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Quantum FWM Control Protocol (QFCP) for IP Optical Environments
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Abstract

This document specifies the Quantum Four-Wave Mixing Control Protocol (QFCP), a lightweight transport protocol designed to operate over UDP in IP optical environments. QFCP enables the transmission of control- plane parameters required for quantum four-wave mixing (FWM) processes and associated optical configurations, including polarization stabilization, timestamp alignment, ROADM port selection, and spectral parameters. The protocol uses a Type-Length-Value (TLV) structure to support versioning and extensibility. This work is motivated by recent demonstrations of a classical-decisive quantum internet using integrated photonics.

Status of This Memo

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1. Introduction

Hybrid quantum-classical networking is emerging as a foundation for distributed quantum information processing. Recent experiments on commercial fiber networks have shown that quantum states can be dynamically routed by classical headers embedded in IP-like packets. To configure downstream optical switches and mitigate errors, a lightweight, extensible protocol is needed. QFCP is intended to be that protocol, running over UDP [RFC768] and supporting modular Type-Length-Value (TLV) extensions. QFCP supports applications aligned with scenarios defined by the IRTF Quantum Internet Research Group (QIRG) [RFC9583].

1.1. Requirements Language

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

2. Protocol Overview

QFCP defines a fixed header followed by TLV-encoded fields. The header carries version and flag information; TLVs encode control-plane parameters such as quantum link layer protocol, polarization state, center frequency, or error-mitigation metadata. UDP provides transport simplicity and compatibility with existing IP infrastructure. Unknown TLVs MUST be ignored to ensure forward compatibility.

3. QFCP Packet Format

The QFCP packet consists of a fixed header followed by a sequence of Type-Length-Value (TLV) payloads.

Packet Format:

```
 0                   1                   2                   3
  0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |  Version  | Flags |               Reserved                      |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |                                                               |
 ~                         TLV Payloads                        ~
 |                                                               |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 1: QFCP Packet Header and TLV Payloads

* Version (4 bits): Protocol version number (currently 0x1).

* Flags (4 bits): Reserved for future use.

* Reserved (24 bits): Set to zero; ignored on receipt.

* TLV Payloads: Sequence of variable-length TLVs.

4. TLV Structures

Each TLV consists of a type, a reserved field, a length (in bytes), and a value. All fields are in network byte order.

TLV Format:

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|      Type     |    Reserved   |            Length             |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                        Value (variable)                       |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 2: TLV Format

Defined TLV Types:

Type	Name	Value Format
0x01	Quantum Protocol	32-bit float (e.g., encoding)
0x02	Polarization State	32-bit float
0x03	Local Timestamp	32-bit int (ns)
0x04	ROADM Output Port ID	32-bit int
0x05	Photon Arrival Timestamp	32-bit int (ns)
0x06	Center Frequency (GHz)	32-bit float
0x07	Optical Linewidth (GHz)	32-bit float
0x08	Error Mitigation Vector	Variable (SU(2) parameters)
0x09	Future Extension	TLV-defined

Figure 3: Initial TLV Type Assignments

5. Example Use Cases

This section illustrates how the Quantum FWM Control Protocol (QFCP) can be applied in practical network environments.

5.1. Dynamic ROADM Configuration

QFCP packets carrying TLVs for ROADM Output Port ID ([RFC4950]) allow classical headers to steer entangled photons through commercial reconfigurable optical add-drop multiplexers (ROADMs). This enables dynamic path selection across metro and campus-scale optical networks, as demonstrated in recent hybrid IP packet experiments ([Zhang2025]).

5.2. Real-Time Error Mitigation

TLVs containing polarization parameters and error-mitigation vectors (Type 0x08) allow active compensation of SU(2) rotations induced by deployed fiber ([ZhangSM2025]). Classical light encodes detection signals in the header, enabling dynamic updates to the error mitigator without disturbing quantum states.

5.3. Hybrid IP Packet Orchestration

The QFCP framework aligns with the IRTF QIRG goals and use-cases ([RFC9583]). By transporting control-plane metadata in TLVs, classical headers and quantum payloads can be synchronized and routed through existing IP infrastructure.

5.4. Timestamp Alignment

TLVs carrying local and photon arrival timestamps can provide synchronization similar to RTP ([RFC3550]). This enables sub-nanosecond correlation of entangled photon arrivals across nodes.

5.5. WDM/TDM Extensions

Additional TLVs may specify per-wavelength parameters, enabling wavelength-division multiplexing (WDM) or time-division multiplexing (TDM) of entangled states ([ZhangSM2025]). This supports scaling of quantum internet bandwidth across multiple frequency channels while preserving compatibility with ITU-T DWDM grids ([ITU-T.G694.1]).

6. UDP Port Assignment

Implementations SHOULD use a configurable default port. IANA is requested to allocate a well-known port for QFCP.

7. IANA Considerations

- Allocate a UDP port for QFCP.

- IANA is also requested to establish a QFCP TLV Types Registry with initial assignments as defined in Section 4.

8. Security Considerations

QFCP inherits the risks of UDP: spoofing, injection, replay. It MUST be run in trusted environments or protected by DTLS/IPsec. TLVs may reveal network state information and SHOULD be protected if confidentiality is required.

9. References

9.1. Normative References

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9.2. Informative References

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