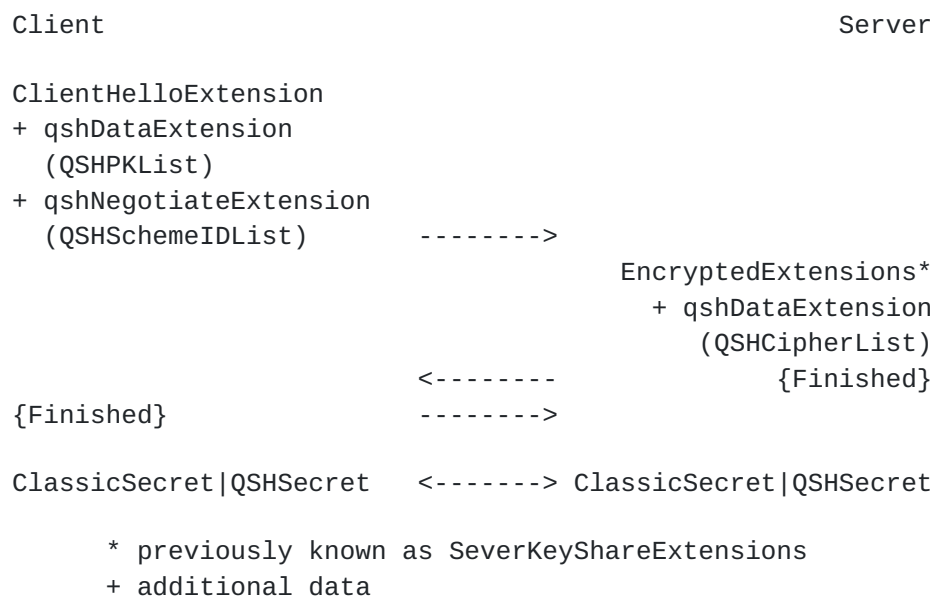
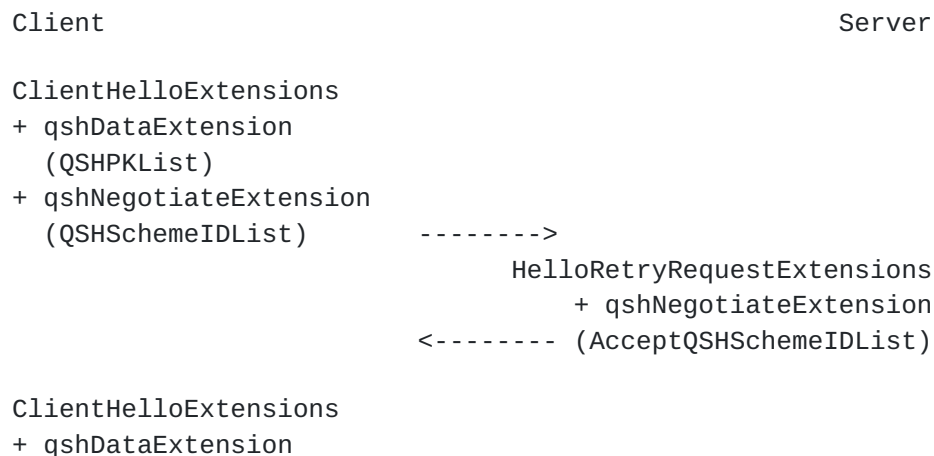


Figure 2: Additional cryptographic data  
for a zero round trip TLS handshake

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.







```

(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:

- o 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:

- o 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:

- o 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 ciphertests:

- 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 Equation (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:

$$\text{QSHSecret} = \text{QSHS1}|\text{QSHS2}|\dots|\text{QSHSk}$$

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), QSHSecret, 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 quantum-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:

- o 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.

## **10. References**

### **10.1. Normative References**

- [EESS1] Consortium for Efficient Embedded Security, "Efficient Embedded Security standards (EESS) #1", March 2015, <<https://github.com/NTRUOpenSourceProject/ntru-crypto/blob/master/doc/EESS1-2015v3.0.pdf>>.
- [FIPS180] NIST, "Secure Hash Standard", FIPS 180-2, 2002.
- [FIPS186] NIST, "Digital Signature Standard", FIPS 186-2, 2000.
- [H2020] Lange, T., "PQCRYPTO project in the EU", April, 2015. <<http://pqcrypto.eu.org/slides/20150403.pdf>>
- [HOF15] Hoffstein, J., Pipher, J., Schanck, J., Silverman, J., Whyte, W., and Zhang, Z., "Choosing Parameters for NTRUEncrypt", 2015. <<https://eprint.iacr.org/2015/708>>
- [LIN11] Lindner, R., and Peikert, C., "Better Key Sizes (and Attacks) for LWE-Based Encryption", 2011.
- [LHL] Impagliazzo, R., Levin, L., and Luby, M., "Pseudo-random generation from one-way functions", 1989.
- [MCBIT] Bernstein, D., Chou, T., and Schwabe, P., "McBits: Fast Constant-Time Code- Based Cryptography", 2013.
- [MCELI] McEliece, R., "A Public-Key Cryptosystem Based On Algebraic Coding Theory", 1978.
- [PKCS1] RSA Laboratories, "PKCS#1: RSA Encryption Standard version 1.5", PKCS 1, November 1993



- [PQCRY] PQCRYPTO, "Initial recommendations of long-term secure post-quantum systems".  
<<http://pqcrypto.eu.org/docs/initial-recommendations.pdf>>
- [QSH12] Schanck, J., Whyte, W., and Zhang, Z., "Quantum-Safe Hybrid (QSH) Ciphersuite for Transport Layer Security (TLS) version 1.2", [draft-whyte-qsh-tls12-00](#), July 2015.
- [QSHPKC] Schanck, J., Whyte, W., and Zhang, Z., "Criteria for selection of public-key cryptographic algorithms for quantum-safe hybrid cryptography", [draft-whyte-select-pkc-qsh-00.txt](#), Sep 2015.
- [REAL] "RFC Editor Abbreviations List", September 2013,  
<<https://www.rfc-editor.org/rfc-style-guide/abbrev.expansion.txt/>>.
- [RFC2119] Bradner, S., "Key Words for Use in RFCs to Indicate Requirement Levels", [RFC 2119](#), March 1997.
- [RFC2246] Dierks, T. and C. Allen, "The TLS Protocol Version 1.0", [RFC 2246](#), January 1999.
- [RFC2434] Narten, T. and H. Alvestrand, "Guidelines for Writing an IANA Considerations Section in RFCs", [RFC 2434](#), October 1998.
- [RFC4346] Dierks, T. and E. Rescorla, "The Transport Layer Security (TLS) Protocol Version 1.1", [RFC 4346](#), April 2006.
- [RFC4366] Blake-Wilson, S., Nysrom, M., Hopwood, D., Mikkelsen, J., and T. Wright, "Transport Layer Security (TLS) Extensions", [RFC 4366](#), April 2006.
- [RFC4492] Blake-Wilson, S., Bolyard, N., Gupta, V., Hawk, C., and B. Moeller, "Elliptic Curve Cryptography (ECC) Cipher Suites for Transport Layer Security (TLS)", [RFC 4492](#), May 2006.
- [RFC5246] Dierks, T. and E. Rescorla, "The Transport Layer Security (TLS) Protocol Version 1.2", [RFC 5246](#), August 2008.
- [TLS1.3] E. Rescorla, "The Transport Layer Security (TLS) Protocol Version 1.3", [draft-ietf-tls-tls13-05](#), March 2015.

## **10.2. Informative References**

- [RFC5990] Randall, J., Kaliski, B., Brainard, J. and Turner S., "Use





of the RSA-KEM Key Transport Algorithm in the  
Cryptographic Message Syntax (CMS)", [RFC 5990](#), September  
2010.

[RFC5859] Krawczyk, H., Eronen, P., "HMAC-based Extract-and-Expand  
Key Derivation Function (HKDF)", [RFC 5859](#), May 2010.

#### Authors' Addresses

John M. Schanck  
Security Innovation, US  
and  
University of Waterloo, Canada  
[jschanck@securityinnovation.com](mailto:jschanck@securityinnovation.com)

William Whyte  
Security Innovation, US  
[wwhyte@securityinnovation.com](mailto:wwhyte@securityinnovation.com)

Zhenfei Zhang  
Security Innovation, US  
[zzhang@securityinnovation.com](mailto:zzhang@securityinnovation.com)

#### Copyright Notice

IETF Trust Legal Provisions of 28-dec-2009, [Section 6.b\(i\)](#), paragraph  
2: Copyright (c) 2015 IETF Trust and the persons identified as the  
document authors. All rights reserved.

IETF Trust Legal Provisions of 28-dec-2009, [Section 6.b\(ii\)](#),  
paragraph 3: This document is subject to [BCP 78](#) and the IETF Trust's  
Legal Provisions Relating to IETF Documents  
(<http://trustee.ietf.org/license-info>) in effect on the date of  
publication of this document. Please review these documents  
carefully, as they describe your rights and restrictions with respect  
to this document.

