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P. Thubert, Ed.  
Cisco Systems  
J. Hui  
Nest Labs  
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LLN Fragment Forwarding and Recovery  
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## Abstract

Considering that an LLN link-layer frame can have a payload below 100 bytes, an IPv6 packet might be fragmented more than 10 fragments at the 6LoWPAN layer. In a 6LoWPAN mesh-under mesh network, the fragments can be forwarded individually across the mesh, whereas a route-over mesh network, a fragmented 6LoWPAN packet must be reassembled at every hop, which causes latency and congestion. This draft introduces a simple protocol to forward individual fragments across a route-over mesh network, and, regardless of the type of mesh, recover the loss of individual fragments across the mesh and protect the network against bloat with a minimal flow control.

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## 1. Introduction

In most Low Power and Lossy Network (LLN) applications, the bulk of the traffic consists of small chunks of data (in the order few bytes to a few tens of bytes) at a time. Given that an IEEE Std. 802.15.4 [IEEE.802.15.4] frame can carry 74 bytes or more in all cases, fragmentation is usually not required. However, and though this happens only occasionally, a number of mission critical applications do require the capability to transfer larger chunks of data, for instance to support a firmware upgrades of the LLN nodes or an extraction of logs from LLN nodes. In the former case, the large chunk of data is transferred to the LLN node, whereas in the latter, the large chunk flows away from the LLN node. In both cases, the size can be on the order of 10<sup>4</sup> bytes or more and an end-to-end reliable transport is required.

"Transmission of IPv6 Packets over IEEE 802.15.4 Networks" [RFC4944] defines the original 6LoWPAN datagram fragmentation mechanism for LLNs. One critical issue with this original design is that routing an IPv6 packet across a route-over mesh requires to reassemble the full packet at each hop, which may cause latency along a path and an overall buffer bloat in the network. Those undesirable effects can be alleviated by a hop-by-hop fragment forwarding technique such as the one proposed in this specification, and arguably this could be achieved without the need to define a new protocol. However, adding that capability alone to the local implementation of the original 6LoWPAN fragmentation would not address the bulk of the issues raised against it, and may create new issues like uncontrolled state in the network.

Another issue against RFC 4944 [RFC4944] is that it does not define a mechanism to first discover the loss of a fragment along a multi-hop path (e.g. having exhausted the link-layer retries at some hop on the way), and then to recover that loss. With RFC 4944, the forwarding of a whole datagram fails when one fragment is not delivered properly to the destination 6LoWPAN endpoint. End-to-end transport or application-level mechanisms may require a full retransmission of the datagram, wasting resources in an already constrained network.

In that situation, the source 6LoWPAN endpoint will not be aware that a loss occurred and will continue sending all fragments for a datagram that is already doomed. The original support is missing signaling to abort a multi-fragment transmission at any time and from either end, and, if the capability to forward fragments is implemented, clean up the related state in the network. It is also lacking flow control capabilities to avoid participating to a congestion that may in turn cause the loss of a fragment and trigger the retransmission of the full datagram.

This specification proposes a method to forward fragments across a multi-hop route-over mesh, and to recover individual fragments between LLN endpoints. The method is designed to limit congestion loss in the network and addresses the requirements that are detailed in Appendix B.

## 2. Updating RFC 4944

This specification deprecates the fragmentation mechanism that is specified in RFC 4944 [RFC4944] and replaces it with a model where fragments can be forwarded end-to-end across a 6LoWPAN mesh network of any type, and where fragments that are lost on the way can be recovered individually. New dispatch types are defined in Section 4.

### 3. Terminology and Referenced Work

Past experience with fragmentation has shown that miss-associated or lost fragments can lead to poor network behavior and, occasionally, trouble at application layer. The reader is encouraged to read [RFC 963](#) [RFC4963] and follow the references for more information.

That experience led to the definition of "Path MTU discovery" [RFC1191] (PMTUD) protocol that limits fragmentation over the Internet.

Specifically in the case of UDP, valuable additional information can be found in "UDP Usage Guidelines for Application Designers" [RFC5405].

Readers are expected to be familiar with all the terms and concepts that are discussed in "IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs): Overview, Assumptions, Problem Statement, and Goals" [RFC4919] and "Transmission of IPv6 Packets over IEEE 802.15.4 Networks" [RFC4944].

"The Benefits of Using Explicit Congestion Notification (ECN)" [RFC8087] provides useful information on the potential benefits and pitfalls of using ECN.

Quoting the "Multiprotocol Label Switching (MPLS) Architecture" [RFC8087]: with MPLS, "packets are "labeled" before they are forwarded. At subsequent hops, there is no further analysis of the packet's network layer header. Rather, the label is used as an index into a table which specifies the next hop, and a new label". That technique is leveraged in this specification to forward fragments that actually do not have a network layer header, since the fragmentation occurs below IP.

This specification uses the following terms:

#### 6LoWPAN endpoints

The LLN nodes in charge of generating or expanding a 6LoWPAN header from/to a full IPv6 packet. The 6LoWPAN endpoints are the points where fragmentation and reassembly take place.

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in [RFC2119].

#### 4. New Dispatch types and headers

This specification aims at enabling to provide an MHO that is equivalent to 2048 bytes to the upper layer, which can be the 6LoWPAN Header Compression that is defined in the "Compression Format for IPv6 Datagrams" [RFC6282] specification. In order to achieve this, this specification enables the fragmentation and the reliable transmission of fragments over a multihop 6LoWPAN mesh network.

This specification provides a technique that is derived from MPLS and allows to forward fragments across a 6LoWPAN route-over mesh, but is not needed in the mesh-under case. The datagram\_tag is used as the label and is locally unique to the node that is the MAC-layer source of the fragment. There is thus no need for a global registry of datagram\_tags and a node may build the datagram\_tag in its own locally-significant way, as long as the resulting tag stays unique to the particular datagram for the lifetime of that datagram.

This specification extends RFC 4944 [RFC4944] with 4 new Dispatch types, for Recoverable Fragment (RFRAG) headers with or without Acknowledgment Request (RFRAG vs. RFRAG-ARQ), and for the RFRAG Acknowledgment back, with or without ECN Echo (RFRAG-ACK vs. RFRAG-ECN).

(to be confirmed by IANA) The new 6LoWPAN Dispatch types use the Value Bit Pattern of 11 1010xx, as follows:

Pattern	Header Type
11 101000	RFRAG - Recoverable Fragment
11 101001	RFRAG-ARQ - RFRAG with Ack Request
11 101010	RFRAG-ACK - RFRAG Acknowledgment
11 101011	RFRAG-ECN - RFRAG Ack with ECN Echo

Figure 1: Additional Dispatch Value Bit Patterns

##### 4.1. Recoverable Fragment Dispatch type and Header

In this specification, the size and offset of the fragments are expressed on the compressed packet payload as opposed to the uncompressed - native packet - form.

The first fragment is recognized by a sequence of 0; it carries its fragment\_size and the datagram\_size of the compressed packet, whereas the other fragments carry their fragment\_size and fragment\_offset. The last fragment for a datagram is recognized when its fragment\_offset and its fragment\_size add up to the datagram\_size.

Recoverable Fragments are sequenced and a bitmap is used in the RFRAG Acknowledgment to indicate the received fragments by setting the individual bits that correspond to their sequence.

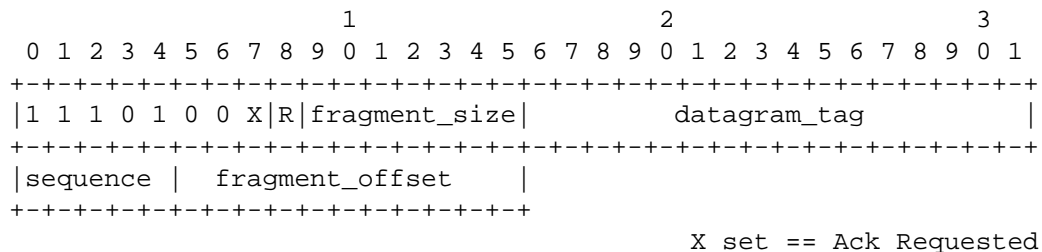


Figure 2: RFRAG Dispatch type and Header

X: 1 bit; Ack Requested: when set, the sender requires an RFRAG Acknowledgment from the receiver.

R: 1 bit; Reserved, MUST be set to 0 by the source and ignored by all nodes.

Fragment\_size: 7 bits unsigned integer. The size of this fragment in units that depend on the M layer technology. For IEEE Std. 802.15.4, the unit is octet.

Sequence: 5 bits unsigned integer; the sequence number of the fragment. Fragments are sequence numbered [0..N] where N is in [0..31].

Fragment\_offset: 10 bits unsigned integer; when set to 0, this field indicates an abort condition; else, its value depends on the value of the Sequence. When the sequence is not 0, this field indicates the offset of the fragment in the compressed form. When the sequence is 0, denoting the first fragment of a datagram, this field is overloaded to indicate the total\_size of the compressed packet, to help the receiver allocate an adapted buffer for the reception and reassembly operations.

#### 4.2. RFRAG Acknowledgment Dispatch type and Header

The specification also defines a 4-octet RFRAG Acknowledgment bitmap that is used to confirm selectively the reception of individual fragments. A given offset in the bitmap maps one to one with a given sequence number.

The offset of the bit in the bitmap indicates which fragment is acknowledged as follows:

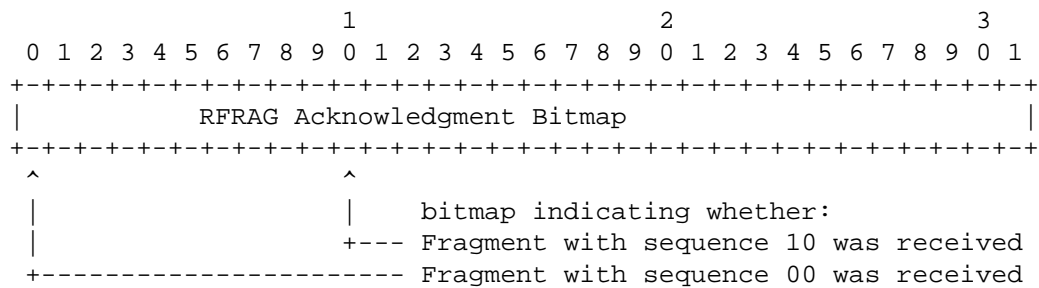


Figure 3: RFRAG Acknowledgment bitmap encoding

Figure 4 shows an example Acknowledgment bitmap which indicates that all fragments from sequence 0 to 20 were received, except for fragments 1, 2 and 16 that were either lost or are still in the network over a slower path.

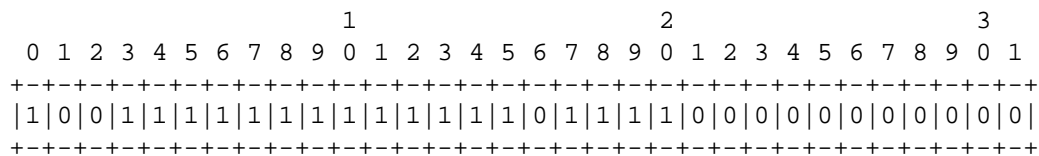


Figure 4: Expanding 3 octets encoding

The RFRAG Acknowledgment Bitmap is included in a RFRAG Acknowledgment header, as follows:

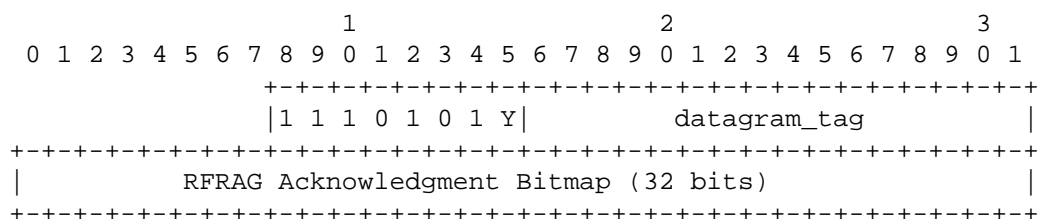


Figure 5: RFRAG Acknowledgment Dispatch type and Header

Y: 1 bit; Explicit Congestion Notification

When set, the sender indicates that at least one of the acknowledged fragments was received with an Explicit Congestion Notification, indicating that the path followed by the fragments is subject to congestion.

RFRAG Acknowledgment Bitmap

An RFRAG Acknowledgment Bitmap whereby but at offset x indicates that fragment x was received

## 5. Fragments Recovery


The Recoverable Fragment headers RFRAG and RFRAG-ARQ are used to transport a fragment and optionally request an RFRAG Acknowledgment that will confirm the good reception of a one or more fragments. An RFRAG Acknowledgment can optionally carry an ECN indication; it is carried as a standalone header in a message that is sent back to the 6LoWPAN endpoint that was the source of the fragments, as known by its MAC address. The process ensures that at every hop, the source MAC address and the datagram\_tag in the received fragment are enough information to send the RFRAG Acknowledgment back towards the source 6LoWPAN endpoint.


The 6LoWPAN endpoint that fragments the packets at 6LoWPAN level (the sender) also controls the RFRAG Acknowledgments by setting the Ack Requested flag in the RFRAG packets. It may set the Ack Requested flag on any fragment so as to implement its own policy or perform congestion control by limiting the number of fragments in the air, fragments that have been sent but for which reception or loss was not positively confirmed by the other 6LoWPAN endpoint. When the sender of the fragment knows that an underlying link-layer mechanism protects the Fragments already it may refrain from using the RFRAG Acknowledgment mechanism, and never set the Ack Requested bit. When it receives a fragment with the ACK Request flag set, the 6LoWPAN endpoint that reassembles the packets at 6LoWPAN level (the receiver) sends back an RFRAG Acknowledgment to confirm reception of all the fragments it has received so far, though it may slightly defer it to let additional packets in.



The sender transfers a controlled number of fragments and MAY flag the last fragment of a series with an RFRAG Acknowledgment Request. The receiver MUST acknowledge a fragment with the acknowledgment request bit set. If any fragment immediately preceding an acknowledgment request is still missing, the receiver MAY intentionally delay its acknowledgment to allow in-transit fragments to arrive. delaying the acknowledgment might defeat the round trip delay computation so it should be configurable and not enabled by default.

The receiver interacts with the sender using an Acknowledgment message with a bitmap that indicates which fragments were actually received. The bitmap is a 32bit bitstring (a DWORD), which accommodates up to 32 fragments and is sufficient to transport 2028 bytes over an IEEE Std. 802.15.4 MAC payload. For all n in [0..31], bit n is set to 1 in the bitmap to indicate that fragment with





sequence *n* was received, otherwise the bit is set to 0. All  is a NULL bitmap that indicates that the fragmentation process was canceled by the receiver for that datagram.

The receiver MAY issue unsolicited acknowledgments.  unsolicited acknowledgment enables the sender endpoint to resume sending if it had reached its maximum number of outstanding fragments or indicate that the receiver has cancelled the process of an individual datagram. Note that acknowledgments might consume precious resources so the use of unsolicited acknowledgments should be configurable and not enabled by default.

The sender arms a retry timer to co  the fragment that carries the Acknowledgment request. Upon time out, the sender assumes that all the fragments on the way are received or lost. The process must have completed within an acceptable time that is within the boundaries of upper layer retries. The method detailed in [RFC6298] is recommended for the computation of the retry timer. It is expected that the  upper layer retries obey the same or friendly rules in which case a single round of fragment recovery should fit within the upper layer recovery timers.

Fragments are sent in a round robin fashion: the sender sends all the fragments for a first time before it retries any lost fragment; lost fragments are retried in sequence, oldest first. This mechanism enables the receiver to acknowledge fragments that were delayed in the network before they are actually retried.

When the sender decides that a packet should be dropped and the fragmentation process canceled, it sends a pseudo fragment with the `fragment_offset`, sequence and `fragment_size` all set to 0, and no data. Upon reception of this message, the receiver should clean up all resources for the packet associated to the `datagram_tag`. If an acknowledgment is requested, the receiver responds with a NULL bitmap.

The receiver might need to cancel the process of a fragmented packet for internal reasons, for instance if it is out of reassembly buffers, or considers that this packet is already fully reassembled and passed to the upper layer. In that case, the receiver SHOULD indicate so to the sender with  NULL bitmap. Upon an acknowledgment with a NULL bitmap, the sender  MUST drop the datagram.

## 6. Forwarding Fragments

It is assumed that the first Fragment is large enough to carry the IPv6 header and make routing decisions. If that is not so, then this specification MUST NOT be used.

This specification enables intermediate routers to forward fragments with no intermediate reconstruction of the entire packet. Upon the first fragment, the routers lay an label along the path that is followed by that fragment (that is IP routed), and all further fragments are label switched along that path. As a consequence, alternate routes not possible for individual fragments. The datagram\_tag is used to carry the label, that is swapped at each hop.

### 6.1. Upon the first fragment

In Route-Over mode, the MAC address changes at each hop. The label that is formed and placed in the datagram\_tag is associated to the source MAC and only valid (and unique) for that source MAC. Say the first fragment has:

Source IPv6 address = IP\_A (maybe hops away)

Destination IPv6 address = IP\_B (maybe hops away)

Source MAC = MAC\_prv (prv as previous)

Datagram\_tag= DT\_prv

The intermediate router that forwards individual fragments does the following:

route lookup to get next hop IPv6 towards IP\_B, which resolves as IP\_nxt (nxt as next)

MAC address resolution to get the MAC address associated to IP\_nxt, which resolves as MAC\_nxt

Since it is a first fragment of a packet from that source MAC address MAC\_prv for that tag DT\_prv, the router:

cleans up any leftover resource associated to the tuple (MAC\_prv, DT\_prv)

allocates a new label for that flow, DT\_nxt, from a Least Recently Used pool or some similar procedure.

allocates a Label swap structure indexed by (MAC\_prv, DT\_prv) that contains (MAC\_nxt, DT\_nxt)

allocates a Label swap structure indexed by (MAC\_nxt, DT\_nxt) that contains (MAC\_prv, DT\_prv)

swaps the MAC info to from self MAC\_nxt

Swaps the datagram\_tag to DT\_nxt

At this point the router is all set and can forward the packet to  
nxt.

## 6.2. Upon the next fragments

Upon next fragments (that are not first fragment), the router expects to have already a swap structure indexed by (MAC\_prv, DT\_prv). The router:

looks up the Label swap entry for (MAC\_prv, DT\_prv), which resolves as (MAC\_nxt, DT\_nxt)

swaps the MAC info to from self to MAC\_nxt;

swaps the datagram\_tag to DT\_nxt

At this point the router is all set and can forward the packet to  
nxt.

If the Label swap entry for (MAC\_prv, DT\_prv) is not found, the router builds an RFRAG-ACK to indicate the error. The resulting message has the following information:

MAC info set to self to MAC\_prv as found in the fragment

Swaps the datagram\_tag set to DT\_prv

Bitmap of all 0es to indicate the error

At this point the router is all set and can send the RFRAG-ACK back to the previous router.

## 6.3. Upon the RFRAG Acknowledgments



Upon an RFRAG Acknowledgment, the router expects to have already a Label swap structure indexed by (MAC\_nxt, DT\_nxt), which are respectively the source MAC address of the received frame and the received datagram\_tag. DT\_nxt should have been computed by this router and this router should have assigned it to this particular datagram. The router:





looks up the Label swap entry for (MAC\_nxt, DT\_nxt), which resolves as (MAC\_prv, DT\_prv)

swaps the MAC info to from self to MAC\_prv;

Swaps the datagram\_tag to DT\_prv

At this point the router is all set and can forward the RFRAG-ACK to prv.

 the Label swap entry for (MAC\_nxt, DT\_nxt) is not found, it  simply drops the packet.

 the RFRAG-ACK indicates either an error  that the fragment was fully received  the router schedules the Label swap entries for recycling. If the RFRAG-ACK is lost on the way back, the source may retry the last fragment  which will result as an error RFRAG-ACK from the first router on the way that has already cleaned up.

## 7. Security Considerations

The process of recovering fragments does not appear to create any opening for new threat compared to "Transmission of IPv6 Packets over IEEE 802.15.4 Networks" [RFC4944].

## 8. IANA Considerations

Need extensions for formats defined in "Transmission of IPv6 Packets over IEEE 802.15.4 Networks" [RFC4944].

## 9. Acknowledgments

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## Appendix A. Rationale

There are a number of uses for large packets in Wireless Sensor Networks. Such usages may not be the most typical or represent the largest amount of traffic over the LLN; however, the associated functionality can be critical enough to justify extra care for ensuring effective transport of large packets across the LLN.

The list of those usages includes:

Towards the LLN node:

Packages of Commands: A number of commands or a full configuration can be packaged as a single message to ensure consistency and enable atomic execution or complete roll back. Until such commands are fully received and interpreted, the intended operation will not take effect.



firmware update: For example, a new version of the LLN node software is downloaded from a system manager over unicast or multicast services. Such a reflashing operation typically involves updating a large number of similar LLN nodes over a relatively short period of time.


From the LLN node:

Waveform captures: A number of consecutive samples are measured at a high rate for a short time and then transferred from a sensor to a gateway or an edge server as a single large report.


Data logs: LLN nodes may generate large logs of sampled data for later extraction. LLN nodes may also generate system logs to assist in diagnosing problems on the node or network.

Large data packets: Rich data types might require more than one fragment.

Uncontrolled firmware download or waveform upload can easily result in a massive increase of the traffic and saturate the network.

When a fragment is lost in transmission  all fragments are resent, further contributing to the congestion that caused the initial loss, and potentially leading to congestion collapse.

This saturation may lead to excessive radio interference, or random early discard (leaky bucket) in relaying nodes. Additional queuing and memory congestion may result while waiting for a low power next hop to emerge from its sleeping state.

Considering that [RFC4944] defines an MTU is 1280 bytes and that in most incarnations (but 802.15.4 ) a 802.15.4 frame can limit the MAC payload to as few as 74 bytes, a packet might be fragmented into at least 18 fragments at the 6LoWPAN shim layer. Taking into account the worst-case header overhead for 6LoWPAN Fragmentation and Mesh Addressing headers will increase the number of required fragments to around 32. This level of fragmentation is much higher than that traditionally experienced over the Internet with IPv4 fragments. At the same time, the use of radios increases the probability of transmission loss and Mesh-Under techniques compound that risk over multiple hops.

Mechanisms such as TCP or application-layer segmentation could be used to support end-to-end reliable transport. One option to support bulk data transfer over a frame-size-constrained LLN is to set the Maximum Segment Size to fit within the link maximum frame size. Doing so, however, can add significant header overhead to each

802.15.4 frame. In addition, deploying such a mechanism requires that the end-to-end transport is aware of the delivery properties of the underlying LLN, which is a layer violation, and difficult to achieve from the far end of the IPv6 network.

## Appendix B. Requirements

For one-hop communications, a number of Low Power and Lossy Network (LLN) link-layers propose a local acknowledgment mechanism that is enough to detect and recover the loss of fragments. In a multihop environment, an end-to-end fragment recovery mechanism might be a good complement to a hop-by-hop MAC level recovery. This draft introduces a simple protocol to recover individual fragments between 6LoWPAN endpoints that may be multiple hops away. The method addresses the following requirements of a LLN:

### Number of fragments

The recovery mechanism must support highly fragmented packets, with a maximum of 32 fragments per packet.

### Minimum acknowledgment overhead

Because the radio is half duplex, and because of silent time spent in the various medium access mechanisms, an acknowledgment consumes roughly as many resources as data fragment.

The new end-to-end fragment recovery mechanism should be able to acknowledge multiple fragments in a single message and not require an acknowledgment at all if fragments are already protected at a lower layer.

### Controlled latency

The recovery mechanism must succeed or give up within the time boundary imposed by the recovery process of the Upper Layer Protocols.

### Support for out-of-order fragment delivery

Forwarding over a mesh network with rerouting and load balancing can introduce out-of-sequence packets.



The recovery mechanism must account for packets that appear lost but are actually only delayed over a different path.

### Optional congestion control



The aggregation of multiple concurrent flows may lead to the saturation of the radio network and congestion collapse.

The recovery mechanism should provide means for controlling the number of fragments in transit over the LLN.

### Appendix C. Considerations On Flow Control

Considering that a multi-hop LLN can be a very sensitive environment due to the limited queuing capabilities of a large population of its nodes, this draft recommends a simple and conservative approach to congestion control, based on TCP congestion avoidance.

Congestion on the forward path is assumed in case of packet loss, and packet loss is assumed upon time out. The draft allows to control the number of outstanding fragments, that have been transmitted but for which an acknowledgment was not received yet. It must be noted that the number of outstanding fragments should not exceed the number of hops in the network, but the way to figure the number of hops is out of scope for this document.

Congestion on the forward path can also be indicated by an Explicit Congestion Notification (ECN) mechanism. Though whether and how ECN [RFC3168] is carried out over the LoWPAN is out of scope, this draft provides a way for the destination endpoint to echo an ECN indication back to the source endpoint in an acknowledgment message as represented in Figure 5 in [Section 4.2](#).

It must be noted that congestion and collision are different topics. In particular, when a mesh operates on a same channel over multiple hops, then the forwarding of a fragment over a certain hop may collide with the forwarding of a next fragment that is following over a previous hop but in a same interference domain. This draft enables an end-to-end flow control, but leaves it to the sender stack to pace individual fragments within a transmit window, so that a given fragment is sent only when the previous fragment has had a chance to progress beyond the interference domain of this hop. In the case of 6TiSCH [[I-D.ietf-6tisch-architecture](#)], which operates over the TimeSlotted Channel Hopping [[RFC7554](#)] (TSCH) mode of operation of IEEE802.14.5, a fragment is forwarded over a different channel at a different time and it makes all sense to forward the next fragment as soon as the previous fragment has had its chance to be forwarded at the next hop, every (ARQ) operations included.

From the standpoint of a source 6LoWPAN endpoint, an outstanding fragment is a fragment that was sent but for which no explicit acknowledgment was received yet. This means that the fragment might be on the way, received but not yet acknowledged, or the

acknowledgment might be on the way back. It is also possible that either the fragment or the acknowledgment was lost on the way.

Because a meshed LLN might deliver frames out of order, it is virtually impossible to differentiate these situations. In other words, from the sender standpoint, all outstanding fragments might still be in the network and contribute to its congestion. There is an assumption, though, that after a certain amount of time, a frame is either received or lost, so it is not causing congestion anymore. This amount of time can be estimated based on the round trip delay between the 6LoWPAN endpoints. The method detailed in [\[RFC6298\]](#) is recommended for that computation.

The reader is encouraged to read through "Congestion Control Principles" [\[RFC2914\]](#). Additionally [\[RFC2309\]](#) and [\[RFC5681\]](#) provide deeper information on why this mechanism is needed and how TCP handles Congestion Control. Basically, the goal here is to manage the amount of fragments present in the network; this is achieved by reducing the number of outstanding fragments over a congested path by throttling the sources.

[Section 5](#) describes how the sender decides how many fragments are (re)sent before an acknowledgment is required, and how the sender adapts that number to the network conditions.

#### Authors' Addresses

Pascal Thubert (editor)  
Cisco Systems, Inc  
Building D  
45 Allee des Ormes - BP1200  
MOUGINS - Sophia Antipolis 06254  
FRANCE

Phone: +33 497 23 26 34  
Email: [pthubert@cisco.com](mailto:pthubert@cisco.com)

Jonathan W. Hui  
Nest Labs  
3400 Hillview Ave  
Palo Alto, California 94304  
USA

Email: [jonhui@nestlabs.com](mailto:jonhui@nestlabs.com)