

Internet Engineering Task Force  
Internet-Draft  
Intended status: Informational  
Expires: 7 November 2022

N. Kuhn  
Thales Alenia Space  
E. Stephan  
Orange  
G. Fairhurst  
T. Jones  
University of Aberdeen  
C. Huitema  
Private Octopus Inc.  
6 May 2022

Carefully Resume QUIC Session  
draft-kuhn-quic-careful-resume-01

## Abstract

This document provides a method to allow a QUIC session to carefully resume using a previously utilised Internet path.

The method uses a set of computed congestion control parameters that are based on the previously observed path characteristics, such as the bottleneck bandwidth, available capacity, or the RTT. These parameters are stored and can then used to modify the congestion control behaviour of a subsequent connection. The draft discusses assumptions around how a server ought to utilise the parameters to provide opportunities for a new flow to more quickly get up to speed (i.e. utilise available capacity). It discusses how these changes impact the capacity at a shared network bottleneck and the response that is needed after any indication that the new rate is inappropriate.

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Internet-Draft

Carefully Resume QUIC Session

May 2022

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## [1.](#) Introduction

The specification for the QUIC transport protocol [[RFC9000](#)] notes "Generally, implementations are advised to be cautious when using previous values on a new path." The method uses a set of computed Congestion Control (CC) parameters that are based on the previously observed path characteristics, such as the bottleneck bandwidth, available capacity, or the Round Trip Time (RTT). These parameters are stored and can then used to modify the congestion control behaviour of a subsequent connection.

All Internet transports are required to use a CC method. In 2010, [RFC 5783](#) provided a survey of alternative CC methods, and noted that there are challenges when a CC operates across paths with a high and/or variable bandwidth-delay product (BDP) [[RFC5783](#)].

A CC algorithm typically takes time to ramp-up the packet rate, called the "slow-start phase", informally known as the time to "Get up to speed". The slow start phase is a period in which a sender intentionally uses less capacity than might be available with the intention to avoid overshooting the actual capacity at a bottleneck, which would result in increased queueing (latency/jitter) and/or congestion packet loss. An overshoot in the capacity can also have a detrimental effect on other flows sharing a common bottleneck. In the extreme case, persistent congestion can result in unwanted starvation of other flows [[RFC8867](#)] (i.e. Preventing other flows from successfully sharing a common bottleneck).

In Reno, the slow-start phase consists of a sequence of increases in the congestion window (cwnd) starting from the Initial Window (IW). Each step lasts approximately one path RTT, until the sender estimate that the capacity has reached (or is nearing) the capacity at the bottleneck for the path).

To fully-utilise the capacity along a path with a certain path RTT, the transport needs to determine an appropriate volume of bytes in

flight, based on the product of the available capacity and the RTT. [RFC6349] defines the BDP as follows: "Derived from Round-Trip Time (RTT) and network Bottleneck Bandwidth (BB), the Bandwidth-Delay Product (BDP) determines the Send and Received Socket buffer sizes required to achieve the maximum TCP Throughput." The BDP estimated by a server includes all buffering experienced along a network path. Various approaches are possible to determine the BDP, based on measurements of the path characteristics. [RFC6349] specifies one procedure for TCP. CC for QUIC is specified in [RFC9002] and does not specify a required method to measure the BDP, allowing the sender to implement an appropriate method.

This document specifies a method for QUIC that can improve traffic delivery (e.g. throughput) by allowing a QUIC connection to reduce the total duration of the slow start phase under specific conditions. This introduces an alternative way to discover initial key path parameters, including a way to more rapidly and safely grow the cwnd.

There are scenarios where sharing previously computed parameters relating to path characteristics, such as the bottleneck bandwidth or RTT, can help to save round-trip times at the start of a new connection. For example:

1. To optimize sessions that use a series of short flows over the same path, each of which needs to individually learn the available capacity/rtt (e.g., a client using Dynamic Adaptive Streaming over HTTPS, DASH);
2. After a pause in transmission (e.g., when a user uses a path, pauses a session, and then wishes to resume the session over the same path;
3. To resume a session after a service disruption (e.g., where the network service temporarily reduced due to a link propagation impairment, or where a user on a train journey travels through different areas of connectivity with a temporary change in path characteristics before the user returns to the original path characteristics).

In all of these cases, specific characteristics of the path may have been learned, including CC information, such as the available

capacity and RTT. This CC information might be expected to be similar when a new connection is made between the same local and remote endpoints.

While the server could take optimization decisions without considering the client's preference, in some cases a client could have information that is not available at the server. A client may provide hints, for example: (1) information about how the upper layers expect to use a connection - such as the expected size of transfer; (2) an indication that the path/local interface has changed; (3) information related to current hardware limitations of the client or (4) an understanding about the capacity needs of other concurrent flows that would compete for shared capacity. As a result, a client could explicitly ask for tuning the slow start of the resumed connection, or to inhibit tuning. This is discussed further later in the document.

There are also cases where using the parameters of a previous connection are not appropriate, and a need to evaluate the potential malicious use of the method.

The remainder of this document:

1. discusses use-cases where carefully resuming QUIC sessions is expected to have benefit;
2. proposes guidelines for how to carefully utilise the previously stored CC information;
3. describes implementation considerations for the proposed method using QUIC;
4. discusses the trade-offs associated with the different implementation solutions.

## [2.](#) Language, notations and terms

This section provides a brief summary of key terms and the requirements language that is used. The document uses language drawn

from a range of IETF RFCs.

## [2.1.](#) Requirements Language

The keywords "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.

## [2.2.](#) Notations and Terms

This document defines current, and saved values for a set of CC parameters:

- \* IW: Initial Window [[RFC9002](#)];
- \* current\_iw: Current IW;
- \* recom\_iw: Recommended IW;
- \* current\_bb : Current estimated bottleneck bandwidth;
- \* saved\_bb: Estimated bottleneck bandwidth preserved from a previous connection;

- \* current\_rtt: Current RTT;
- \* saved\_rtt: RTT measure RTT preserved from a previous connection;
- \* client\_ip : IP address of the client;
- \* current\_client\_ip : Current IP address of the client;
- \* saved\_client\_ip : IP address of a previous connection by the client;
- \* remembered BDP parameters: a combination of saved\_rtt and saved\_bb

Congestion controllers, such as CUBIC or RENO, could estimate the saved\_bb and current\_bb values by utilizing a combination of the

cwnd/flight\_size and the minimum RTT. A different method could be used to estimate the same values when using a rate-based congestion controller, such as BBR [[I-D.cardwell-iccr-g-bbr-congestion-control](#)]. It is important to consider whether the methods could result in over-estimating the bottleneck bandwidth, and the preserved values there ought to be used with caution.

### [3.](#) Scenarios of Interest

#### [3.1.](#) Large BDP Scenarios

QUIC introduces the concept of transport parameters ([section 4 of \[RFC9000\]](#)). This document notes that a new connection can utilise a set of key transport parameters from a previous connection to reduce the completion time for a transfer of size much larger than the IW over paths where the available capacity is also significantly larger than the IW. This benefit is particularly evident for a path where the RTT is much larger than a typical Internet RTT.

For example, a satellite access network, a 5.3 MB transfer takes up to 9 seconds using standard congestion control, whereas using the specified method this could reduce to 4 seconds [[IJSCN](#)]; and the time to complete a 1 MB transfer could be reduced by 62 % [[MAPRG111](#)]. Benefits is also expected for other sizes of transfer and for different path characteristics that also result in a higher BDP.

#### [3.2.](#) Accomodating from a Known Reduction in Capacity

A transport protocol is not able to assume that the path characteristics it experiences remain the same. Variation can arise from a combination of various factors:

- \* Competing network traffic sharing a common bottleneck can result in short or long term variation;
- \* Changes in forward path can change the set of links/routers over which the flow is forwarded (from routing/mobility/circuit restoration/interface change), result in a change in the bandwidth and the other traffic that shares all/part of the path;

- \* Link conditions can result in a change of the total bandwidth (e.g., as a result of changes in propagation conditions or sharing of a medium);
- \* Application/endpoint Behavior can change the capacity available to a flow.

The characteristics of an Internet path therefore need to be measured by the transport protocol, and may not reflect the actual path used by a new connection. Older measurements, or cases where measurements are known to vary significantly are more likely to be invalid.

In some cases (e.g., after a change in the interface used by the local endpoint), a client may be aware of such a change, and might be able to infer that a previously available path has again become available. However, to utilise the previous information, the client would need assurance that the path was to the same endpoint, and that the characteristics have not significantly changed from those previously measured. When the path is expected to be the same, there is then an opportunity to save time (eliminate RTTs consumed by slow start) by utilising saved CC information for the path.

### [3.3.](#) Optimizing Client Requests

Some styles of usage do not use long-lasting connections at the transport layer. Instead, they use a series of shorter connections. For example, a client using Dynamic Adaptive Streaming over HTTPS (DASH). Such a client might be unable to reach the video playback quality that is supported by the path, because for each video chunk, the transport protocol needs to independently determine the path capacity. The lower transfer rate is safe, but can also lead to an overly conservative requested rate by the client, because clients often adapt their application-layer requests based on the transport performance (i.e., the client could fail to increase the requested quality of video chunks, or to fill buffers to avoid stalling playback or to send high quality advertisements).

There are other cases where applications could provide additional services if a client knew the path characteristics.

### [3.4.](#) Sharing Transport Information across Multiple Connections

There can be benefit in sharing transport information across multiple concurrent connections. [RFC9040] considers the sharing of transport parameters between TCP connections that originate from the same host. The proposal in this document has the advantage of storing server-generated information at the client and not requiring the server to retain additional state for each client.

### [3.5.](#) Connection Establishment, Client and Server

In the previously detailed scenarios, the application data transfer was unidirectional towards the client, i.e., the main flow of data was from a server to a client (e.g., downloading a file or web page). This is the focus of the current version of the document.

In a different example, the application data transfer can still be unidirectional, but towards the server, e.g., uploading an image/video to a server.

There are also use cases where a client initiates a connection for a bidirectional service where both endpoints send appreciable data to each other, such as to support a remote executing application, or a video conference call.

In general, the guidelines proposed in this document apply when a congestion controller is sending data to a remote peer and that remote endpoint resumes the session. Both endpoints can assume the role of a client or a server.

## [4.](#) The Phases of CC

This document defines a series of different phases through which the CC algorithm moves as a connection gets up to speed. The phases are labelled as follows:

1. **Observe:** During a previous connection, the current RTT (`current_rtt`), bottleneck bandwidth (`current_bb`) and current client IP (`current_client_ip`) are stored as `saved_rtt`, `saved_bb` and `saved_client_ip`;
2. **Reconnaissance:** When resuming a session between the same pair of IP addresses, the server measures the path characteristics of a new connection to confirm the path appears the same as observed previously (e.g., path with similar RTT). The server also seeks assurance that initial data is not lost, to avoid resuming under congested conditions.

3. Unvalidated: Utilise the saved path characteristics to send at a rate higher than allowed by slow start. The convergence towards the previous rate is expected be quicker than when using traditional slow-start mechanisms, but should not be instantaneous, to avoid adding congestion to a congested bottleneck.
  1. If the unvalidated rate was used without inducing noticeable congestion to the path, the server is permitted to continue sending at this rate in the 'Normal' phase.
  2. If the validation phase determines that previous parameters are not valid (due to a change) or congestion was experienced, the sender must withdraw rapidly to a safe rate, before it enters the 'Normal' phase.
4. Normal: Resume using the normal CC method.

## [5.](#) Safe Jump

### [5.1.](#) Rationale behind the Safety Guidelines

NOTE: The sender ought not to re-utilise all capacity it previously used, to avoiding starving flows that started after the measurement. How strong should this be stated: ... MUST or SHOULD ... What safety factor is appropriate for the resuming sender? If using slow-start it would anyway double the rate on the next RTT, so is capacity/2 appropriate to initially try?

A connection MUST NOT use the previously measured saved\_rtt and saved\_bb to simply initialise a new flow to resume sending at the same rate.

- \* Rationale #1: Bottleneck bandwidth and network traffic can change at any time. An Internet method needs to be robust to network conditions that can differ from one session to the next, due to variations in the forwarding path, reconfiguration of equipment or changes in the link conditions. An Internet method needs to be robust to changes in network traffic, including the arrival of new traffic flows that compete for the bottleneck capacity. Behaviours need to be designed that avoid sending excessive data into a congestion bottleneck because this can have a material impact on any flows using that bottleneck, and the ability of those flows to control their own sending rate.

- \* Rationale #2: Information sent by a malicious client is not relevant. A client could request a server to use a cwnd higher than appropriate, to gain an unfair share of capacity for itself or to induce congestion for other flows. A server might anyway decide whether to fully use the new allowed rate.

## [5.2.](#) Rationale #1: Variable Network Conditions

The server MUST check the validity of any received saved\_rtt and saved\_bb parameters, whether these are sent by a client or are stored at the server. The following events indicates cases where the use of these parameters is inappropriate:

- \* IP address change: If the client changes its local IP address (i.e., the saved\_client\_ip is different from the current\_client\_ip), the different source address is a assumed an indication of a different network path. This new path does not necessarily exhibit the same characteristics as the old one. If the server changes its IP address after a migration, it would not be safe to exploit previously estimated parameters.
- \* RTT change: A significant change in RTT might be an indication that the network conditions have changed. Since the CC information is directly impacted by the RTT, a significant change in the RTT is a strong indication that the previously estimated BDP parameters are likely to not be valid for the current path. NOTE: This document needs to define a significant change.
- \* Lifetime of the information: The CC information is temporal. Frequent connections to the same IP address are likely to track changes, but long-term use of previous values is not appropriate. NOTE: This document needs to define how long.
- \* BB over-estimation: There are cases where using a measured cwnd would inflate the bottleneck bandwidth. At the end of the CC slow start phase, the value of cwnd can be significantly larger than the minimum value needed to utilise the path (i.e., cwnd overshoot). In most case, the cwnd finally converges to a stable value after a few more RTTs. It would be inappropriate to use an

overshoot in the cwnd as a basis for estimating the bottleneck bandwidth. NOTE: One mitigation could be to further restrict to only a fraction (e.g., 1/2) of the previously used cwnd; another mitigation might be to calculate the bottleneck bandwidth based on the flight\_size or an averaged cwnd.

- \* Preventing Starvation of New Flows: It would not be appropriate to fully use a bottleneck bandwidth estimate based on a previous measurement of capacity, because new flows might have started

using the available capacity since that measurement was made. The mitigation could be to restrict to only a fraction (e.g., 1/2) of the previously used cwnd.

There are several solutions to mitigate the impact of changes in network conditions:

- \* Rationale #1 - Solution #1 : When resuming a session, restore the current\_bb and current\_rtt from the saved\_bb and saved\_rtt parameters estimated from a previous connection.
- \* Rationale #1 - Solution #2 : When resuming a session, implement a safety check to measure avoid using the saved\_bb and saved\_rtt parameters to cause congestion over the path. In this case, the current\_bb and current\_rtt might not be set directly to the saved\_bb and saved\_rtt: the server might wait for the completion of the safety check before this is done.

[Section 6](#) describes various approaches for Rationale #1 - Solution #2.

### [5.3](#). Rationale #2: Malicious clients

The server MUST check the integrity of the saved\_rtt and saved\_bb parameters received from a client.

There are several solutions to avoid attacks by malicious clients:

- \* Rationale #2 - Solution #1 : The server stores a local estimate of the bottleneck bandwidth and RTT parameters as the saved\_bb and saved\_rtt.

- \* Rationale #2 - Solution #2 : The server sends the estimate of the bottleneck bandwidth and RTT parameters to the client as the saved\_bb and saved\_rtt in a block of information that is authenticated. This information also could be encrypted by the server. The client resends the same information when resuming a connection. The server can use its local key information to authenticate the information, without needing to keep a local copy.
- \* Rationale #2 - Solution #3 : This approach is the same as above, except that the server sends an estimate of the saved\_rtt and saved\_bb parameters in a form that may be read by the client. The information might not be encrypted, or the information might be duplicated outside of the encrypted block. This allows a client to read, but not modify, the saved\_rtt and saved\_bb parameters and could enable a client to decide whether it thinks the new

parameters are appropriate, based on client-side information about the network conditions, connectivity, or needs of the session using the connection.

[Appendix A](#) describes various implementation approaches for each of these solutions using local storage ( [Appendix A.2](#) for Rationale #2 - Solution #1), NEW\_TOKEN Frame ( [Appendix A.3](#) for Rationale #2 - Solution #2), BDP extension Frame ( [Appendix A.4](#) for Rationale #2 - Solution #3).

#### [5.4.](#) Trade-off between the different solutions

This section provides a description of several implementation options and discusses their respective advantages and drawbacks.

While there are some discussions for the solutions regarding Rationale #2, the server MUST consider Rationale #1 - Solution #2 and avoid Rationale #1 - Solution #1: the server MUST implement a safety check to measure whether the saved BDP parameters (i.e. saved\_rtt and saved\_bb) are relevant or check that their usage would not cause excessive congestion over the path.

Security consideration are discussed in [Section 9](#) .

##### [5.4.1.](#) Interoperability and Use Cases

A server that stores a resumption ticket for each client to protect against replay on a third party IP, it could also store the IP address (i.e., saved\_client\_ip) and BDP parameters (i.e., saved\_rtt and saved\_bb) of the previous session of the client.

When the BDP Frame extension is used, locally stored BDP parameters at the server can provide a cross-check of the BDP parameters sent by a client. The server can anyway enable a safe jump, but without the BDP Frame extension. However, using the parameters enables a client to choose whether to request this or not, enabling it to utilize local knowledge of the network conditions, connectivity, or session requirements.

XXX-Editor-note: Text to be improved: Storing local values related to the BDP would help improve the ingress for 0-RTT connections, however, not using a BDP Frame extension could reduce the interest of the approach where (1) the client knows the BDP estimation at the server, (2) the client decides to accept or reject ingress optimization, (3) the client tunes application level requests.

#### [5.4.2.](#) Summary

Local storage of values can be secure and the BDP Frame extension provides more information to the client and more interoperability. The Figure 1 provides a summary of the advantages and drawbacks of each approach.

Rationale	Solution	Advantage	Drawback	Comment
#1 Variable Network	#1 set current_* to saved_*	Ingress optim.	Risk of adding congestion	MUST NOT implement
	#2 Implement safety	Reduce risk of adding	Negative impact on ingress	MUST implement

	check	congestion	optim.	<a href="#">Section 3</a>
#2 Malicious client	#1 Local storage	Enforced security	Client unable to decide to reject Malicious server could fill client's buffer Limited use-cases	<a href="#">Section 4.2</a>
	#2 NEW_TOKEN	Save resource at server Opaque token protected	Malicious client could change token even if protected Malicious server could fill client's buffer Server may not trust client	<a href="#">Section 4.3</a>
	#3 BDP extension	Extended use-cases Save resource	Malicious client could change BDP	

		at server Client can read and decide to reject BDP extension protected	even if protected Server may not trust client	<a href="#">Section 4.4</a>
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XXX-Editor-Note: Need to clarify the text around changing the authenticated token.

Figure 1: Comparing solutions

## 6. Safety Guidelines

The following safety guidelines refer to the labelling defined in [Section 4](#).

The safety guidelines are designed to mitigate the risk that a server adds excessive congestion to an already congested path. The following mechanisms help in fulfilling this objective:

- \* (observation phase) The server SHOULD NOT store and/or send information related to a previously estimated bottleneck bandwidth (saved\_bb) (see [Section 2.2](#) for more details on bottleneck bandwidth definition), if the cwnd is not at least four times larger than the IW.
- \* (reconnaissance phase) The server MUST NOT send more than the recommended maximum IW (recom\_iw) in the first RTT of transmitting data [[RFC9000](#)]. (When used in a controlled network, additional information about local path characteristics could be known that might be used to configure a non-standard IW).
- \* (reconnaissance phase) The server MUST compare the measured transport parameters (in particular current\_rtt) of the 0-RTT connection with those of the 1-RTT connection (in particular saved\_rtt). The method MUST NOT be used when the path fails to be validated;
- \* (unvalidated phase) The server MUST NOT use the parameters unless the first IW packets when packets are detected as lost or acknowledgements indicate the packets were ECN CE-marked. These are indication of potential congestion and therefore the method MUST NOT be used;

- \* (unvalidated phase) The server MUST implement the retreat method when packets are detected as lost or acknowledgements indicate the packets were ECN CE-marked. These are indication of potential congestion and therefore the method MUST NOT be used.

The proposed mechanisms SHOULD be limited by any rate-limitation mechanisms of QUIC, such as flow control mechanisms or amplification attack prevention. In particular, it may be necessary to issue proactive MAX\_DATA frames to increase the flow control limits of a connection. In particular, the maximum number of packets that can be sent without acknowledgements needs to be chosen to avoid the creation and the increase of congestion for the path.

This extension MUST NOT provide an opportunity for the current connection to be a vector of an amplification attack. The address validation process, used to prevent amplification attacks, SHOULD be performed [[RFC9000](#)].

XXX-Editor-note: This probably should be a range rather than an inequality ( $\text{current\_rtt} < 1.2 * \text{saved\_rtt}$ ).

The following mechanisms could be implemented:

\* Exploit a standard IW:

1. The server sends the first data packet using the IW - this is a safe starting point for any path where there is no path information or congestion control information. This avoids adding excessive congestion to a path;
2. The sender monitors the reception of the IW data. If the path characteristics resemble those of a recent previous session from to the same server (i.e.,  $\text{current\_rtt} < 1.2 * \text{saved\_rtt}$ ) and all data was acknowledged without reported congestion), the method permits the sender to utilise the saved\_bb as an input to adapt current\_bb to rapidly determine a new safe rate;
3. The sender needs to avoid a burst of packets resulting from a step-increase in the congestion window [[RFC9000](#)]. Pacing the packets as a function of the current\_rtt can provide this additional safety during the period in which the CWND is increased by the method.

\* Identify a relevant pacing rhythm:

- The server estimates the pacing rhythm using `saved_rtt` and `saved_bb`. The Inter-packet Transmission Time (ITT) is determined by the ratio between the current Maximum Message Size (MMS) and the ratio between the `saved_bb` and `saved_rtt`. A tunable safety margin can avoid sending more than a recommended maximum IW (`recom_iw`):
    - o `current_iw = min(recom_iw,saved_bb)`
    - o `ITT = MSS/(current_iw/saved_rtt)`
  - When the successful receipt of the IW data is acknowledged, the server returns to a standard slow-start mechanism.
- \* Tune slow-start mechanisms: After transport parameters are set to a previously estimated bottleneck bandwidth, if the slow-start mechanisms continue, the sender can then overshoot the bottleneck capacity. This can occur even when using the safety check described in this section.
- For NewReno and CUBIC, it is recommended to exit slow-start and enter the congestion avoidance phase.
  - For BBR, it is recommended to enter the "probe bandwidth" state.

This follows the idea presented in [\[RFC4782\]](#), [\[I-D.irtf-iccrs-sallantin-initial-spreading\]](#) and [\[CONEXT15\]](#).

## [7.](#) Acknowledgments

The authors would like to thank Gabriel Montenegro, Patrick McManus, Ian Swett, Igor Lubashev, Robin Marx, Roland Bless and Franklin Simo for their fruitful comments on earlier versions of this document.

## [8.](#) IANA Considerations

TBD: Text is required to register the BDP Frame and the `enable_bdp` transport parameter. Parameters are registered using the procedure defined in [\[RFC9000\]](#).

## [9.](#) Security Considerations

Security considerations for QUIC are discussed in [Section 6](#)

The client can send information related to the `saved_rtt` and `saved_bb` to the server with the BDP Frame extension using either Rationale #2

SHOULD NOT trust the client. Indeed, even if 0-RTT packets containing the BDP Frame are encrypted, a client could modify the values within the extension and encrypt the 0-RTT packet. Authentication mechanisms might not guarantee that the values are safe. It is not an easy operation for a client to modify authenticated or encrypted data without this being detected by a server. Modification could be realized by malicious clients. One way to avoid this is for a server to also store the saved\_rtt and saved\_bb parameters.

A malicious client might modify the saved\_bb parameter to convince the server to use a larger CWND than appropriate. Using the algorithms proposed in [Section 6](#), the server may reduce any intended harm and can check that part of the information provided by the client are valid.

Storing the BDP parameters locally at the server reduces the associated risks by allowing the client to transmit information related to the BDP of the path in the case of a malicious client trying to break the encryption mechanism that it had received.

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## [Appendix A](#). Implementation Considerations

### [A.1](#). Rationale behind the different implementation options

The NewSessionTickets message of TLS can offer a solution. The proposal is to add a 'bdp\_metada' field in the NewSessionTickets, which the client is able to read. The only extension currently defined in TLS1.3 that can be seen by the client is max\_early\_data\_size (see [Section 4.6.1 of \[RFC8446\]](#)). However, in the general design of QUIC, TLS sessions are managed by a TLS stack.

Three distinct approaches are presented: sending an opaque blob to the client that the client may return to the server when establishing a future new connection (see [Appendix A.3](#)), enabling local storage of the BDP infromation (see [Appendix A.2](#)) and a BDP Frame extension (see [Appendix A.4](#)).

## [A.2.](#) Independent Local Storage of Values

This approach independently lets both a client and a server store their BDP parameters:

- \* During a 1-RTT session, the endpoint stores the RTT (as the `saved_rtt`) and bottleneck bandwidth (as the `saved_bb`) together in the session resume ticket. The client can also store the IP address of the server;
- \* The server maintains a table of previously issued tickets, indexed by the random ticket identifier that is used to guarantee uniqueness of the Authenticated Encryption with Associated Data (AEAD) encryption. Old tokens are removed from the table using the Least Recently Used (LRU) logic. For each ticket identifier, the table holds the RTT and bottleneck bandwidth (i.e. `saved_rtt` and `saved_bb`), and also the IP address of the client (i.e. `saved_client_ip`).

During the 0-RTT session, the local endpoint waits for the first RTT measurement from the remote endpoint IP address. This is used to verify that the `current_rtt` has not significantly changed from the `saved_rtt` (used as an indication that the BDP information is appropriate for the current path).

If this RTT is confirmed, the endpoint also verifies that an IW of data has been acknowledged without requiring retransmission or resulting in an ECN CE-mark. This second check detects whether a path is experiencing significant congestion (i.e., where it would not be safe to update the `cwnd` based on the `saved_bb`). In practice, this could be realized by a proportional increase in the `cwnd`, where the increase is  $(\text{saved\_bb}/\text{IW}) \times \text{proportion\_of\_IW\_currently-ACKed}$ .

This solution does not allow a client to request the server not to use the BDP parameters. If the server does not want to store the metrics from previous connections, an equivalent of the `tcp_no_metrics_save` for QUIC may be necessary. This option could be negotiated that allows a client to choose whether to use the saved

information.

### [A.3.](#) Using NEW\_TOKEN frames

A server can send a NEW\_TOKEN Frame to the client. The token is an opaque (encrypted) blob and the client can not read its content (see [section 19.7 of \[RFC9000\]](#)). The client sends the received token in the header of an Initial packet of a later connection.

### [A.4.](#) BDP Frame

Using BDP Frames, the server could send information relating to the path characteristics to the client. The use of the BDP Frame is negotiated with the client. The client can read its content. If the client agrees with the usage of previous session parameters, it can send the BDP Frame back to the server in an Initial packet of a later connection.

#### Authors' Addresses

Nicolas Kuhn  
Thales Alenia Space  
Email: nicolas.kuhn.ietf@gmail.com

Emile Stephan  
Orange  
Email: emile.stephan@orange.com

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Godred Fairhurst  
University of Aberdeen  
Department of Engineering  
Fraser Noble Building  
Aberdeen  
Email: gorry@erg.abdn.ac.uk

Tom Jones  
University of Aberdeen  
Department of Engineering  
Fraser Noble Building

Aberdeen  
Email: tom@erg.abdn.ac.uk

Christian Huitema  
Private Octopus Inc.  
Email: huitema@huitema.net