

Internet Engineering Task Force
Internet-Draft
Intended status: Experimental
Expires: 4 April 2026

A. Zhu
Y. Zhang
R. Broberg
L. Feng
JM. Smith
1 October 2025

University of Pennsylvania School of Engineering and Applied Science

Quantum FWM Control Protocol (QFCP) for IP Optical Environments
draft-zhu-qirg-qfcp-00

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

This Internet-Draft is submitted in full conformance with the provisions of BCP 78 and BCP 79.

Internet-Drafts are working documents of the Internet Engineering Task Force (IETF). Note that other groups may also distribute working documents as Internet-Drafts. The list of current Internet-Drafts is at <https://datatracker.ietf.org/drafts/current/>.

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

This Internet-Draft will expire on 4 April 2026.

Copyright Notice

Copyright (c) 2025 IETF Trust and the persons identified as the document authors. All rights reserved.

This document is subject to BCP 78 and the IETF Trust's Legal Provisions Relating to IETF Documents (<https://trustee.ietf.org/license-info>) in effect on the date of publication of this document. Please review these documents carefully, as they describe your rights and restrictions with respect to this document. Code Components extracted from this document must include Revised BSD License text as described in Section 4.e of the Trust Legal Provisions and are provided without warranty as described in the Revised BSD License.

Table of Contents

1. Introduction	2
1.1. Requirements Language	3
2. Protocol Overview	3
3. QFCP Packet Format	3
4. TLV Structures	4
5. Example Use Cases	4
5.1. Dynamic ROADM Configuration	4
5.2. Real-Time Error Mitigation	5
5.3. Hybrid IP Packet Orchestration	5
5.4. Timestamp Alignment	5
5.5. WDM/TDM Extensions	5
6. UDP Port Assignment	5
7. IANA Considerations	5
8. Security Considerations	5
9. References	6
9.1. Normative References	6
9.2. Informative References	6
Authors' Addresses	7

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:

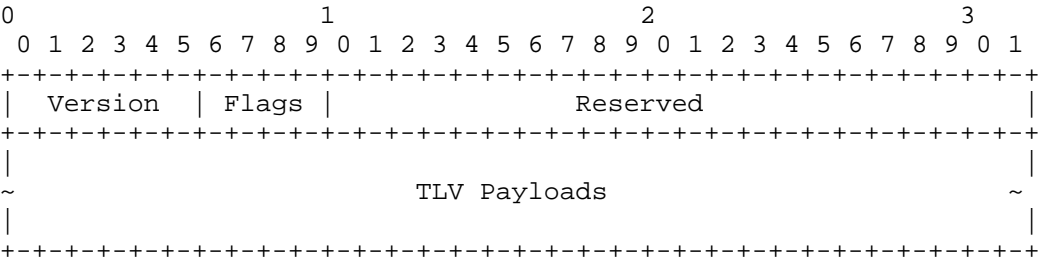


Figure 1: QFCP Packet Header and TLV Payloads

- * 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:

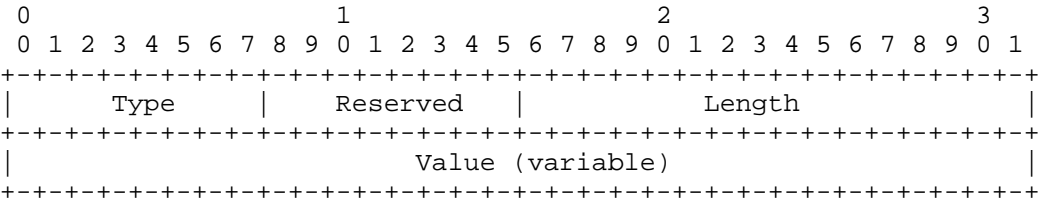


Figure 2: TLV Format

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

- [RFC2119] Bradner, S., "Key words for use in RFCs to Indicate Requirement Levels", BCP 14, RFC 2119, DOI 10.17487/RFC2119, March 1997, <<https://www.rfc-editor.org/info/rfc2119>>.
- [RFC8174] Leiba, B., "Ambiguity of Uppercase vs Lowercase in RFC 2119 Key Words", BCP 14, RFC 8174, DOI 10.17487/RFC8174, May 2017, <<https://www.rfc-editor.org/info/rfc8174>>.
- [RFC768] Postel, J., "User Datagram Protocol", STD 6, RFC 768, DOI 10.17487/RFC0768, August 1980, <<https://www.rfc-editor.org/info/rfc768>>.
- [RFC4950] Bonica, R., Gan, D., Tappan, D., and C. Pignataro, "ICMP Extensions for Multiprotocol Label Switching", RFC 4950, DOI 10.17487/RFC4950, August 2007, <<https://www.rfc-editor.org/info/rfc4950>>.

9.2. Informative References

- [RFC9583] Wang, C., Rahman, A., Li, R., Aelmans, M., and K. Chakraborty, "Application Scenarios for the Quantum Internet", RFC 9583, DOI 10.17487/RFC9583, June 2024, <<https://www.rfc-editor.org/info/rfc9583>>.
- [RFC3550] Schulzrinne, H., Casner, S., Frederick, R., and V. Jacobson, "RTP: A Transport Protocol for Real-Time Applications", STD 64, RFC 3550, DOI 10.17487/RFC3550, July 2003, <<https://www.rfc-editor.org/info/rfc3550>>.
- [ITU-T.G694.1] International Telecommunication Union (ITU-T), "Spectral grids for WDM applications: DWDM frequency grid", Recommendation G.694.1, February 2012, <<https://www.itu.int/rec/T-REC-G.694.1/en>>.
- [Zhang2025] Zhang, Y., Broberg, R., Zhu, A., Li, G., Ge, L., Smith, J.M., and L. Feng, "Classical-decisive quantum internet by integrated photonics", DOI: 10.1126/science.adx6176, Science Vol. 389, pp. 940-944, August 2025, <<https://doi.org/10.1126/science.adx6176>>.

[ZhangSM2025]

Zhang, Y., Broberg, R., Zhu, A., Li, G., Ge, L., Smith, J.M., and L. Feng, "Supplementary Materials for Classical-decisive quantum internet by integrated photonics", Science Supplementary Materials, August 2025.

Authors' Addresses

Alan Zhu

University of Pennsylvania School of Engineering and Applied Science
Philadelphia, PA 19104
United States
Email: alzhu@seas.upenn.edu

Yichi Zhang

University of Pennsylvania School of Engineering and Applied Science
Philadelphia, PA 19104
United States
Email: zyc@seas.upenn.edu

Robert Broberg

University of Pennsylvania School of Engineering and Applied Science
Philadelphia, PA 19104
United States
Email: rbroberg@seas.upenn.edu

Liang Feng

University of Pennsylvania School of Engineering and Applied Science
Philadelphia, PA 19104
United States
Email: fenglia@seas.upenn.edu

Jonathan M. Smith

University of Pennsylvania School of Engineering and Applied Science
Philadelphia, PA 19104
United States
Email: jms@seas.upenn.edu