

Internet Engineering Task Force
Internet-Draft
Intended status: Experimental
Expires: 3 October 2026

A. Zhu
Y. Zhang
R. Broberg
L. Feng
JM. Smith
1 April 2026

University of Pennsylvania School of Engineering and Applied Science

Quantum Datagram Control Protocol (QDCP) for IP Optical Environments
draft-zhu-qirg-qdcp-01

Abstract

This document specifies the Quantum Datagram protocol a lightweight transport protocol designed to operate over UDP in IP optical environments. QDCP (formerly QFCP) enables the transmission of control- plane parameters required for transporting quantum information 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 and is prototyped for the transport of third-order nonlinear generated quantum information on IP optical infrastructure. 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 3 October 2026.

Copyright Notice

Copyright (c) 2026 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. QDCP Packet Format	3
4. TLV Structures	4
5. Example Use Cases	5
5.1. Dynamic ROADM Configuration	5
5.2. Real-Time Error Mitigation	5
5.3. Hybrid IP Packet Orchestration	5
5.4. Timestamp Alignment	6
5.5. WDM/TDM Extensions	6
6. Example TLV Blocks	6
6.1. 0x08: Error Mitigation Vector	6
7. UDP Port Assignment	8
8. IANA Considerations	8
9. Security Considerations	8
10. Acknowledgements	9
11. References	9
11.1. Normative References	9
11.2. Informative References	9
Authors' Addresses	10

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. QDCP is intended to be that protocol, running over UDP [RFC768] and supporting modular Type-Length-Value (TLV) extensions. QDCP supports applications aligned with scenarios defined by the IRTF Quantum Internet Research Group (QIRG) [RFC9583].

By the no-cloning theorem, quantum information cannot be copied, buffered, or retransmitted without disturbing the underlying state. In the present work, where practical quantum memories and error-corrected storage are not yet available at network scale, quantum information is therefore transmitted as a datagram: loss is terminal, and retransmission is physically meaningless. The accompanying classical control header is sent without guaranteed delivery. If the classical information is lost in transit, the associated quantum state is presumed lost as well. Future implementations may leverage advances in quantum memory, error correction, or entanglement-assisted repeaters to decouple classical and quantum reliability, potentially incorporating reliable classical transports such as QUIC or TCP for control-plane robustness.

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

QDCP 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.

While UDP imposes a maximum datagram length (65,535 bytes), this limitation has no impact on the amount of quantum information conveyed. The quantum payload is not encapsulated within the UDP packet itself but is passed through at the physical layer, with UDP carrying only the associated classical control header. Thus the UDP size constraint applies solely to the metadata, not to the optical or quantum state being transported.

3. QDCP Packet Format

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

Packet Format:

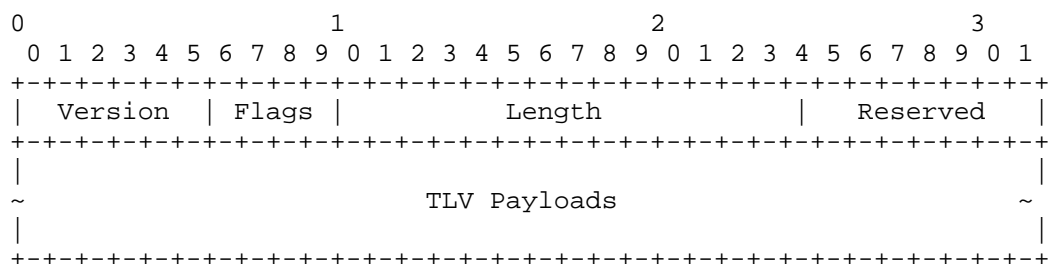


Figure 1: QDCP Packet Header and TLV Payloads

- * Version (4 bits): Protocol version number (currently 0x1).
- * Flags (4 bits): Reserved for future use.
- * Length (16 bits): Specifies length of entire packet.
- * Reserved (8 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. The length specifies the length of the value, not the entire TLV. All fields are in network byte order.

TLV Format:

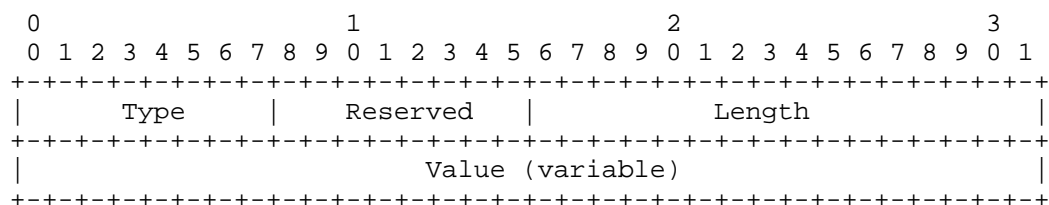


Figure 2: TLV Format

Defined TLV Types:

Type	Name	Value Format
0x01	Quantum Protocol	32-bit int (e.g., encoding)
0x02	Polarization State	32-bit float
0x03	Timestamp of Origination	128-bit int (ps)
0x04	ROADM Output Port ID	32-bit int
0x05	Quantum Packet Delay	128-bit int (ps)
0x06	Duration of quantum information	128-bit int (ps)
0x07	Center Frequency (GHz)	32-bit float
0x08	Optical Linewidth (GHz)	32-bit float
0x09	Polarization Correction	Variable Polarizations

Figure 3: Initial TLV Type Assignments

5. Example Use Cases

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

5.1. Dynamic ROADM Configuration

QDCP 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 QDCP 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.

Figure 4: Error Mitigation Value Structure

The first eight bits specify which polarization is being sent. For simplicity, assume transmitted states must be in a horizontal, vertical, diagonal, anti-diagonal, right-circular, or left-circular polarization. The polarization section for each of these 64-bit structures can then be specified using the following mapping table.

Polarization to Reserved Bit Mapping:

Value	Polarization
-----	-----
0	Horizontal
1	Vertical
2	Diagonal
3	Anti-Diagonal
4	Right-Circular
5	Left-Circular

Figure 5: Polarization to Reserved Bit Mappings

The duration in nanoseconds specifies how long the the specific polarization will be transmitted for. The arrival time specifies how long after the reception of the QDCP packet this specific polarization will arrive with nanosecond precision.

To accurately identify the $SU(2)$ transformation, at least two non-orthogonal polarizations are required to be sent. Zhang et al. experimentally used Horizontal and Right-Circular polarizations for error mitigation, both other combinations are also valid.

For concreteness, consider the example where Horizontal and Right-Circular polarizations are transmitted for error correction.

Example Error Mitigation TLV Structure:

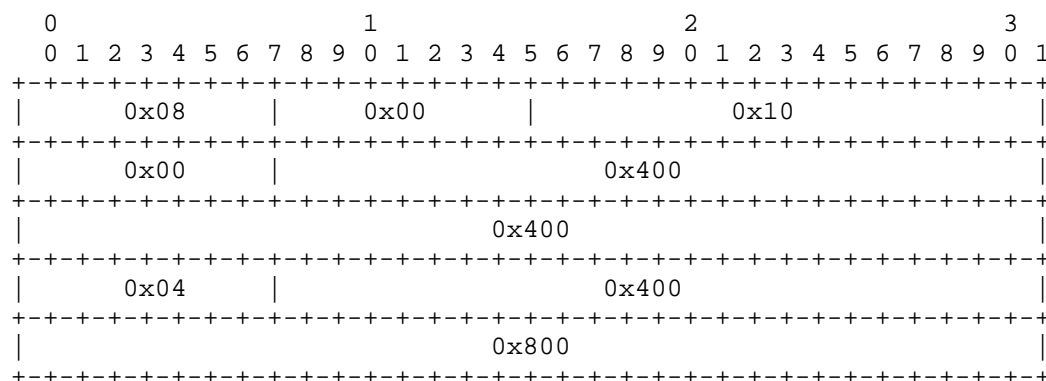


Figure 6: Error Mitigation TLV including Right-Circular and Horizontal Polarizations. 0x08 is the TLV type. 0x00 is the reserved field. 0x10 is the length of the value, which is 16 bytes in this case. The next 0x00 represents horizontal polarization according to Figure 5. The first 0x400 represents the duration of the horizontal polarization in nanoseconds and the second represents the arrival time of the horizontal polarization in nanoseconds. The next 0x04 represents right-circular polarization, with the following 0x400 representing the duration of the right-circular polarization and the 0x800 representing the arrival time of the right-circular polarization.

7. UDP Port Assignment

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

8. IANA Considerations

- Allocate a UDP port for QDCP.
- IANA is also requested to establish a QDCP TLV Types Registry with initial assignments as defined in Section 4.

9. Security Considerations

QDCP 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 MUST be protected if confidentiality is required.

Use of DTLS/IPsec and reliable classical transport mechanisms are reserved for future work.

10. Acknowledgements

The authors would like to thank Steve Schwartz and Wes Harding for their constructive feedback and detailed comments. Their suggestions helped broaden the scope of this document beyond the initial implementation and guided refinements to the protocol design and terminology.

11. References

11.1. 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>>.

11.2. 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