Quantum Secure Tunneling Protocol - QSTP 1.4

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John G. Underhill - john.underhill@protonmail.com

The Quantum Secure Tunneling Protocol (QSTP) is an authenticated three-party system, designed to secure communication between a client and server using quantum-safe encryption and certificate-based authentication. The protocol ensures secure key exchange, message integrity and confidentiality.

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Foreword

This document is intended as the preliminary draft of a new standards proposal, and as a basis from which that standard can be implemented. We intend that this serves as an explanation of this new technology, and as a complete description of the protocol.

This document is the first revision of the specification of QSTP, further revisions may become necessary during the pursuit of a standard model, and revision numbers shall be incremented with changes to the specification. The reader is asked to consider only the most recent revision of this draft, as the authoritative implementation of the QSTP specification.

The author of this specification is John G. Underhill, and can be reached at john.underhill@protonmail.com

1. Introduction

The Quantum Secure Tunneling Protocol (QSTP) is a cryptographic protocol designed to enable secure communication between clients and servers. It leverages a key exchange process authenticated by a root server, which signs the certificates of the participating servers and clients. The protocol's design focuses on ensuring post-quantum security, protecting communications even in the presence of quantum computing threats.

QSTP differs from traditional peer-to-peer tunneling protocols, such as Quantum Secure Messaging Protocol (QSMP), by incorporating a root server for certificate management. This server is responsible for signing the certificates that authenticate key exchanges between the client and server.

The key goals of QSTP are:

1. **Post-quantum security**: The protocol is designed to withstand quantum-based attacks by relying on secure cryptographic primitives.
2. **Authenticated key exchange**: The client and server engage in a secure key exchange process, using certificates issued by the root server.
3. **Confidentiality and Integrity**: QSTP ensures that communication between the client and server remains confidential and tamper-proof.

The following sections will outline the design, mathematical foundation, and security analysis of QSTP, providing an in-depth review of the design and implementation of a QSTP crypto-system.

2. Scope

This document provides a comprehensive description of the QSTP secure tunneling protocol, focusing on establishing encrypted and authenticated communication channels between two hosts. It outlines the complete processes involved in key exchange, message authentication, and the establishment of secure communication tunnels using the QSTP protocol.

The QSTP specification includes detailed descriptions of the following elements:

- **Cryptographic Primitives**: An in-depth look at the mathematical foundations and quantum-resistant algorithms used in QSTP.
- **Key Derivation Functions**: The specific methods and algorithms used to generate secure session keys from shared secrets.
- **Client-to-Server Messaging Protocols**: A step-by-step breakdown of the message exchanges required to establish a secure communications stream between clients and servers.

2.1 Application

QSTP is designed primarily for institutions and organizations that require secure communication channels to handle sensitive information exchanged between remote terminals. It is ideally suited for sectors where data confidentiality, integrity, and authenticity are paramount, including financial institutions, government agencies, defense contractors, and enterprises managing critical infrastructure.

The protocol is versatile enough to be applied in various settings, such as secure messaging, VPNs, and other network communication systems where robust encryption and authentication are essential. QSTP's design ensures that even if the cryptographic landscape changes due to advancements in quantum computing, its security framework remains resilient and flexible.

Mandatory Protocol Components:

- The key exchange, message authentication, and encryption functions defined in this document are integral to the construction of a QSTP communication stream. These components MUST be implemented to ensure secure operations and protocol compliance.

Use of Keywords for Compliance:

- **SHOULD**: Indicates best practices or recommended settings that are not compulsory but are strongly advised for optimal performance and security.
- **SHALL**: Denotes mandatory requirements that must be followed to ensure full compliance with the QSTP protocol. Deviations from these guidelines result in non-conformity and may compromise the protocol's effectiveness.

2.2 Protocol Flexibility and Use Cases

QSTP is engineered to be highly adaptable, supporting various deployment scenarios ranging from simple client-server architectures to more complex multi-party distributed systems. This flexibility makes it ideal for cloud-based infrastructures, secure messaging applications, VPNs, and IoT networks that demand high-performance encryption and authentication.

Key use cases for QSTP include:

- **Institutional Communications**: Securely encrypting and authenticating sensitive data exchanges between financial institutions, government agencies, and corporate networks.
- **Internet of Things (IoT)**: Enabling secure communication for connected devices that require lightweight, efficient, and scalable encryption protocols to protect data integrity.
- **Secure Messaging Platforms**: Providing end-to-end encryption for messaging services that need to resist both classical and quantum attacks.

The protocol's ability to integrate with existing network infrastructure without requiring extensive modifications ensures that organizations can transition to post-quantum security seamlessly while maintaining high levels of operational efficiency.

2.3 Compliance and Interoperability

The QSTP protocol is designed to maintain strict compliance with its core cryptographic principles while ensuring interoperability with other secure communication frameworks. To guarantee that different QSTP implementations can interact securely, adherence to the standards outlined in this document is crucial.

To facilitate future upgrades and adaptations, QSTP is structured to support modular cryptographic components. This approach allows for the addition of new cryptographic primitives or the enhancement of existing ones without disrupting the overall architecture. As new advancements in cryptographic techniques emerge, QSTP can be easily updated to include these innovations, maintaining its position as a state-of-the-art security protocol.

Key elements of compliance:

- **Interoperability Standards**: QSTP is developed to work seamlessly with other post-quantum cryptographic standards, ensuring that its communication channels can operate in diverse network environments.
- **Modular Design**: The protocol's flexible design allows for straightforward upgrades, facilitating the incorporation of future cryptographic advancements with minimal impact on existing deployments.

2.4 Recommendations for Secure Implementation

In addition to outlining the core requirements for QSTP's secure communication, this document provides best practice recommendations to enhance implementation security, performance, and reliability:

- **Regular Cryptographic Updates**: Institutions are advised to keep informed of developments in post-quantum cryptography and to periodically update their cryptographic algorithms to maintain compliance with industry standards.
- **Security Audits and Assessments**: Routine security assessments should be conducted to identify potential vulnerabilities in the protocol implementation and to apply necessary mitigations.
- **Infrastructure Optimization**: It is recommended to configure network infrastructure in a way that supports QSTP's low-latency, high-throughput capabilities, ensuring that performance remains consistent even under heavy loads.

These guidelines aim to help organizations maximize QSTP's security potential, ensuring that their communication channels remain secure against both current and future threats.

2.5 Document Organization

This document is structured to provide a detailed, logical flow of information about the QSTP protocol's operation and implementation. It includes the following key sections:

- **Cryptographic Primitives**: Detailed explanations of the mathematical algorithms that form the foundation of QSTP's encryption and authentication processes.
- **Key Exchange Mechanisms**: Comprehensive breakdowns of how session keys are established securely through QSTP's key exchange protocol.
- **Message Authentication**: Detailed descriptions of the techniques used to verify the authenticity and integrity of messages exchanged within QSTP communications.
- **Error Handling and Fault Tolerance**: Guidelines on how to manage protocol errors and disruptions while maintaining secure and stable communication channels.
- **Implementation Examples**: Practical examples, code snippets, and detailed use cases demonstrating the integration of QSTP in various application contexts.

3.Terms and Definitions

3.1 Cryptographic Primitives

3.1.1 Kyber

The Kyber asymmetric cipher and NIST Post Quantum Competition winner.

3.1.2 McEliece

The McEliece asymmetric cipher and NIST Round 3 Post Quantum Competition candidate.

3.1.3 Dilithium

The Dilithium asymmetric signature scheme and NIST Post Quantum Competition winner.

3.1.4 AES-GCM

The Advanced Encryption Standard in Galois/Counter Mode (AES-GCM), an authenticated encryption with associated data (AEAD) cipher standardized in NIST SP 800-38D.

3.1.5 RCS

The wide-block Rijndael AEAD authenticated symmetric stream cipher.

3.1.6 SHA-3

The SHA3 hash function NIST standard, as defined in the NIST standards document FIPS-202; SHA-3 Standard: Permutation-Based Hash and Extendable-Output Functions.

3.1.7 SHAKE

The NIST standard Extended Output Function (XOF) defined in the SHA-3 standard publication FIPS-202; SHA-3 Standard: Permutation-Based Hash and Extendable-Output Functions.

3.1.8 KMAC

The SHA3 derived Message Authentication Code generator (MAC) function defined in NIST special publication SP800-185: SHA-3 Derived Functions: cSHAKE, KMAC, TupleHash and ParallelHash.

3.2 Network References

3.2.1 Bandwidth

The maximum rate of data transfer across a given path, measured in bits per second (bps).

3.2.2 Byte

Eight bits of data, represented as an unsigned integer ranged 0-255.

3.2.3 Certificate

A digital certificate, a structure that contains a signature verification key, expiration time, and serial number and other identifying information. A certificate is used to verify the authenticity of a message signed with an asymmetric signature scheme.

3.2.4 Domain

A virtual grouping of devices under the same authoritative control that shares resources between members. Domains are not constrained to an IP subnet or physical location but are a virtual group of devices, with server resources typically under the control of a network administrator, and clients accessing those resources from different networks or locations.

3.2.5 Duplex

The ability of a communication system to transmit and receive data; half-duplex allows one direction at a time, while full-duplex allows simultaneous two-way communication.

3.2.6 Gateway: A network point that acts as an entrance to another network, often connecting a local network to the internet.

3.2.7 IP Address

A unique numerical label assigned to each device connected to a network that uses the Internet Protocol for communication.

3.2.8 IPv4 (Internet Protocol version 4): The fourth version of the Internet Protocol, using 32-bit addresses to identify devices on a network.

3.2.9 IPv6 (Internet Protocol version 6): The most recent version of the Internet Protocol, using 128-bit addresses to overcome IPv4 address exhaustion.

3.2.10 LAN (Local Area Network)

A network that connects computers within a limited area such as a residence, school, or office building.

3.2.11 Latency

The time it takes for a data packet to move from source to destination, affecting the speed and performance of a network.

3.2.12 Network Topology

The arrangement of different elements (links, nodes) of a computer network, including physical and logical aspects.

3.2.13 Packet

A unit of data transmitted over a network, containing both control information and user data.

3.2.14 Protocol

A set of rules governing the exchange or transmission of data between devices.

3.2.15 TCP/IP (Transmission Control Protocol/Internet Protocol)
A suite of communication protocols used to interconnect network devices on the internet.

3.2.16 Throughput: The actual rate at which data is successfully transferred over a communication channel.

3.2.17 UDP (User Datagram Protocol)
A communication protocol that offers a limited amount of service when messages are exchanged between computers in a network that uses the Internet Protocol.

3.2.18 VLAN (Virtual Local Area Network)
A logical grouping of network devices that appear to be on the same LAN regardless of their physical location.

3.2.19 VPN (Virtual Private Network)
Creates a secure network connection over a public network such as the internet.

3.3 Normative References

The following documents serve as references for cryptographic components used by QSTP:

3.3.1 FIPS 202: SHA-3 Standard: Permutation-Based Hash and Extendable Output Functions: This standard specifies the SHA-3 family of hash functions, including SHAKE extendable-output functions. https://doi.org/10.6028/NIST.FIPS.202

3.3.2 FIPS 203: Module-Lattice-Based Key Encapsulation Mechanism (ML-KEM): This standard specifies ML-KEM, a key encapsulation mechanism designed to be secure against quantum computer attacks. https://doi.org/10.6028/NIST.FIPS.203

3.3.3 FIPS 204: Module-Lattice-Based Digital Signature Standard (ML-DSA): This standard specifies ML-DSA, a set of algorithms for generating and verifying digital signatures, believed to be secure even against adversaries with quantum computing capabilities. https://doi.org/10.6028/NIST.FIPS.204

3.3.4 NIST SP 800-185: SHA-3 Derived Functions: cSHAKE, KMAC, TupleHash, and ParallelHash: This publication specifies four SHA-3-derived functions: cSHAKE, KMAC, TupleHash, and ParallelHash. https://doi.org/10.6028/NIST.SP.800-185

3.3.5 NIST SP 800-90A Rev. 1: Recommendation for Random Number Generation Using Deterministic Random Bit Generators: This publication provides recommendations for the generation of random numbers using deterministic random bit generators. https://doi.org/10.6028/NIST.SP.800-90Ar1

3.3.6 NIST SP 800-108: Recommendation for Key Derivation Using Pseudorandom Functions: This publication offers recommendations for key derivation using pseudorandom functions. https://doi.org/10.6028/NIST.SP.800-108

3.3.7 FIPS 197: The Advanced Encryption Standard (AES): This standard specifies the Advanced Encryption Standard (AES), a symmetric block cipher used widely across the globe. https://doi.org/10.6028/NIST.FIPS.197

3.3.8 NIST SP 800-38D: Recommendation for Block Cipher Modes of Operation: Galois/Counter Mode (GCM) and GMAC: This publication specifies the GCM authenticated encryption mode for use with AES. https://doi.org/10.6028/NIST.SP.800-38D

4. Cryptographic Primitives

QSTP relies on a robust set of cryptographic primitives designed to provide resilience against both classical and quantum-based attacks. The following sections detail the specific cryptographic algorithms and mechanisms that form the foundation of QSTP's encryption, key exchange, and authentication processes.

4.1 Asymmetric Cryptographic Primitives

QSTP employs post-quantum secure asymmetric algorithms to ensure the integrity and confidentiality of key exchanges, as well as to facilitate digital signatures. The primary asymmetric primitives used are:

- **Kyber**: A lattice-based key encapsulation mechanism that provides secure, efficient key exchange resistant to quantum attacks. Kyber is valued for its balance between computational speed and cryptographic strength, making it suitable for scenarios requiring rapid key generation and exchange.
- **McEliece**: A code-based cryptosystem that remains one of the most established post-quantum algorithms. It leverages the difficulty of decoding general linear codes, offering a high level of security even against advanced quantum decryption techniques.
- **Dilithium**: A lattice-based digital signature algorithm that offers fast signing and verification processes while maintaining strong security guarantees against quantum attacks.

These asymmetric primitives are selected for their proven resilience against quantum cryptanalysis, ensuring that QSTP's key exchange and signature operations remain secure in the face of evolving computational threats. ML-DSA (Dilithium) is the sole supported signature scheme; its lattice-based hardness assumption provides strong EUF-CMA security and fast signing and verification suitable for real-time certificate authentication.

4.2 Symmetric Cryptographic Primitives

4.2 Symmetric Cryptographic Primitives

QSTP supports two selectable AEAD symmetric cipher configurations, chosen at compile time via the QSTP_USE_RCS_ENCRYPTION preprocessor flag.

4.2.1 RCS (Rijndael Cryptographic Stream) - Default

The RCS cipher is the recommended option for post-quantum deployments. It is a stream cipher adapted from the Rijndael permutation with the following properties:

- Wide-Block Cipher Design: RCS operates on a 256-bit wide Rijndael state, with an increased number of transformation rounds compared to standard AES, enhancing resistance to differential and linear cryptanalysis.

- Enhanced Key Schedule: The key schedule is cryptographically strengthened using Keccak, ensuring derived round keys are resistant to algebraic and differential attacks.
- Post-Quantum AEAD: RCS integrates with KMAC (Keccak-based Message Authentication Code) or QMAC to provide authenticated encryption and message authentication in a single operation, without a separate MAC pass.

RCS leverages AVX/AVX2/AVX-512 intrinsics and AES-NI instructions on supporting CPUs.

4.2.2 AES-256-GCM - Compliance Alternative

AES-256-GCM is provided as an alternative symmetric cipher for deployments that require conformance to NIST SP 800-38D or interoperability with existing GCM-based infrastructure. AES-GCM provides standard AEAD authentication via GHASH. It is selected by leaving QSTP_USE_RCS_ENCRYPTION undefined. When AES-GCM is selected, the tunnel AEAD security reduces to the classical AES-GCM construction; post-quantum resistance of the symmetric layer then depends solely on the 256-bit key size.

Both cipher options use the same key derivation path (cSHAKE-256 over the shared secret and transcript hash) and produce identical key and nonce output lengths.

4.3 Hash Functions and Key Derivation

Hash functions and key derivation functions (KDFs) are essential to QSTP's ability to transform raw cryptographic data into secure keys and hashes. The following primitives are used:

- **SHA-3**: SHA-3 serves as QSTP's primary hash function, providing secure, collision-resistant hashing capabilities.
- **SHAKE**: QSTP employs the Keccak SHAKE XOF function for deriving symmetric keys from shared secrets. This ensures that each session key is uniquely generated and unpredictable, enhancing the protocol's security against key reuse attacks.

These cryptographic primitives ensure that QSTP's key management processes remain secure, even in scenarios involving high-risk adversaries and quantum-capable threats.

5. Protocol Description

The QSTP key exchange is a three-party, one-way trust, client-server key exchange model in which the client trusts the server based on certificate authentication facilitated by a root domain security server. A single shared secret is securely exchanged between the server and client, and used to create an encrypted tunnel. Designed for efficiency, the QSTP exchange is fast and lightweight, while providing 256-bit post-quantum security, ensuring protection against future quantum-based threats.

This protocol is versatile and can be used in a wide range of applications, such as client registration on networks, secure cloud storage, hub-and-spoke model communications, commodity trading, and electronic currency exchange; essentially, any scenario where an encrypted tunnel using strong, quantum-safe cryptography is required.

The server in this model is built as a multi-threaded communications platform capable of generating a uniquely keyed encrypted tunnel for each connected client. With a lightweight state footprint of less than 4 kilobytes per client, a single server instance has the capability to handle potentially hundreds of thousands of simultaneous connections. The cipher encapsulation keys utilized during each key exchange are ephemeral and unique, ensuring that every key exchange remains secure and independent from previous key exchanges.

The root domain security server (RDS) distributes a public signature verification certificate to every client in its domain. This certificate is used to authenticate an QSTP application server (QAS) public certificate. The server's certificate is used to verify signed messages from the server to the client.

5.1 Root Certificate Generation

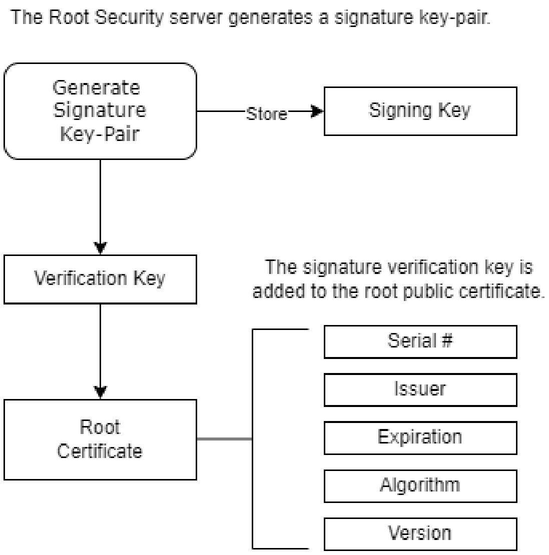

The Root Security server generates a signature key-pair.
Generate Signature Key-Pair
Store
Signing Key
Verification Key
The signature verification key is added to the root public certificate.
Root Certificate
Serial #
Issuer
Expiration
Algorithm
Version

Figure 5.1: QSTP root certificate creation.

The root security server generates an asymmetric signature key pair. The public verification key, together with identifying metadata (serial number, issuer, expiration dates, algorithm identifier, and version), forms the root certificate. By default, the root certificate is self-signed: a SHA3-256 hash of the certificate fields is computed and signed by the root's own private signing key, with the resulting signature stored in the csig field of the root certificate. This self-signature allows clients to verify the integrity of the root certificate's own fields.

When the QSTP_EXTERNAL_SIGNED_ROOT compilation flag is defined, the root certificate SHALL instead be signed by an external authority. In this mode, the root certificate includes additional fields for the external authority identity, external key identifier, and signing scheme. The external signature replaces the self-signature in the csig field.

The root server stores the private signing key, which it uses offline to sign application server certificates. The application server certificate is hashed, and the hash is signed by the root private signing key, with the signature populating the csig field of the server certificate. The client uses the asymmetric signature verification key embedded in the root certificate to verify server certificate authenticity.

The root certificate hash function commits the following fields in order: verification key, issuer, serial number, expiration-from timestamp, expiration-to timestamp, algorithm identifier, and version. All fields are hashed at their full declared sizes using SHA3-256. No variable-length string operations are used, ensuring that the hash value is fully deterministic and portable across implementations.

5.2 Connection Request

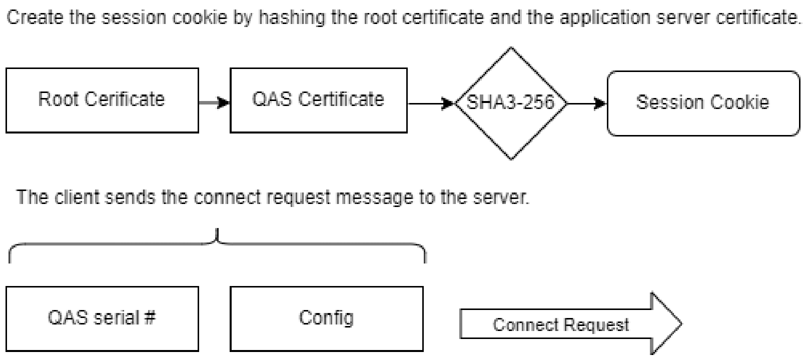

Create the session cookie by hashing the root certificate and the application server certificate.
Root Cerificate
QAS Certificate
SHA3-256
Session Cookie
The client sends the connect request message to the server.
QAS serial #
Config
Connect Request

Figure 5.2: QSTP connection request.

1) The client inspects the packet header for the correct flag, sequence number, expected message size, and that the valid-time has not expired.
2) The client begins the key exchange operation by sending a connect request packet to the server. This packet contains the server certificate serial number and the protocol configuration string.
3) The client computes the initial transcript hash (sch_0) by hashing the configuration string, the server certificate serial number, and the server's public signature verification key: $sch_0 \leftarrow H(cfg \| serial \| pvk)$. This hash seeds the running transcript and ensures that the session state is uniquely bound to the certificate pairing and the negotiated protocol set.
4) The client adds the application server’s certificate serial number and the configuration string to the message, and sends the connection request to the server.

5.3 Connection Response

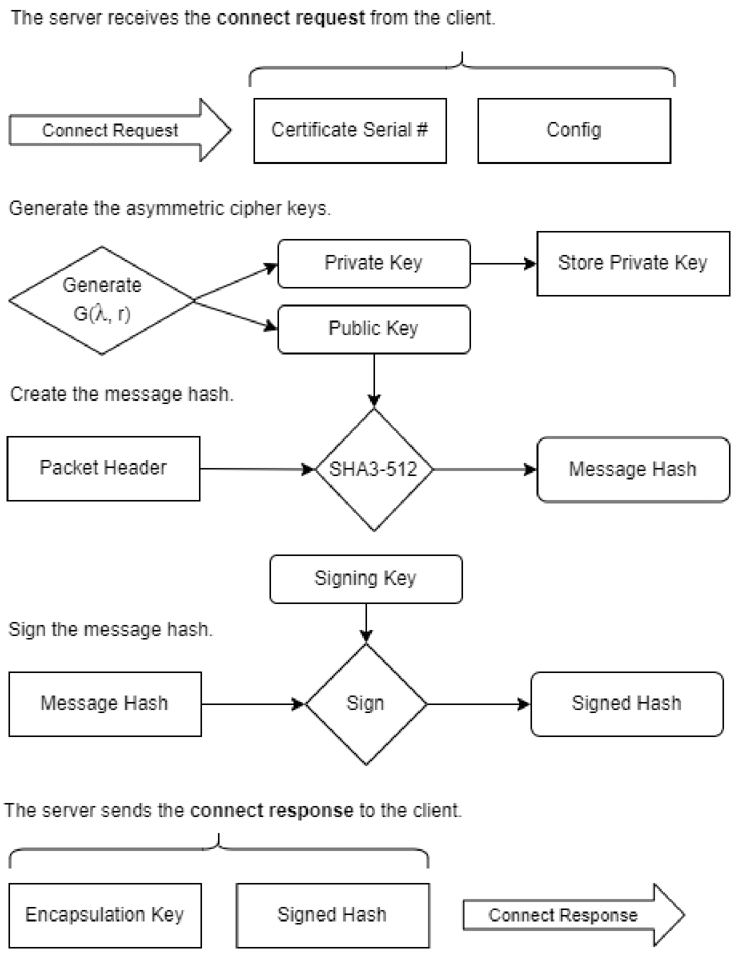
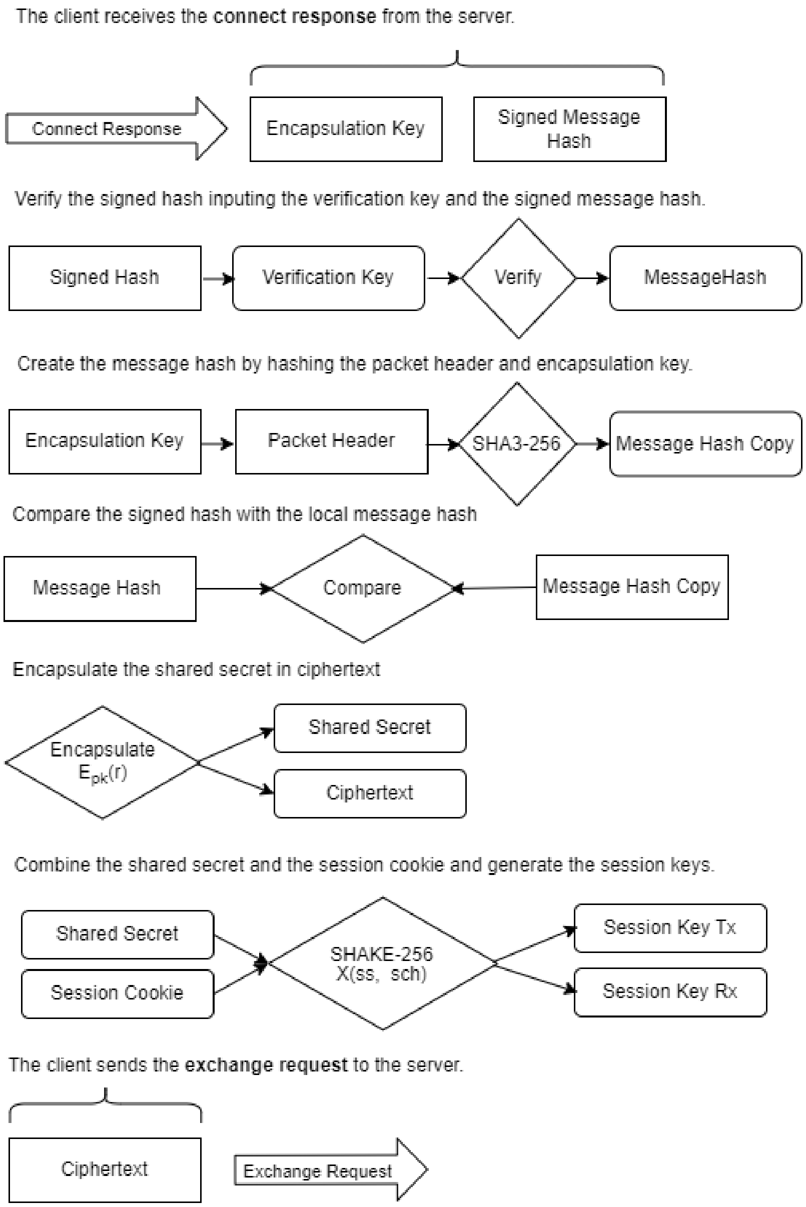


Figure 5.3: QSTP server connection response.

1) The server inspects the packet header for the correct flag, sequence number, expected message size, and that the valid-time has not expired.
2) The server checks its database for a key that matches the certificate serial number provided in the request. If the verification key is not found, the server sends an *unknown certificate* error message to the client, aborts the key exchange, logs the event, and tears down the session.
3) The server compares the protocol configuration string sent by the client with its own stored protocol string to ensure compatibility.
4) The server verifies the expiration time of the certificate. If all these fields are validated successfully, the server loads the signature key into its active state.
5) The server generates a new ephemeral public/private asymmetric cipher key pair. It computes a message hash phash ← H(phdr || sch || pk_kem) where phdr is the serialized connection response packet header, sch is the current transcript hash, and pk_kem is the ephemeral public encapsulation key. It then signs phash with its private signing key to produce the signed hash spkh. Following this, the server advances the transcript hash: $sch_1 \leftarrow H(sch_0 \,||\, phash)$.
6) The server places the signed hash spkh and the ephemeral public encapsulation key pk_kem into the connect response message and transmits it to the client to continue the key exchange

process. The private encapsulation key is retained in server state for use in the next step.

5.4 Exchange Request



The client receives the **connect response** from the server.

Verify the signed hash inputing the verification key and the signed message hash.

Create the message hash by hashing the packet header and encapsulation key.

Compare the signed hash with the local message hash

Encapsulate the shared secret in ciphertext

Combine the shared secret and the session cookie and generate the session keys.

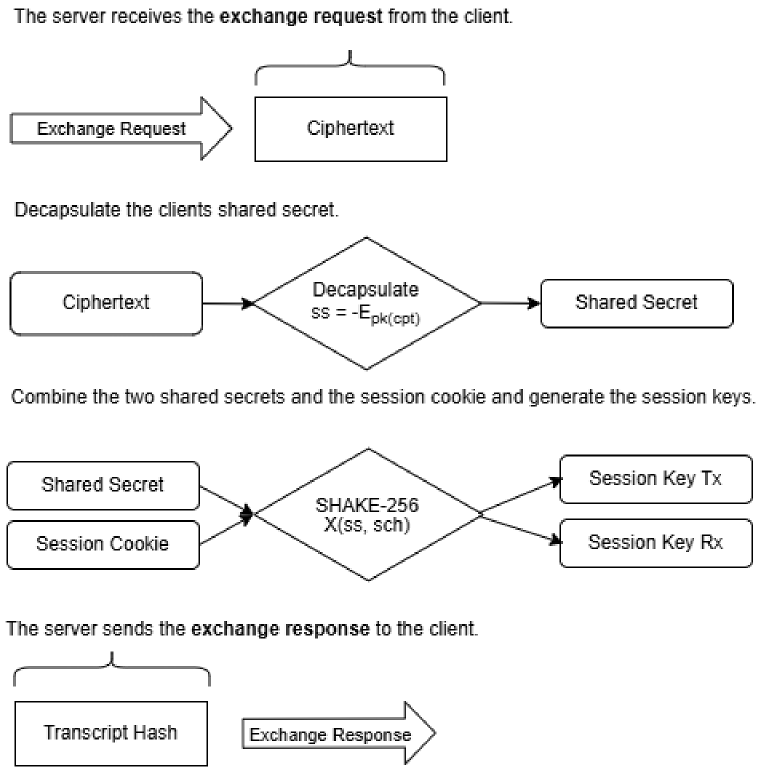
The client sends the **exchange request** to the server.

Figure 5.4: QSTP client exchange request.

1) The client inspects the packet header for the correct flag, sequence number, expected message size, and that the valid-time has not expired.
2) The client uses the server's signature verification key to verify the signature on the hash of the asymmetric encapsulation key and serialized packet header. If the signature verification fails, the client sends an *authentication failure* message to the server and terminates the connection.

3) If the signature is successfully verified, the client independently computes phash ← H(phdr || sch || pk_kem) using the received packet header, current local transcript value, and received encapsulation key, then compares this against the hash recovered from the signature. If they do not match, the client sends a hash invalid error message and closes the connection. On success, the client advances the transcript hash: $sch_1 \leftarrow H(sch_0 \| phash)$.
4) The client uses the asymmetric cipher key to encapsulate a *shared secret*, creating the ciphertext.
5) The client commits the ciphertext to the transcript hash: $sch_2 \leftarrow H(sch_1 \| cpta)$. The final transcript hash sch_2 and the shared secret sec are then passed to the KDF: $prnd \leftarrow cSHAKE(sec, sch_2)$, which generates the symmetric cipher keys and nonces used to key the transmit and receive cipher instances.
6) The cipher *rx* and *tx* symmetric instances are initialized and ready to transmit and receive data.
7) The asymmetric ciphertext is then included in the exchange request packet, which the client sends to the server.

5.5 Exchange Response



The server receives the **exchange request** from the client.

Decapsulate the clients shared secret.

Combine the two shared secrets and the session cookie and generate the session keys.

The server sends the **exchange response** to the client.

Figure 5.5: QSTP server exchange response.

1) The server inspects the packet header for the correct flag, sequence number, expected message size, and that the valid-time has not expired.
2) The server uses its stored asymmetric cipher private key to decapsulate the shared secret from the ciphertext.
3) The server commits the received ciphertext to its local transcript hash: $sch_2 \leftarrow H(sch_1 \| cpta)$. The decapsulated shared secret and the final transcript hash are then passed to the KDF: $prnd \leftarrow cSHAKE(sec, sch_2)$, which derives the symmetric cipher keys and nonces. The private encapsulation key is securely erased from memory.
4) These derived session keys are used to initialize the symmetric cipher instances, activating both the transmit and receive channels of the encrypted tunnel. The server then places the final transcript hash sch_2 in the exchange response message body and transmits it to the client.

5.6 Establish Verify

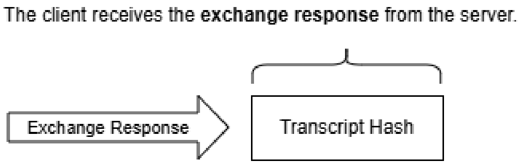


Figure 5.6: QSTP client establish verify.

1) The client inspects the packet header for the correct flag, sequence number, expected message size, and that the valid-time has not expired.
2) The client extracts the transcript hash value sch_2 transmitted by the server in the exchange response message body, and performs a constant-time comparison against its own locally computed transcript hash. If the values are identical, the tunnel is confirmed and the session state is set to established. If the values differ, the client SHALL immediately initiate a connection teardown and report an authentication failure.
3) The session is not considered established until this transcript hash comparison succeeds. This comparison constitutes explicit key confirmation: both parties have independently derived the same session keys from the same protocol transcript, providing assurance that no message was substituted or altered during the handshake.
4) The client SHALL handle any failure by tearing down the connection and informing the application layer of the specific error condition.

5.7 Root Certificate Self-Signing

The root certificate self-signing procedure is invoked during root certificate generation when the QSTP_EXTERNAL_SIGNED_ROOT flag is not defined. The procedure is as follows:

1) The root signature key pair is generated: $pk\_root, sk\_root \leftarrow G(\lambda, r)$.
2) The root certificate fields are populated: verification key, issuer, serial number, expiration

timestamps, algorithm identifier, and version.

3) A SHA3-256 hash of the certificate fields is computed in a canonical fixed-size order: hash ← H(verkey || issuer || serial || expiration.from || expiration.to || algorithm || version).
4) The hash is signed using the root's own private signing key: csig ← Ssk_root(hash).
5) The csig field is written into the root certificate, producing a self-authenticated root certificate. Any recipient in possession of the root public verification key may verify the root certificate's own field integrity by repeating steps 3-4 and verifying the signature.

When QSTP_EXTERNAL_SIGNED_ROOT is defined, steps 4-5 are performed by an external authority, and the csig field contains the external authority's signature. The additional fields authority, keyid, and scheme are populated accordingly and are included in the hash input for that mode.

5.8 Symmetric Ratchet

The [optional] **symmetric ratchet** mechanism in QSTP periodically updates the symmetric session keys using a randomly generated token. This process introduces new entropy into the encrypted stream and ensures that even if the current session keys are compromised, past keys remain secure.

The initiator of the symmetric ratchet generates a random token and transmits it over the encrypted channel. After sending the encrypted key, the initiator hashes this token together with the persistent ratchet key, which itself is a hash of the initial session key stored in the ratchet state. The combined hash of the random token and the ratchet key is added to the key derivation function and used to derive a new set of session keys. These derived session keys are used to re-key the symmetric cipher instances for both the transmit and receive channels, ensuring forward secrecy.

On the receiving end, the receiver decrypts the random token, then hashes it along with the ratchet key from its own persistent state. The resulting hash is used to key the KDF and derive the new symmetric session keys, which are then applied to re-key the transmit and receive channels.

This symmetric ratchet mechanism offers strong **forward secrecy**, it ensures that the knowledge of the current state alone is not sufficient to determine any of the previous session keys. This continuous re-keying process prevents attackers from gaining insight into past communications, even if they manage to compromise the current session key.

6. Mathematical Description

Mathematical Symbols

$\leftarrow \leftrightarrow \rightarrow$	-Assignment and direction symbols
:=, !=, ?=	-Equality operators; assign, not equals, evaluate
C	-The client host, initiates the exchange
S	-The server host, listens for a connection
$G(\lambda, r)$	-The asymmetric cipher key generation with parameter set and random source

$-E_{sk}$ -The asymmetric cipher decapsulation function and secret key

E_{pk} -The asymmetric cipher encapsulation function and public key

S_{sk} -Sign data with the secret signature key

V_{pk} -Verify a signature the public verification key

cfg -The protocol configuration string

cpr_{rx} -A receive channels symmetric cipher instance

cpr_{tx} -A transmit channels symmetric cipher instance

cpt -The symmetric ciphers cipher-text

cpta -The asymmetric ciphers cipher-text

$-E_k$ -The symmetric decryption function and key

E_k -The symmetric encryption function and key

H -The hash function (SHA3)

k, *mk* -A symmetric cipher and MAC key

KDF -The key expansion function (SHAKE)

kid -The public keys unique identity array

M_{mk} -The MAC function and key (KMAC)

pk, *sk* -Asymmetric public and secret keys

pvk -Public signature verification key

sch -The running transcript hash; initialized as H(cfg || serial || pvk) and iteratively updated to commit each protocol message into the session key derivation

sch_0 -The initial transcript hash: H(cfg || serial || pvk)

sch_1 -The transcript hash after committing the server's ephemeral public key hash: H(sch_0 || phash)

sch_2 -The transcript hash after committing the encapsulation ciphertext: H(sch_1 || cpta)

phash -The message hash committed during Connect Response: H(phdr || sch || pk_kem)

phdr -The serialized packet header

pk_kem -The server's ephemeral asymmetric public encapsulation key

sec -The shared secret derived from asymmetric encapsulation and decapsulation

spkh -The signed hash of the asymmetric public encapsulation-key

Key Exchange Sequence

Preamble

The client retains a copy of the root server's public certificate. This certificate is used to validate the application server's certificate. The server certificate contains a signature field (*csig*), that has a hash of the server certificate, signed by the root authentication server. When the client first connects to an application server, the server sends its root signed certificate to the client. The client verifies the signature in the certificate signature field using the root server's validation key. The client hashes the certificate, and compares it to the signed hash for equivalency. The server's certificate is further checked for a valid expiration time (which is checked every time a key exchange between the client and server is initiated), as well as for a matching protocol set, and QSTP protocol version fields. Once the server certificate has been verified, it is cached by the client, and used to validate messages signed by the application server.

The key exchange sequence begins with the client verifying the validity of the server's public certificate and signature verification key. The client checks the expiration date of this key, and if it is found to be invalid or expired, the client initiates a re-authentication session with the server. During this session, a new key is distributed over an encrypted channel, and the client verifies the new key's certificate using the designated authentication authority or scheme implemented by the server and client software.

6.1 Connect Request

The client sends a connection request with its configuration string, and asymmetric public signature key serial number. The serial number is a multi-part 16-byte certificate identification array, used to match the intended target to the corresponding key.

The configuration string defines the cryptographic protocol set being used; this must match both implementations configuration settings. The client stores a hash of the configuration string, the serial number, and of the server's public asymmetric signature verification-key, which is used as a session cookie during the exchange.

Where:

- cfg is the protocol configuration string.
- serial is the server certificate serial number (16 bytes).
- pvk is the server's public asymmetric signature verification key.

$sch_0 \leftarrow \mathrm{H}(cfg \parallel serial \parallel pvk)$

This forms the initial transcript hash. It binds the negotiated protocol set, the target server identity, and the server's long-term verification key into all subsequently derived key material.

The client sends the key identity string, and the configuration string to the server.

C{ *serial*, *cfg* } → S

Certificate Serial Number

The certificate serial number is a 16-byte array that acts as a public asymmetric serial number and device identification string. It is used to match the target server to its corresponding cryptographic key, ensuring that the correct key is used during the exchange.

Configuration String

The *configuration string* (*cfg*) specifies the cryptographic protocol set being used in the key exchange process. For the exchange to proceed successfully, the configuration strings used by both the client and server must match, indicating that they are using the same cryptographic parameters.

Session Cookie

To securely manage the state of the key exchange, the client generates a *session cookie hash* by hashing a combination of the root server's public certificate and the server public certificate. This session cookie (*sch*) serves as an identifier for the session, helping to ensure that the correct certificates are referenced in the exchange. The server has this cookie stored in its state, whereas the client generates the cookie when a key exchange is initialized. The cookie will be unique to every root and application server certificate pairing.

The client then sends the key certificate serial number (*ser*) and the protocol configuration string (*cfg*) to the server to initiate the connection:

C{ *ser*, *cfg* } → S

6.2 Connect Response

The server responds with either an error message, or a response packet. Any error during the key exchange will generate an error-packet sent to the remote host, which will trigger a tear down of the session and network connection on both sides.

The server first checks that it has the requested asymmetric signature verification key corresponding to that host using the serial number array, then verifies that it has a compatible protocol configuration.

The server computes the same initial transcript hash as the client, binding configuration, serial,

and verification key:

$sch_0 \leftarrow \mathrm{H}(cfg \,||\, serial \,||\, pvk)$

The server generates an asymmetric encryption key-pair, stores the private key, hashes the public encapsulation key, and signs the hash of the public encapsulation key and the serialized connect response packet header using the asymmetric signing key. The public signature verification key can itself be enveloped by a 'chain of trust' model, like X.509, using a signature verification extension to this protocol.

$pk, sk \leftarrow G(\lambda, r)$

$phash \leftarrow H(phdr \| sch_0 \| pk\_kem)$

$spkh \leftarrow S_{sk}(phash)$

The server sends a connect response message containing a signed hash of the public asymmetric encapsulation-key, and a copy of that key.

$S\{ spkh, pk \} \rightarrow C$

Key Verification and Protocol Check

The server begins by verifying that it has the correct certificate that corresponds to the client's request, by comparing the certificate serial number in the request to the server's certificate serial number.

It then checks that its protocol configuration matches the one specified by the client.

Asymmetric Key Generation and Signing

The server generates a new asymmetric encryption key pair and securely stores the private key. It hashes the public encapsulation key and the serialized connect response packet header, and signs this hash using its private asymmetric signature key. The signature provides a cryptographic guarantee that the public asymmetric cipher key has not been tampered with during transmission.

Key generation and signing steps:

Generate the public (*pk*) and private (*sk*) asymmetric encryption keys.

$pk, sk \leftarrow G(\lambda, r)$

Create a hash of the public asymmetric encapsulation key, the session cookie, and the serialized *connect response* packet header (*sh*).

$phash \leftarrow H(phdr \| sch_0 \| pk\_kem)$

where phdr is the serialized connect response packet header and pk_kem is the ephemeral public encapsulation key. The server signs this hash:

$spkh \leftarrow S_{sk}(phash)$

The server then advances the transcript hash:

$sch_1 \leftarrow H(sch_0 \,||\, phash)$

Server Response

The server sends a connect response message back to the client, containing the signed hash of the public asymmetric encapsulation key (*spkh*) and a copy of the public key:

$S\{\ spkh, pk\ \} \rightarrow C$

6.3 Exchange Request

The client verifies the signature of the hash, generates its own hash of the asymmetric cipher public key, cookie, and packet header, and compares it with the hash contained in the message.

If the hash matches, the client uses the public-key to encapsulate a shared secret.

Signature Verification and Hash Check

The client begins by verifying the signature of the hash using the server's public verification key. It generates its own hash of the server's public key and compares it to the hash contained in the server's message. If the hashes match, the client proceeds to encapsulate the shared secret. If the hashes do not match, the key exchange is aborted.

The client uses the server's public verification key to check the signature of the public key hash. If the verification is successful, the process continues; otherwise, the key exchange fails.

Vpk(spkh) → phash   (true ?= phash : abort)

The client independently recomputes:

$phash' \leftarrow H(phdr \,||\, sch_0 \,||\, pk\_kem)$

and verifies phash' = phash by constant-time comparison. On mismatch, the key exchange is aborted.

The client then advances its local transcript hash:

$sch_1 \leftarrow \mathrm{H}(sch_0 \,||\, phash)$

The public encapsulation key and connect response packet header are hashed, and the hash is compared with signed hash received from the server. Once the packet header and public key are verified, the client uses the server's public key to encapsulate a shared secret.

The client generates a ciphertext (*cpt*) and encapsulates the shared secret (*sec*) using the server's public key.

$cpt, sec \leftarrow \mathrm{E}_{\mathrm{pk}}(r)$

The client combines the shared secret and the session cookie to derive the session keys and two unique nonces for the communication channels.

The Key Derivation Function (KDF) generates two session keys (*k1*, *k2*) and two nonces (*n1*, *n2*) using the shared secret (*sec*) and the session cookie (*sch*).

The client commits the ciphertext to the transcript:

$sch_2 \leftarrow \mathrm{H}(sch_1 \,||\, cpta)$

Session keys and nonces are then derived:

$prnd \leftarrow \mathrm{cSHAKE}(sec, sch_2)$

$k1, n1, k2, n2 \leftarrow prnd$

Cipher Initialization

The receive and transmit channel ciphers are then initialized using the derived keys and nonces.

Initializes the receive channel cipher with key *k2* and nonce *n2*.

$\mathrm{cpr}_{\mathrm{rx}}(k2, n2)$

Initializes the transmit channel cipher with key *k1* and nonce *n1*.

$\mathrm{cpr}_{\mathrm{tx}}(k1, n1)$

Client Transmission

The client sends the ciphertext to the server as part of the exchange request.

The client transmits the encapsulated shared secret to the server.

C{ *cpt* } → S

6.4 Exchange Response

The server processes the client's exchange request by decapsulating the shared secret, deriving the session keys, and confirming the secure communication channel.

Shared Secret Decapsulation

The server decapsulates the shared secret from the ciphertext received from the client.

The server uses its private asymmetric key to decapsulate the shared secret (*sec*) from the received ciphertext (*cpt*).

$sec \leftarrow -E_{sk}(cpt)$

Session Key Derivation

The server combines the decapsulated shared secret and the session cookie hash to derive two session keys and two unique nonces for the communication channels.

The Key Derivation Function (SHAKE) generates two symmetric session keys (*k1*, *k2*) and two nonces (*n1*, *n2*) using the shared secret (*sec*) and the session cookie (*sch*).

The server commits the ciphertext to its local transcript:

$sch_2 \leftarrow H(sch_1 \| cpta)$

Session keys and nonces are derived identically to the client:

$prnd \leftarrow \text{cSHAKE}(sec, sch_2)$

$k1, n1, k2, n2 \leftarrow prnd$

Cipher Initialization

The server initializes the symmetric ciphers for the receive and transmit channels.

Initializes the receive channel cipher with key *k1* and nonce *n1*.

$\mathrm{cpr}_{rx}(k1, n1)$

Initializes the transmit channel cipher with key *k2* and nonce *n2*.

$\mathrm{cpr}_{tx}(k2, n2)$

Server Response

The server sets the packet flag to *exchange response*, indicating that the encrypted channels have been successfully established. It then sends this notification back to the client to confirm the secure communication channel.

The server places the final transcript hash in the exchange response message body, and sends it to the client:

$S\{ sch_2 \} \rightarrow C$

This constitutes explicit key confirmation. The client MUST verify that the received sch_2 matches its locally computed value before declaring the session established.The server updates its operational state to *session established*, indicating that it is now ready to securely process data over the encrypted channels.

6.5 Establish Verify

In the final step of the key exchange sequence, the client verifies the status of the encrypted tunnel based on the server's exchange response.

Client Verification

The client receives the exchange response packet and extracts the transcript hash value sch_2 transmitted by the server. It performs a constant-time comparison: sch_2(server) ?= sch_2(client). If the values are equal, the handshake is confirmed and both parties have derived identical session keys from an identical transcript. The session state is set to established. If the values differ, the client SHALL immediately tear down the connection without processing any further data, and SHALL report an authentication failure to the application layer. This check constitutes the explicit key confirmation step of the protocol.

Operational State

Once the verification is complete and the tunnel is confirmed, the client updates its internal state to *session established*, indicating that the secure communication channels are fully operational. The client is now ready to process data over the encrypted tunnel.

6.6 Transmission

During the transmission phase, either the client or server sends messages over the established encrypted tunnel using the RCS stream cipher's MAC, AEAD (Authenticated Encryption with Associated Data), and encryption functions. This process ensures the integrity and confidentiality of the transmitted data.

Message Serialization and Encryption

The transmitting host (client or server) starts by serializing the packet header, which includes critical details such as the message size, timestamp, protocol flag, and sequence number. This serialized header is then added to the symmetric cipher’s associated data parameter, which adds metadata authentication to the encryption process.

The message encryption process is as follows:

1. **Encrypt the Message**: The plaintext message is encrypted using the symmetric encryption function of the RCS stream cipher. The symmetric encryption function (E_k) is applied to the plaintext message (*m*) to produce the ciphertext (*cpt*).
   cpt ← $E_k(m)$

2. **Update the MAC State**: The serialized packet header is added to the MAC (Message Authentication Code) state through the additional-data parameter of the RCS cipher. The MAC function (M_{mk}) is updated with the serialized packet header (*sh*) and the ciphertext (*cpt*) to produce the MAC code (*mc*).
   $mc \leftarrow M_{mk}(sh, cpt)$

3. **Append the MAC Code**: The MAC code is appended to the end of the ciphertext, ensuring that any tampering with the data during transmission will be detected.

Packet Decryption and Verification

Upon receiving the packet, the recipient host deserializes the packet header and adds it to the MAC state along with the received ciphertext. The MAC computation is then finalized and compared with the MAC code that was appended to the ciphertext. The packet timestamp is compared to the *UTC* time, if the time is outside of a tolerance threshold, the packet is rejected and the session is torn down.

1. **Generate the MAC Code:** Add the serialized packet header to the cipher AEAD. Add the ciphertext and generate the MAC code.
   $mc` \leftarrow M_{mk}(sh, cpt)$
   Compare the MAC tag copy with the MAC tag appended to the ciphertext.
   $mc` ?= mc$
   If the MAC check fails, indicating potential data tampering or corruption, the decryption function returns an empty message array and an error status. The application **shall** handle this error accordingly.

2. **Decrypt the Ciphertext:** If the MAC code matches, the ciphertext is considered authenticated, and the message is decrypted.
   The ciphertext (*cpt*) is decrypted back into the plaintext message (*m*) if the MAC verification succeeds.
   $m \leftarrow -E_k(cpt)$

This process ensures that the transmitted data remains confidential and tamper-evident, providing both encryption and authentication to protect the integrity of the communication. Any errors during decryption signal an immediate response to prevent the further exchange of potentially compromised data.

7: QSTP API

7.1 Definitions and Shared API

Header:

qstp.h

Description:

The QSTP header contains shared constants, types, and structures, as well as function calls common to both the QSTP server and client implementations.

Structures:

The **QSTP_ERROR_STRINGS** is a static string-array containing QSTP error descriptions, used in the error reporting functionality.

Data Set	Purpose
QSTP_ERROR_STRINGS	A string array of readable error descriptions.

Table 7.1a QSTP error strings.

The **QSTP_CONFIG_STRING** is a static string containing the readable QSTP configuration string.

Data Set	Purpose
QSTP_CONFIG_STRING	The QSTP configuration string.

Table 7.1b QSTP configuration string.

The **qstp_packet** contains the QSTP packet structure.

Data Name	Data Type	Bit Length	Function
flag	Uint8	0x08	The packet flag
msglen	Uint32	0x20	The packets message length
sequence	Uint64	0x40	The packet sequence number
utctime	Uint64	0x40	The UTC packet creation time
message	Uint8 Array	Variable	The packets message data

Table 7.1c QSTP packet structure.

The **qstp_server_certificate** contains the QSTP server public certification state.

Data Name	Data Type	Bit Length	Function
csig	Uint8 Array	Variable	The certificates root signed hash
issuer	Uint8 Array	0x0200	The certificates issuer identity
rootser	Uint8 Array	0x80	The root certificate serial number
serial	Uint8 Array	0x80	The certificate serial number
verkey	Uint8 Array	Variable	The asymmetric signatures verification key
expiration	Uint64	0x40	The certificate expiration time
algorithm	Uint8	0x10	The algorithm identifier
version	Uint8	0x10	The QSTP version number

Table 7.1d QSTP server public certificate structure.

The **qstp_server_signature_key** contains the QSTP server signature key state.

Data Name	Data Type	Bit Length	Function
schash	Uint8 Array	0x0200	The certificate token hash
issuer	Uint8 Array	0x0200	The certificates issuer identity
sigkey	Uint8 Array	Variable	The server certificate signing key
serial	Uint8 Array	0x80	The certificate serial number
verkey	Uint8 Array	Variable	The asymmetric signatures verification key
expiration	Uint64	0x40	The certificate expiration time
algorithm	Uint8	0x10	The algorithm identifier
version	Uint8	0x10	The QSTP version number

Table 7.1e QSTP server secret certificate structure.

Enumerations:

The **qstp_messages** enumeration defines the network messages.

Enumeration	Purpose
qstp_messages_none	No message was specified
qstp_messages_accept_fail	The socket accept failed
qstp_messages_listen_fail	The listener socket could not connect
qstp_messages_bind_fail	The listener socket could not bind to the address
qstp_messages_create_fail	The listener socket could not be created
qstp_messages_connect_success	The server connected to a host
qstp_messages_receive_fail	The socket receive function failed
qstp_messages_allocate_fail	The server memory allocation request has failed
qstp_messages_kex_fail	The key exchange has experienced a failure

qstp_messages_disconnect	The server has disconnected the client
qstp_messages_disconnect_fail	The server has disconnected the client due to an error
qstp_messages_socket_message	The server has had a socket level error
qstp_messages_queue_empty	The server has reached the maximum number of connections
qstp_messages_listener_fail	The server listener socket has failed
qstp_messages_sockalloc_fail	The server has run out of socket connections
qstp_messages_decryption_fail	The message decryption has failed
qstp_messages_connection_fail	The connection failed or was interrupted
qstp_messages_invalid_request	The function received an invalid request

Table 7.1g QSTP messages enumeration.

The **qstp_errors** enumeration is a list of the QSTP error code values.

Enumeration	**Purpose**
qstp_error_none	No error was detected
qstp_error_accept_fail	The socket accept function returned an error
qstp_error_authentication_failure	The symmetric cipher had an authentication failure
qstp_error_channel_down	The communications channel has failed
qstp_error_connection_failure	The device could not make a connection to the remote host
qstp_error_connect_failure	The transmission failed at the KEX connection phase
qstp_error_decapsulation_failure	The asymmetric cipher failed to decapsulate the shared secret
qstp_error_decryption_failure	The decryption authentication has failed
qstp_error_establish_failure	The transmission failed at the KEX establish phase
qstp_error_exchange_failure	The transmission failed at the KEX exchange phase
qstp_error_hash_invalid	The public-key hash is invalid
qstp_error_hosts_exceeded	The server has run out of socket connections
qstp_error_invalid_input	The expected input was invalid
qstp_error_invalid_request	The packet flag was unexpected
qstp_error_keep_alive_expired	The keep alive has expired with no response
qstp_error_key_expired	The QSTP public key has expired
qstp_error_key_unrecognized	The key identity is unrecognized
qstp_error_keychain_fail	The ratchet operation has failed
qstp_error_listener_fail	The listener function failed to initialize
qstp_error_memory_allocation	The server has run out of memory
qstp_error_message_time_invalid	The packet has valid time expired
qstp_error_packet_unsequenced	The packet was received out of sequence
qstp_error_random_failure	The random generator has failed

qstp_error_receive_failure	The receiver failed at the network layer
qstp_error_signature_failure	The signing function has failed
qstp_error_transmit_failure	The transmitter failed at the network layer
qstp_error_verify_failure	The expected data could not be verified
qstp_error_unknown_protocol	The protocol string was not recognized

Table 7.1h QSTP errors enumeration.

The **qstp_flags** enum contains the QSTP packet flags.

Enumeration	**Purpose**
qstp_flag_none	No flag was specified
qstp_flag_connect_request	The QSTP key-exchange client connection request flag
qstp_flag_connect_response	The QSTP key-exchange server connection response flag
qstp_flag_connection_terminate	The connection is to be terminated
qstp_flag_encrypted_message	The message has been encrypted flag
qstp_flag_exstart_request	The QSTP key-exchange client exstart request flag
qstp_flag_exstart_response	The QSTP key-exchange server exstart response flag
qstp_flag_exchange_request	The QSTP key-exchange client exchange request flag
qstp_flag_exchange_response	The QSTP key-exchange server exchange response flag
qstp_flag_establish_request	The QSTP key-exchange client establish request flag
qstp_flag_establish_response	The QSTP key-exchange server establish response flag
qstp_flag_keep_alive_request	The packet contains a keep alive request
qstp_flag_remote_connected	The remote host is connected flag
qstp_flag_remote_terminated	The remote host has terminated the connection
qstp_flag_session_established	The exchange is in the established state
qstp_flag_session_establish_verify	The exchange is in the established verify state
qstp_flag_unrecognized_protocol	The protocol string is not recognized
qstp_flag_symmetric_ratchet_request	The host has received a symmetric key ratchet request
qstp_flag_transfer_request	The host has received a transfer request
Qst p_flag_error_condition	The connection experienced an error

Table 7.1i QSTP flags enumeration.

The **qstp_configuration_sets** enumeration defines the QSTP configuration sets.

Enumeration	**Purpose**
qstp_configuration_set_none	No configuration set was specified

qstp_configuration_set_dilithium1_kyber1_rcs256_shake256	The Dilithium-S1/Kyber-S1/RCS-256/SHAKE-256 algorithm set
qstp_configuration_set_dilithium3_kyber3_rcs256_shake256	The Dilithium-S3/Kyber-S3/RCS-256/SHAKE-256 algorithm set
qstp_configuration_set_dilithium5_kyber5_rcs256_shake256	The Dilithium-S5/Kyber-S5/RCS-256/SHAKE-256 algorithm set
qstp_configuration_set_dilithium5_kyber6_rcs512_shake512	The Dilithium-S5/Kyber-S6/RCS-256/SHAKE-256 algorithm set
qstp_configuration_set_dilithium1_mceliece1_rcs256_shake256	The Dilithium-S1/McEliece-S1/RCS-256/SHAKE-256 algorithm set
qstp_configuration_set_dilithium3_mceliece3_rcs256_shake256	The Dilithium-S3/McEliece-S3/RCS-256/SHAKE-256 algorithm set
qstp_configuration_set_dilithium5_mceliece5_rcs256_shake256	The Dilithium-S5/McEliece-S5a/RCS-256/SHAKE-256 algorithm set
qstp_configuration_set_dilithium5_mceliece6_rcs256_shake256	The Dilithium-S5/McEliece-S6/RCS-256/SHAKE-256 algorithm set
qstp_configuration_set_dilithium5_mceliece7_rcs256_shake256	The Dilithium-S5/McEliece-S7/RCS-256/SHAKE-256 algorithm set

Table 7.1j QSTP configuration set enumeration.

Constants:

Constant Name	Value	Purpose
QSTP_CONFIG_DILITHIUM_KYBER	N/A	Sets the asymmetric cryptographic primitive-set to Dilithium/Kyber
QSTP_CONFIG_DILITHIUM_MCELIECE	N/A	Sets the asymmetric cryptographic primitive-set to Dilithium/McEliece
QSTP_SERVER_PORT	32119	The default server port address

QSTP_ASYMMETRIC_CIPHER_TEXT_SIZE	Variable	The byte size of the asymmetric cipher-text array
QSTP_ASYMMETRIC_PRIVATE_KEY_SIZE	Variable	The byte size of the asymmetric cipher private-key array
QSTP_ASYMMETRIC_PUBLIC_KEY_SIZE	Variable	The byte size of the asymmetric cipher public-key array
QSTP_ASYMMETRIC_SIGNING_KEY_SIZE	Variable	The byte size of the asymmetric signature signing-key array
QSTP_ASYMMETRIC_VERIFICATION_KEY_SIZE	Variable	The byte size of the asymmetric signature verification-key array
QSTP_ASYMMETRIC_SIGNATURE_SIZE	Variable	The byte size of the asymmetric signature array
QSTP_ACTIVE_VERSION	1	The QSTP active version
QSTP_CERTIFICATE_ALGORITHM_SIZE	1	The algorithm type size
QSTP_CERTIFICATE_DESIGNATION_SIZE	1	The size of the certificate designation field
QSTP_CERTIFICATE_EXPIRATION_SIZE	16	The certificate expiration date length
QSTP_CERTIFICATE_HASH_SIZE	32	The size of the certificate the certificate hash in bytes
QSTP_CERTIFICATE_ISSUER_SIZE	32	The maximum certificate issuer string length.
QSTP_CERTIFICATE_DEFAULT_PERIOD	31536000	The default certificate validity period in seconds
QSTP_CERTIFICATE_DEFAULT_DURATION_DAYS	365	The default number of days a

		public key remains valid
QSTP_CERTIFICATE_DEFAULT_DURATION_SECONDS	31536000	The number of seconds a public key remains valid
QSTP_CERTIFICATE_LINE_LENGTH	64	The line length of the printed QSTP public key
QSTP_CERTIFICATE_MAXIMUM_PERIOD	63072000	The maximum certificate validity period in seconds
QSTP_CERTIFICATE_MINIMUM_PERIOD	86400	The minimum certificate validity period in seconds
QSTP_CERTIFICATE_SERIAL_SIZE	16	The certificate serial number field length
QSTP_CERTIFICATE_SERIAL_ENCODED_SIZE	32	The hex encoded certificate serial number string length
QSTP_CERTIFICATE_SIGNED_HASH_SIZE	Variable	The line length of the printed QSTP public key
QSTP_CERTIFICATE_TIMESTAMP_SIZE	8	The key expiration timestamp size
QSTP_CERTIFICATE_VERSION_SIZE	1	The version id size
QSTP_CONNECTIONS_INIT	1000	The initial QSTP connections queue size
QSTP_CONNECTIONS_MAX	50000	The maximum number of connections
QSTP_CONNECTION_MTU	1500	The QSTP packet buffer size
QSTP_MACTAG_SIZE	32	The mac key size
QSTP_NONCE_SIZE	32	The size of the symmetric cipher nonce
QSTP_PACKET_ERROR_SEQUENCE	0xFF00000000000000	The packet error sequence number
QSTP_PACKET_ERROR_SIZE	1	The packet error message size

QSTP_PACKET_FLAG_SIZE	1	The packet flag size
QSTP_PACKET_HEADER_SIZE	21	The QSTP packet header size
QSTP_PACKET_MESSAGE_LENGTH_SIZE	4	The size of the packet message length
QSTP_PACKET_MESSAGE_MAX	0x3D090000	The maximum message size used during the key exchange (1 GB)
QSTP_PACKET_REVOCATION_SEQUENCE	0xFF	The revocation packet sequence number
QSTP_PACKET_SEQUENCE_SIZE	8	The size of the packet sequence number
QSTP_PACKET_SEQUENCE_TERMINATOR	0xFFFFFFFF	The sequence number of a packet that closes a connection
QSTP_PACKET_TIME_THRESHOLD	60	The maximum number of seconds a packet is valid
QSTP_SECRET_SIZE	32	The size of the shared secret for each channel
QSTP_CLIENT_PORT	32118	The default client port address
QSTP_SERVER_PORT	32119	The default server port address
QSTP_ROOT_PORT	32120	The default root port address
QSTP_SYMMETRIC_KEY_SIZE	32	The Simplex 256-bit symmetric cipher key size
QSTP_STORAGE_PATH_MAX	260	The maximum path size
QSTP_ROOT_CERTIFICATE_SIZE	Variable	The root certificate length
QSTP_ROOT_SIGNATURE_KEY_SIZE	Variable	The root signature key size
QSTP_SERVER_CERTIFICATE_SIZE	Variable	A server certificate length

QSTP_SERVER_SIGNATURE_KEY_SIZE	Variable	A server signing key length
QSTP_USE_RCS_ENCRYPTION	N/A	When defined, the RCS cipher is used as the symmetric AEAD.

Table 7.1k QSTP constants.

The **qstp_connection_state** contains the QSTP connection state.

Data Name	Data Type	Bit Length	Function
target	Struct	0x440	The target host socket structure
rxcpr	Struct	Variable	The receive channel cipher state
txcpr	Struct	Variable	The transmit channel cipher state
rxseq	Uint64	0x40	The receive channels packet sequence number
txseq	Uint64	0x40	The transmit channels packet sequence number
cid	Uint32	0x20	The connections instance count
exflag	Uint8	0x08	The KEX position flag
receiver	bool	0x08	The hosts receiver status

Table 7.11 QSTP connection state structure.

Functions:

Configuration From String

Convert a configuration string to an enumeration member.

```
qstp_configuration_sets qstp_configuration_from_string(const char* config)
```

Configuration To String

Convert a configuration enumeral to a configuration string.

```
const char* qstp_configuration_to_string(qstp_configuration_sets cset)
```

Connection Close

Close the network connection between hosts.

```
void qstp_connection_close(qstp_connection_state* cns, qstp_errors err, bool
notify)
```

Connection State Dispose

Reset the connection state to zero.

```
void qstp_connection_state_dispose(qstp_connection_state* cns)
```

Decrypt Packet

Decrypt a message and copy it to the message output.

```
qstp_errors qstp_decrypt_packet(qstp_connection_state* cns, uint8_t* message,
size_t* msglen, const qstp_network_packet* packetin)
```

Encrypt Packet

Encrypt a message and build an output packet.

```
qstp_errors qstp_encrypt_packet(qstp_connection_state* cns,
qstp_network_packet* packetout, const uint8_t* message, size_t msglen)
```

Error To String

Return a pointer to a string description of an error code.

```
const char* qstp_error_to_string(qstp_errors error)
```

Header Create

Populate a packet header and set the creation time.

```
void qstp_header_create(qstp_network_packet* packetout, qstp_flags flag,
uint64_t sequence, uint32_t msglen)
```

Header Validate

Validate a packet header and timestamp.

```
qstp_errors qstp_header_validate(qstp_connection_state* cns, const
qstp_network_packet* packetin, qstp_flags flag, uint64_t sequence, uint32_t
msglen)
```

Get Error Description

Get the error string description.

```
const char* qstp_get_error_description(qstp_messages emsg)
```

Header Deserialize

Deserialize a byte array to a packet header.

```
void qstp_packet_header_deserialize(const uint8_t* header,
qstp_network_packet* packet)
```

Header Serialize

Serialize a packet header to a byte array.

```
void qstp_packet_header_serialize(const qstp_network_packet* packet, uint8_t*
header)
```

Log Error

Log the message, socket error, and string description.

```
void qstp_log_error(const qstp_messages emsg, qsc_socket_exceptions err,
const char* msg)
```

Log Message

Log the message.

```
void qstp_log_message(const qstp_messages emsg)
```

Log Write

Log the message, and string description.

```
void qstp_log_write(const qstp_messages emsg, const char* msg)
```

Packet Clear

Clear a packet's state.

```
size_t qstp_packet_clear(const qstp_network_packet* packet)
```

Packet Error Message

Populate a packet structure with an error message.

```
void qstp_packet_error_message(qstp_network_packet* packet, qstp_errors
error)
```

Packet Set UTC Time

Sets the local UTC seconds time in the packet header.

```
void qstp_packet_set_utc_time(qstp_network_packet* packet)
```

Packet Time Valid

Checks the local UTC seconds time against the packet sent time for validity within the packet time threshold.

```
bool qstp_packet_time_valid(const qstp_network_packet* packet)
```

Packet To Stream

Serialize a packet to a byte array.

```
size_t qstp_packet_to_stream(const qstp_network_packet* packet, uint8_t*
pstream)
```

Root Certificate Compare

Compare two root certificates for equivalence.

```
bool qstp_root_certificate_compare(const qstp_root_certificate* a, const
qstp_root_certificate* b)
```

Root Certificate Decode

Copy a root certificate structure to a file.

```
bool qstp_root_certificate_decode(qstp_root_certificate* root, const char*
enck, size_t enclen)
```

Roor Certificate Deserialize

Deserialize a root certificate

```
void qstp_root_certificate_deserialize(qstp_root_certificate* root, const
uint8_t input[QSTP_ROOT_CERTIFICATE_SIZE])
```

Root Certificate Encode

Encode a root certificate into a readable string

```
size_t qstp_root_certificate_encode(char* enck, size_t enclen, const
qstp_root_certificate* root)
```

Root Certificate Encoded Size

Get the root encoding string size.

```
size_t qstp_root_certificate_encoded_size()
```

Root Certificate Extract

Extract the root certificate from the server key.

```
void qstp_root_certificate_extract(qstp_root_certificate* root, const
qstp_root_signature_key* kset)
```

Root Certificate Hash

Hash a root certificate

```
void qstp_root_certificate_hash(uint8_t output[QSTP_CERTIFICATE_HASH_SIZE],
const qstp_root_certificate* root)
```

Root Certificate Serialize

Serialize a root certificate to an array.

```
void qstp_root_certificate_serialize(uint8_t
output[QSTP_ROOT_CERTIFICATE_SIZE], const qstp_root_certificate* root)
```

Root Certificate Sign

Sign a server certificate.

```
size_t qstp_root_certificate_sign(qstp_server_certificate* cert, const
qstp_root_certificate* root, const uint8_t* rsigkey)
```

Root Certificate Verify

Verify a certificate is signed by the root.

```
bool qstp_root_certificate_verify(const qstp_root_certificate* root, const
qstp_server_certificate* cert)
```

Root Certificate To File

Copy a root certificate structure to a file.

```
bool qstp_root_certificate_to_file(const qstp_root_certificate* root, const
char* fpath)
```

Root File To Certificate

Copy a certificate from a file to a root certificate structure.

```
bool qstp_root_file_to_certificate(qstp_root_certificate* root, const char*
fpath)
```

Root File To Key

Copy a root key from a file to a root key structure.

```
bool qstp_root_file_to_key(qstp_root_signature_key* kset, const char* fpath)
```

Root Get Issuer

Get the root certificate issuer name.

```
void qstp_root_get_issuer(char issuer[QSTP_CERTIFICATE_ISSUER_SIZE])
```

Root Key Deserialize

Deserialize a root signature key.

```
void qstp_root_key_deserialize(qstp_root_signature_key* kset, const uint8_t
input[QSTP_ROOT_SIGNATURE_KEY_SIZE])
```

Root Key To File

Copy a root key structure to a file.

```
bool qstp_root_key_to_file(const qstp_root_signature_key* kset, const char*
fpath)
```

Root Key Serialize

Serialize a root key to an array.

```
void qstp_root_key_serialize(uint8_t serk[QSTP_ROOT_SIGNATURE_KEY_SIZE],
const qstp_root_signature_key* kset)
```

Server Certificate Compare

Compare two server certificates for equivalence.

```
bool qstp_server_certificate_compare(const qstp_server_certificate* a, const
qstp_server_certificate* b)
```

Server Certificate Deserialize

Deserialize a server stream to a certificate structure.

```
void qstp_server_certificate_deserialize(qstp_server_certificate* cert, const
uint8_t input[QSTP_SERVER_CERTIFICATE_SIZE])
```

Server Certificate Encode

Encode a public server certificate into a readable string.

```
size_t qstp_server_certificate_encode(char* enck, size_t enclen, const
qstp_server_certificate* cert)
```

Server Certificate Encoding Size

Get the encoding size of a server certificate.

```
size_t qstp_server_certificate_encoded_size()
```

Server Certificate Extract

Extract the server certificate from the server key.

```
void qstp_server_certificate_extract(qstp_server_certificate* cert, const
qstp_server_signature_key* kset)
```

Server Certificate Hash

Hash a server certificate.

```
void qstp_server_certificate_hash(uint8_t output[QSTP_CERTIFICATE_HASH_SIZE],
const qstp_server_certificate* cert)
```

Server Root Certificate Hash

Hash the root and server certificates.

```
void qstp_server_root_certificate_hash(uint8_t
rshash[QSTP_CERTIFICATE_HASH_SIZE], const qstp_root_certificate* root, const
qstp_server_certificate* cert)
```

Server Certificate To File

Copy a server certificate structure to a file.

```
bool qstp_server_certificate_to_file(const qstp_server_certificate* cert,
const char* fpath)
```

Server File To Certificate

Copy a serialized certificate from a file to a server certificate structure.

```
bool qstp_server_file_to_certificate(qstp_server_certificate* cert, const
char* fpath)
```

Server File To Key

Copy a key from a file to a server key structure.

```
bool qstp_server_file_to_key(qstp_server_signature_key* kset, const char*
fpath)
```

Server Get Issuer

Get the server certificate issuer name.

```
void qstp_server_get_issuer(char issuer[QSTP_CERTIFICATE_ISSUER_SIZE])
```

Server Key Deserialize

Deserialize a server signature to a key structure.

```
void qstp_server_key_deserialize(qstp_server_signature_key* kset, const
uint8_t input[QSTP_SERVER_SIGNATURE_KEY_SIZE])
```

Server Key Serialize

Serialize a server key structure to an array.

```
void qstp_server_key_serialize(uint8_t
output[QSTP_SERVER_SIGNATURE_KEY_SIZE], const qstp_server_signature_key*
kset)
```

Server Key To File

Copy a server key structure to a file.

```
bool qstp_server_key_to_file(const qstp_server_signature_key* kset, const
char* fpath)
```

Server Version From String

Copy a server key structure to a file.

```
uint8_t qstp_version_from_string(const char* sver, size_t sverlen
```

Server Version To String

Convert the version number to a hexidecimal string.

```
void qstp_version_to_string(char* sver, uint8_t version)
```

Stream To Packet

Deserialize a byte array to a packet.

```
void qstp_stream_to_packet(const uint8_t* pstream, qstp_network_packet*
packet)
```

7.2 Server API

Header:

server.h

Description:

Functions used to implement the QSTP server.

Functions:

Expiration Check
Check the expiration status of a server key.

```
bool qstp_server_expiration_check(const qstp_server_signature_key* kset)
```

Key Generate
Generate a signature key.

```
void qstp_server_key_generate(qstp_server_signature_key* kset, const char
issuer[QSTP_CERTIFICATE_ISSUER_SIZE], uint32_t exp)
```

Pause
Pause the server, suspending new joins.

```
void qstp_server_pause()
```

Quit
Quit the server, closing all connections.

```
void qstp_server_quit()
```

Resume
Resume the server listener function from a paused state.

```
void qstp_server_resume()
```

Listen IPv4
Run the IPv4 networked key exchange function. Returns the connected socket and the QSTP server connection state.

```
qstp_errors qstp_server_start_ipv4(qsc_socket* source, const
qstp_server_signature_key* kset,void
(*receive_callback)(qstp_connection_state*, const char*, size_t), void
(*disconnect_callback)(qstp_connection_state*))
```

Listen IPv6
Run the IPv6 networked key exchange function. Returns the connected socket and the QSTP server state.

```
qstp_errors qstp_server_start_ipv6(qsc_socket* source, const
qstp_server_signature_key* kset, void
(*receive_callback)(qstp_connection_state*, const char*, size_t), void
(*disconnect_callback)(qstp_connection_state*))
```

7.3 Client API

Header:
`client.h`

Description:
Functions used to implement the QSTP client.

Functions

Connect IPv4
Run the IPv4 networked key exchange function. Returns the connected socket and the QSTP client state.

```
qstp_errors qstp_client_connect_ipv4(const qstp_root_certificate* root, const
qstp_server_certificate* cert, const qsc_ipinfo_ipv4_address* address,
uint16_t port, void (*send_func)(qstp_connection_state*), void
(*receive_callback)(qstp_connection_state*, const char*, size_t))
```

Connect IPv6
Run the IPv6 networked key exchange function. Returns the connected socket and the QSTP client state.

```
qstp_errors qstp_client_connect_ipv6(const qstp_root_certificate* root, const
qstp_server_certificate* cert, const qsc_ipinfo_ipv6_address* address,
uint16_t port, void (*send_func)(qstp_connection_state*), void
(*receive_callback)(qstp_connection_state*, const char*, size_t))
```

8. Security Analysis

The security analysis of QSTP focuses on evaluating its robustness against various cryptographic attacks, ensuring its reliability in real-world scenarios. The analysis primarily covers the key exchange, encryption, and message authentication mechanisms.

8.1 Key Exchange Security

The QSTP key exchange relies on public-key cryptography and certificates signed by a trusted root server. Key elements of the security model include:

1. **Asymmetric Key Signatures:** The server's public certificate C_{srv} is signed by the root server using S_{sroot}, ensuring that an authenticated party has control over the key exchange. This process prevents man-in-the-middle (MITM) attacks, as the client can verify the authenticity of the server's public certificate using the root server's public key P_{sroot}.
2. **Shared Secret Generation:** The client generates a shared secret key using the server's public asymmetric cipher key. Since the operation uses ephemeral asymmetric cipher keys it provides forward secrecy. Even if an attacker compromises a later session key, past communications remain secure.
3. **Replay and Timing Attacks:** The use of UTC timestamps and sequence numbers in each key exchange session prevents replay attacks. Since the time periods are unique for each session, an attacker cannot reuse old messages or signatures. Additionally, the sequence numbers included in packet headers help mitigate reordering attacks.
4. **Quantum-Resistant Algorithms:** The use of post-quantum primitives means that QSTP can provide long-term security against quantum computing attacks. This makes QSTP future-proof against quantum adversaries.

8.2 Symmetric Key Encryption

QSTP uses symmetric-key encryption to secure communication between the client and server once the shared secret key is established. The symmetric encryption algorithm RCS is designed to provide:

1. **Confidentiality:** The encryption ensures that unauthorized parties cannot read the plaintext message. The security of the encryption depends on the strength of the chosen algorithm and key length.
2. **Authenticated Encryption:** QSTP applies authenticated encryption with associated data (AEAD) to ensure both confidentiality and integrity. The encryption and MAC generation processes are integrated, meaning an attacker cannot alter the ciphertext without being detected.
3. **Resistance to Known Attacks:** By using an AEAD symmetric cipher (RCS), QSTP provides security against attacks such as chosen-ciphertext attacks (CCA), ciphertext manipulation, and differential cryptanalysis.

8.3 Message Authentication and Integrity

The Message Authentication Code (MAC) by RCS ensures the integrity of transmitted messages. The key points of MAC security include:

1. **MAC Forgery Resistance:** Since the MAC is computed over the encrypted message C using the session key, an adversary cannot forge a valid MAC without access to the session key. This prevents unauthorized modifications to the ciphertext or message.
2. **Tamper Detection:** Any attempt to modify the message will result in a MAC mismatch upon verification, triggering an error. This mechanism ensures that the recipient can trust that the message has not been tampered with.
3. **Protection Against Replay Attacks:** The inclusion of nonces and sequence numbers and timestamps in each message ensures that even if a message is intercepted, it cannot be replayed. Each message has unique associated data, which is used in the MAC computation.

8.4 Forward Secrecy

QSTP provides forward secrecy through its key exchange mechanism. Even if a long-term private key (such as S_{srv} or S_{li}) is compromised in the future, previous session keys and encrypted communications remain secure. The ephemeral session key $k_{session}$ is unique to each communication session, preventing retrospective decryption.

8.5 Resistance to Quantum Attacks

As quantum computing continues to advance, traditional public-key algorithms like RSA and ECC become vulnerable to quantum attacks. QSTP's use of post-quantum cryptographic primitives in its key exchange and encryption mechanisms ensures that it is resistant to quantum adversaries. Algorithms such as lattice-based or code-based cryptography (e.g., Kyber, McEliece) are designed to withstand quantum attacks, providing future-proof security.

9. Cryptanalysis of the QSTP Key-Exchange and Tunnel

9.1 Methodological Framework

Analysis follows the **Canetti–Krawczyk (CK)** model for authenticated key-exchange and the **ACCE** paradigm for channel protocols. The adversary is granted full network control, adaptive chosen-ciphertext oracle access to the KEM, adaptive chosen-message queries to the signature scheme, compromise of long-term keys, and post-session quantum computation. Security objectives are:

- **Server authentication** (one-way trust)
- **Explicit key confirmation**
- **IND-CCA confidentiality** & **INT-CTXT integrity** of tunnel data
- **Forward secrecy (FS)** and **post-compromise security (PCS)**
- **Replay, reflection and downgrade resilience**

Notation mirrors § 6 (*Mathematical Description*) of the specification.

9.2 Handshake Message Flow (idealized)

1. $C \rightarrow S$: ⟨*ser, cfg*⟩
2. $S \rightarrow C$: ⟨pk, Sig_{s}(H(pk‖hdr))⟩
3. $C \rightarrow S$: ⟨cpt = $\mathrm{Enc}_{\mathrm{kem}}$(pk, χ)⟩
4. S → C : ⟨sch_{2}⟩

5. C verifies sch_2(received) = sch_2(local); session established on equality.

Both sides derive:

$sch_0 = \mathrm{H}(cfg \parallel serial \parallel pvk)$

$sch_1 = \mathrm{H}(sch_0 \parallel phash),\ \ phash = \mathrm{H}(phdr \parallel sch_0 \parallel pk\_kem)$

$sch_2 = \mathrm{H}(sch_1 \parallel cpta)$

$prnd = \mathrm{cSHAKE}(sec, sch_2),\ \ sec = \text{-}\mathrm{E}_{\mathrm{sk}}(cpta)$

$k1, n1, k2, n2 \leftarrow prnd$

9.3 Cryptanalytic Evaluation

Property	**Argument**	**Result**
Server authentication	*C* verifies Sig_s with *S*'s certified verification key, itself rooted in the RDS certificate. Forgery ⇒ EUF-CMA breach of ML-DSA (Dilithium).	**Provably secure**
Key secrecy / IND-CCA	k is the output of SHAKE on ⟨uniform sec, public sch⟩. IND-CCA security of Kyber / McEliece ⇒ sec indistinguishable; SHAKE is a PRF.	**Secure**
Forward secrecy	*S*'s KEM key-pair is freshly generated per run and sk is erased after step 4; compromise of static signing keys leaks no past sessions.	**Full FS**
Post-compromise	Post compromise Optional symmetric ratchet (§ 5.8) injects fresh entropy every 2^{24} packets; break-and-recover adversary cannot decrypt forward traffic without breaking SHA-3.	**Achieved** if ratchet used
KCI / UKS	Client has no long-term key; Unknown-Key-Share excluded because sch binds both certificate hashes into key derivation.	**Not vulnerable**
Replay & reflection	64-bit UTC + 64-bit sequence authenticated as AEAD-AAD; packets outside ±Δt or out-of-order are dropped (§ 5. 2–5. 6).	**Secure** within Δt window
Downgrade	cfg is hashed into sch; any mismatch aborts. No fallback modes.	**Not vulnerable**
Transcript	Session keys are derived from cSHAKE(sec, sch_2) where	**Provably secure**

	binding sch$_2$ = H(H(H(cfg‖serial‖pvk) ‖ phash) ‖ cpta). Every handshake message is committed into the key material; substitution of any message causes key mismatch and explicit Provably secure verification failure in step 5.	

Observations & Potential Weaknesses

1. **Root-key monoculture** – compromise of the RDS private key subverts authentication for all domains. Mitigation: short-lived root epochs and CRLite-style revocation.
2. **Clock synchronization** – the valid-time field demands < Δt drift; embed a monotone counter or challenge nonce for IoT deployments with poor RTCs.
3. **RCS scrutiny** – tunnel security finally reduces to the un-standardized RCS + KMAC AEAD; commission open cryptanalysis; offers a more conservative AES-GCM compliance profile.

9.4 Formal Verification with Tamarin

- **Auth_S** *Caccept⇒Ssent(pk,Sigs)C accept ⇒ S sent (pk, Sig$_s$)Caccept⇒Ssent(pk,Sigs)*
- **SK_Secrecy** Session key k is unreachable by the adversary unless IND-CCA or EUF-CMA breaks.
- **Forward Secrecy** After erasure of KEM secrets, disclosure of long-term signing keys leaks no prior k.

Average proof times: *Auth_S* ≈ 25 s, *SK_Secrecy* ≈ 30 s, on an Intel i7-1260P with 16 GB RAM.

9.5 Comparative Summary

Dimension	**QSTP (root-anchored)**	**QSMP-SIMPLEX**
Authentication	One-way (server) via RDS	One-way (server)
Session-key entropy	256 bits	256 bits
RTT	RTT 2 + transcript confirm	2
Root-CA dependency	**Yes**	No
Forward secrecy	✓	✓
PCS (ratchet)	Optional	Optional

10. Conclusion

The QSTP (Quantum Secure Tunneling Protocol) offers a robust framework for secure communication between a client and server, leveraging a trusted root server for certificate signing and authentication. Key aspects of QSTP include:

- **Security Foundation:** QSTP provides strong security guarantees through its use of post-quantum asymmetric cryptography for the key exchange, authenticated encryption for data transmission, and authenticated symmetric encryption for message integrity.
- **Post-Quantum Resilience:** The integration of post-quantum cryptographic algorithms ensures that QSTP is resistant to attacks from future quantum adversaries, offering long-term security.
- **Key Exchange:** Key Exchange: The protocol's reliance on certificates signed by a root server strengthens its security model, enabling clients to verify the authenticity of the server's public key before any key material is exchanged. The server signs the ephemeral

encapsulation key hash during Connect Response, binding it to the protocol transcript. Explicit key confirmation is provided in the final handshake step, where the client verifies the server's transcript hash before the session is declared established.

- **Root Certificate Integrity:** The root certificate is self-signed by default, allowing recipients to verify the integrity of its own fields without reliance on external infrastructure. An external signing mode is available for deployments requiring a hierarchical trust chain.
- **Symmetric Cipher Agility:** QSTP supports both the post-quantum RCS cipher (with KMAC authentication) and AES-256-GCM as selectable AEAD constructions, providing a standards-compliant option where required.
- **Authentication and Confidentiality:** QSTP achieves both confidentiality and message integrity through authenticated encryption, protecting against various cryptographic attacks, including man-in-the-middle, replay, and ciphertext manipulation.
- **Forward Secrecy:** The use of ephemeral keys in each session provides forward secrecy, ensuring that even if private keys are compromised in the future, previous communications remain secure.

QSTP is a well-designed protocol that aligns with modern cryptographic standards and ensures secure communication in an era where post-quantum threats are a growing concern. Its careful design around authentication, encryption, and key exchange makes it a solid candidate for secure communications in environments requiring high levels of security, such as financial institutions, government agencies, and post-quantum cryptographic applications.