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Quantum Datagram Control Protocol (QDCP) for IP Optical Environments
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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.

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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. 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:

```
 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 |          Length           |   Reserved    |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |                                                               |
 ~                         TLV Payloads                          ~
 |                                                               |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

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:

```
  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 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.

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. The mechanisms to achieve such precision for distributed-clock synchronization (e.g. NTP, PTP, White Rabbit) are out of scope for this document.

TLVs carrying "Duration of Quantum Information" specify the period during which the optical bypass must remain active to support quantum information transport. After the indicated duration expires, the bypass is automatically reverted back to its normal state to resume classical control-plane processing.

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. Example TLV Blocks

This section specifies the TLV structure for specific TLV types.

6.1. 0x08: Error Mitigation Vector

Error mitigation can be done by sending different known polarization states with respect to the output of the chip and identifying the SU(2) transformation applied to these states by the fiber once they reach the receiver ([ZhangSM2025]). To account for hardware limitations in preparing certain known states, the reserved bits in the TLV will be used to specify which polarization states are transmitted. For simplicity, assume transmitted states must be in a horizontal, vertical, diagonal, anti-diagonal, right-circular, or left-circular polarization. The transmitted states can then be specified by setting the bit corresponding to a specific polarization to one (1), with the following mapping from bit to polarization.

Polarization to Reserved Bit Mapping:

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

Figure 4: Polarization to Reserved Bit Mappings

Using this mapping, if eg. the desired transmitted polarization includes only Horizontal and Right-Circular, then the reserved byte would be "00010001" or equivalently "0x11".

To accurately identify the SU(2) transformation, multiple repetitions of each transmitted polarizations is necessary. Zhang et al. experimentally determined that eight (8) repetitions of each polarization is sufficient. They were also able to recover the full SU(2) transformation with only two polarizations.

Thus, to balance stability and simplicity, the length of the Error Mitigation TLV is limited to 32 bits, allowing up to four (4) different polarizations each repeated eight times. The order that the polarizations are sent will be fixed by their bit position in the Polarization to Reserved Bit Mapping table such that a polarization with a greater bit position will be sent before one with a smaller bit position. If the number of polarizations flagged in the reserved byte exceeds 4, the behavior is undefined.

If the number of polarizations flagged in the reserved byte is less than 4, then in the spirit of [RFC8701], we define GREASE8 as the following set of octaves:

```
{0x0A, 0x1A, 0x2A, 0x3A,
 0x4A, 0x5A, 0x6A, 0x7A,
 0x8A, 0x9A, 0xAA, 0xBA,
 0xCA, 0xDA, 0xEA, 0xFA}
```

Figure 5: GREASE8 Values

To fill the extra bytes after sending the desired polarizations, the sender MUST randomly select from these GREASE8 values to pad the end of the packet. The receiver MUST ignore the GREASE8 values upon receipt.

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

Example Error Mitigation TLV Structure:

```
 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
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|      0x08     |      0x11     |              0x20             |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|    R * 0x08   |    H * 0x08   |    GREASE8    |    GREASE8    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 6: Error Mitigation TLV for Right-Circular and Horizontal Polarizations. 0x08 is the TLV type. 0x11 is the hexadecimal encoding of 00010001 in binary, which specifies that Right-Circular and Horizontal polarizations will be sent in this packet according to Figure 4. 0x20 Specifies the length of the value, which is 32 bits. The actual value then contains eight bits of Right-Circular polarized light followed by eight bits of Horizontal polarized light, followed by two randomly selected GREASE8 values.

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

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