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**The Link Layer service in a Quantum Internet
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Abstract

In a classical network the link layer is responsible for transferring a datagram between two nodes that are connected by a single link, possibly including switches. In a quantum network however, the link layer will need to provide a robust entanglement generation service between two quantum nodes which are connected by a quantum link, possibly including quantum repeaters. This service can be used by higher layers to produce entanglement between distant nodes or to perform other operations such as qubit transmission, without full knowledge of the underlying hardware and its parameters. This draft defines what can be expected from the service provided by a link layer for a Quantum Network and defines an interface between higher layers and the link layer.

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1. Introduction

The most important fundamental operation in a quantum network is the generation of entanglement between nodes. Short-distance entanglement can be used to generate long-distance entanglement with the use of an operation called entanglement swap [1] (also formalised in [2]). If nodes A and B share an entangled pair and similarly for B and C, B can perform a so called Bell measurement [3] and send the measurement outcome (2 bits) over a classical channel to A or C such that in the end A and C share an entangled pair. Furthermore, long-distance entanglement in turn enable long-distance qubit transmission by the use of quantum teleportation [3] (also formalised in [2]). Node A can teleport an unknown qubit state to B by consuming an entangled pair between A and B and sending two classical bits to B.

Entanglement between distant nodes of up to 1.3 km have been demonstrated [4], in a proof-of-principle experiment. The next step towards a quantum network is to turn such an experiment to a reliable service. This is the role of the link layer, which turns an ad-hoc physical setup to a reliable entanglement generation service. Since entanglement generation is typically a probabilistic process, one of the main tasks of the link layer is to manage re-tries performed by the physical layer and with high confidence provide entanglement to

higher layers within a requested time window. Once an entangled pair has been generated, the nodes need to be able to agree on which qubits are involved in which entangled pair to be able to use it, thus another main task of the link layer is to provide an entanglement identifier.

2. Scope

This draft is meant to define the service and interface of an link layer of a quantum network. It does not present a protocol realising this service. However a protocol that indeed does this have been proposed by us in the paper [5].

3. Desired service

This section defines the service that a link layer provides in a quantum network. The interface and header specification is defined in the next section.

A link layer between two nodes A and B of a quantum network must provide the following features:

- o Allow both node A and B to initialize entanglement generation.
- o Allow the initializing node to specify a desired minimum fidelity[3] and maximum waiting time.
- o Notify both nodes of success or failure of entanglement generation before the requested maximum waiting time has passed since the request was initialized.
- o If success is notified, the generated entangled pair has with high confidence higher (or equal) fidelity than the desired minimum fidelity.
- o For successful request, provide an entanglement identifier to allow higher layers to use identify the entangled pair in the network.

4. Interface

This section describes the interface between higher layers and the link layer in a quantum network, along with header specifications for the type of messages. The interface consists of a single type of message from the higher layers to the link layer, which is the CREATE message for requesting entanglement generation. Response messages from the link layer to the higher layers take either the form of an ACK, an OK message or one of many error messages. The ACK is sent

back directly upon receiving a CREATE if the link layer supports the request and contains a CREATE ID such that the higher layer can associated the subsequent OK messages to the correct request. It is assumed that the nodes in the network are assigned a unique ID in the network, which is used in the Remote Node ID parameters of the messages below.

4.1. Higher layers to link layer

The higher layers can send a CREATE message to the link layer to request the generation of entanglement. Along with other parameters, as specified below the higher layers can specify a minimum fidelity, a maximum waiting time and the number of entangled pairs to be produced.

4.1.1. Header specification

The CREATE message contains the following parameters:

- o Remote Node ID (32 bits): Used if the node is directly connected to multiple nodes. Indicates which node to generate entanglement with.
- o Minimum fidelity (16 bits): The desired minimum fidelity, between 0 and 1, of the generated entangled pair. A binary value encoding the integer 'n' represents the fidelity 'n' divided by $(2^{16}-1)$.
- o Max Time (16 bits): The maximum time in seconds the higher layer is willing to wait for the request to be fulfilled. Represented as a binary16 float as specified in [6].
- o Purpose ID (16 bits): Allows the higher layer to tag the request for a specific purpose. If the request is from an application this can be thought of as a port number. The purpose ID can also be used by a network layer to specify that this entanglement request is part of long-distance entanglement generation over a specific path.
- o Number (16 bits): The number of entangled pairs to generate.
- o Priority (4 bits): Can be used to indicate if this request is of high priority and should ideally be fulfilled early. Higher means faster service.
- o Type of request (TPE) (1 bit): Either create and keep (K) or measure directly (M), where K stores the generated entanglement in memory and M measures the entanglement directly.

- o Atomic (ATO) (1 bit): A flag that indicates that the request should be satisfied as a whole, i.e. that all entangled pairs are available in memory at the same time. Only valid for type K requests.
- o Consecutive (CON) (1 bit): A flag indicating that the entangled pairs of the request should be generated close in time. Note that this is different from the atomic flag since the entangled pairs does not need to exist in memory at the same time. Also, Consecutive does not mean high priority, only that when the first entangled pair is generated, the subsequent ones should be generated with high priority.

The complete header specification of the CREATE message is given in Figure 1.

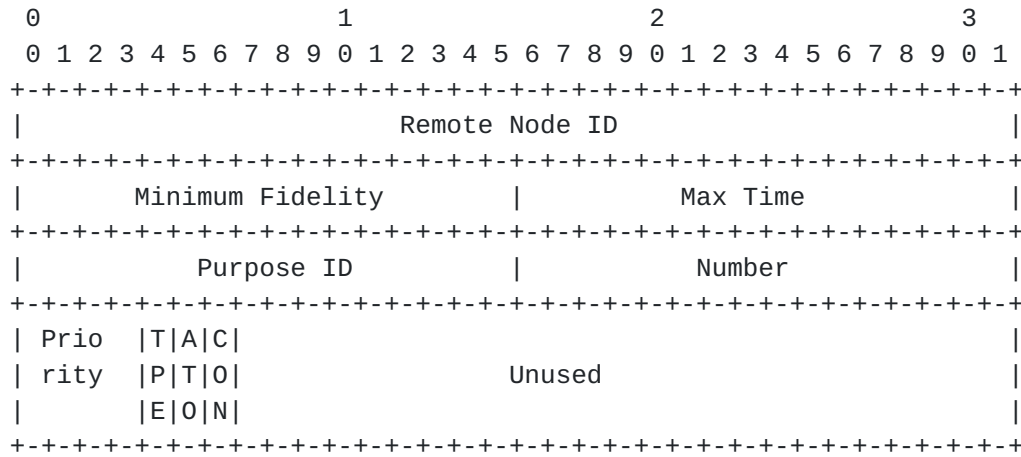


Figure 1: CREATE message header format

4.2. Link layer to higher layers

When receiving a CREATE message from higher layers the link layer will directly respond and notify the higher layer whether requests will be scheduled for generation. If so the link layer responds with an ACK containing a CREATE ID. The higher layer can use this CREATE ID together with the ID of the requesting node to associate OK messages it receives from the link layer to the correct request. Note that the ID of the requesting node is needed since the ACK is returned directly and the CREATE ID is thus not unique for requests from different nodes. If the link layer does not support the given request an error message is instead returned.

When a request is satisfied an OK message is sent to the higher layer. The OK message contains different fields depending on whether the request was of type K or M. For K the OK contains a logical

qubit identifier (LQID) such that the higher layer can know which qubit holds the generated entanglement. For M the OK contains the basis which the qubit was measured and the measurement outcome.

Both during and after an entanglement generation, the link layer can return error messages to the higher layers, as further described below. For example if something happens to the qubit or another error occurs such that the entanglement is not valid anymore, the link layer can issue an ERR_EXPIRE message.

4.2.1. Header specification

To distinguish the different types of messages that the link layer can return to the higher layer, the first part of the header is a 4 bit field which specifies the type of message using the following mapping:

- o 0001: ACK
- o 0010: Type K OK
- o 0011: Type M OK
- o 0100: ERR

The complete header specification for these four types of messages are shown below in Figure 2 to Figure 5.

The ACK message contains the following parameters:

- o Create ID (16 bits): A Create ID that the higher layer can use to associate subsequent OK messages to the request.

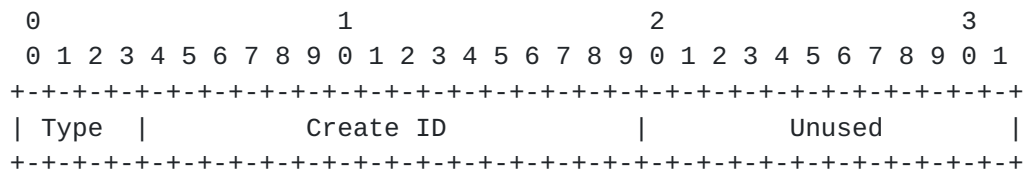


Figure 2: ACK message header format

The type K OK message contains the following parameters:

- o Create ID (16 bits): Must be the same Create ID that was given in the ACK of the corresponding request.
- o Logical Qubit ID (LQID) (4 bits): A logical ID of the qubit which is part of the entangled pair.

- o Directionality flag (D) (1 bit): Specifies if the request came from this node (D=0) or from the remote node (D=1).
- o Sequence number (16 bits): A sequence number for identifying the entangled pair. It is assumed to be unique for entangled pairs between the given nodes. Thus together with the IDs of the nodes, one can create an entanglement identifier which is unique in the network.
- o Purpose ID (16 bits): The purpose ID of the request (only used by the node which did not initiate the request)
- o Remote Node ID (32 bits): Used if the node is directly connected to multiple nodes.
- o Goodness (16 bits): An estimate of the fidelity of the generated entangled pair. Should not be seen as a guarantee.
- o Time of Goodness (ToG) (16 bits): The time of the goodness estimate. Not necessarily the time when the estimate is performed but rather the time for which the estimate is for. Can be used to make an updated estimate based on decoherence times of the qubits.

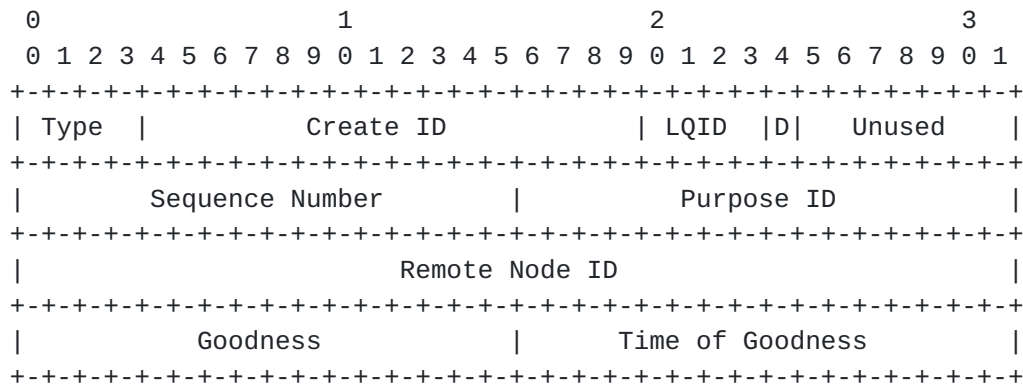


Figure 3: Type K OK message header format

The type M OK message contains the following parameters:

- o Create ID (16 bits): The same Create ID that was given in the ACK of the corresponding request.
- o Measurement outcome (M) (1 bit): The outcome of the measurement performed on the entangled pair.
- o Basis (3 bits): Which basis the entangled pair was measured in, used if the basis is random. The following representation is used:

- * 000: Unused
 - * 001: Z-basis $\{|0\rangle, |1\rangle\}$
 - * 010: (Y-basis) Z-basis rotated by angle $-\pi/2$ around X-axis.
 - * 100: (X-basis) Z-basis rotated by angle $\pi/2$ around Y-axis.
 - * 101: (XZ-basis) Z-basis rotated by angle $\pi/4$ around Y-axis.
 - * 011: (YZ-basis) Z-basis rotated by angle $-\pi/4$ around X-axis.
 - * 110: (XY-basis) X-basis rotated by angle $\pi/4$ around Z-axis.
- o Directionality flag (D) (1 bit): Specifies if the request came from this node (D=0) or from the remote node (D=1).
 - o Sequence number (16 bits): A sequence number for identifying the entangled pair. It is assumed to be unique for entangled pairs between the given nodes. Thus together with the IDs of the nodes, one can create an entanglement identifier which is unique in the network.
 - o Purpose ID (16 bits): The purpose ID of the request (only used by the node which did not initiate the request)
 - o Remote Node ID (32 bits): Used if the node is directly connected to multiple nodes.
 - o Goodness (16 bits): An estimate of the fidelity of the generated entangled pair. Should not be seen as a guarantee.

Note: Time of Goodness is not needed here since there is no decoherence on the measurement outcomes.

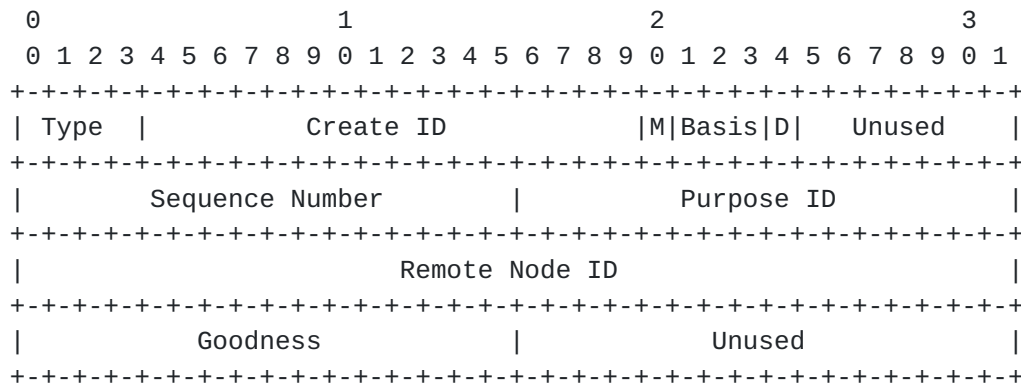


Figure 4: Type M OK message header format

The ERR message contains the following parameters:

- o Create ID (16 bits): The same Create ID that was given in the ACK of the corresponding request.
- o Error code (ERR) (4 bits): Specifies what error occurred. See below what the error codes mean.
- o Expire by sequence numbers (S) (1 bit): Used by ERR_EXPIRE, to specify whether a range of sequence numbers should be expired (S=1) or all sequence numbers associated with the given Create ID and Origin Node (S=0).
- o Sequence number low (16 bits): Used by error code ERR_EXPIRE to identify a range of sequence numbers that needs to be expired. Numbers above Sequence number low (inclusive) and below Sequence number high (exclusive) should be expired.
- o Sequence number high (16 bits): Used by error code ERR_EXPIRE to identify a range of sequence numbers that needs to be expired. Numbers above Sequence number low (inclusive) and below Sequence number high (exclusive) should be expired.
- o Origin Node (32 bits): Used if the node is directly connected to multiple nodes. Needed here since Create IDs are not unique for request from different nodes.

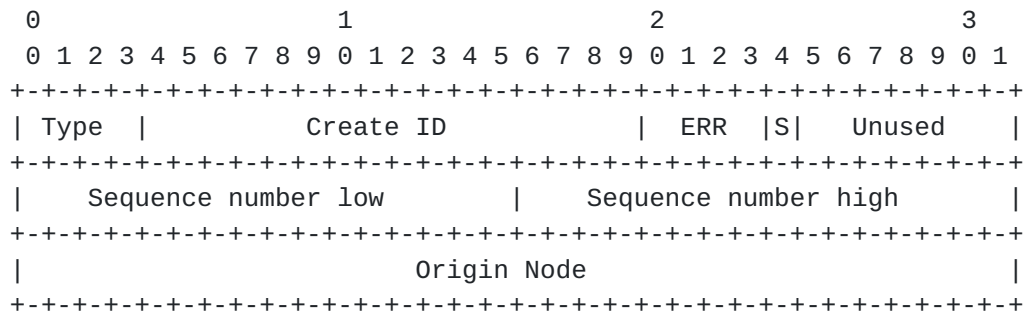


Figure 5: Error message header format

The different error codes using in an error message are the following:

- o Error returned directly when a CREATE message is received:
 - * ERR_UNSUPP (0001): The given request is not supported. For example if the minimum fidelity is not achievable or if the request is of type K and the hardware cannot store entanglement.

- * ERR_CREATE (0010): The create message could not be parsed.
 - * ERR_REJECTED (0011): The request was rejected by this node based on for example the Purpose ID.
 - * ERR_OTHER (0100): An unknown error occurred.
- o Error returned after a CREATE message is received, before or after an OK is returned:
- * ERR_EXPIRE (0101): One or more already sent OK messages have expired and the entangled pair is not available anymore. Can either be specified as a range of sequence numbers or by a create ID by using the S flag.
 - * ERR_REJECTED (0011): The request was rejected by the other node based on for example the Purpose ID.
 - * ERR_TIMEOUT (0110): The request was not satisfied within the requested max waiting time.

5. IANA Considerations

This memo includes no request to IANA.

6. Acknowledgements

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7. Informative References

- [1] Briegel, H., Dur, W., Cirac, J., and P. Zoller, "Quantum repeates: The Role of Imperfect Local Operations in Quantum Communication", Physical Review Letters 81, 26, 1998, <<https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.81.5932>>.
- [2] Kompella, K., Aelmans, M., Wehner, S., Sirbu, C., and A. Dahlberg, "Advertising Entanglement Capabilities in Quantum Networks", QIRG Internet-Draft, 2018, <<https://datatracker.ietf.org/doc/draft-kaws-qirg-advent/>>.

- [3] Nielsen, M. and I. Chuang, "Quantum Computation and Quantum Information", QIRG Internet-Draft, 2018, <<https://doi.org/10.1017/CB09780511976667>>.
- [4] Hensen, B., Bernien, H., Dreau, A., Reiserer, A., Kalb, N., Blok, M., Ruitenberg, J., Vermeulen, R., Schouten, R., Abellan, C., Amaya, W., Pruneri, V., Mitchell, M., Markham, M., Twitchen, D., Elkouss, D., Wehner, S., Taminiau, T., and R. Hanson, "Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres", Nature 526, 682-686, 2015, <<https://arxiv.org/abs/1508.05949>>.
- [5] Dahlberg, A., Skrzypczyk, M., Coopmans, T., Wubben, L., Rozpedek, F., Pompili, M., Stolk, A., Pawelczak, P., Knegjens, R., de Oliveira Filho, J., Hanson, R., and S. Wehner, "A Link Layer Protocol for Quantum Networks", arXiv pre-print (in preparation) arXiv:1903.XXXXX, 2019, <<https://arxiv.org/abs/1903.XXXXX>>.
- [6] IEEE, "754-1985 - IEEE Standard for Binary Floating-Point Arithmetic", IEEE standard 10.1109/IEEESTD.1985.82928, 1990, <<https://ieeexplore.ieee.org/document/30711>>.

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