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PGM Reliable Transport Protocol Specification

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Abstract

Pragmatic General Multicast (PGM) is a reliable multicast transport protocol for applications that require ordered or unordered, duplicate-free, multicast data delivery from multiple sources to multiple receivers. PGM guarantees that a receiver in the group either receives all data packets from transmissions and repairs, or is able to detect unrecoverable data packet loss. PGM is

specifically intended as a workable solution for multicast applications with basic reliability requirements. Its central design goal is simplicity of operation with due regard for scalability and network efficiency.

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Nota Bene:

The publication of this specification is intended to freeze the definition of PGM in the interest of fostering both ongoing and prospective experimentation with the protocol. The intent of that experimentation is to provide experience with the implementation and deployment of a reliable multicast protocol of this class so as to be able to feed that experience back into the longer-term standardization process underway in the Reliable Multicast Transport Working Group of the IETF. Appendix G provides more specific detail on the scope and status of some of this experimentation. Reports of experiments include [16-23]. Additional results and new experimentation are encouraged.

1. Introduction and Overview

A variety of reliable protocols have been proposed for multicast data delivery, each with an emphasis on particular types of applications, network characteristics, or definitions of reliability ([1], [2], [3], [4]). In this tradition, Pragmatic General Multicast (PGM) is a reliable transport protocol for applications that require ordered or unordered, duplicate-free, multicast data delivery from multiple sources to multiple receivers.

PGM is specifically intended as a workable solution for multicast applications with basic reliability requirements rather than as a comprehensive solution for multicast applications with sophisticated ordering, agreement, and robustness requirements. Its central design goal is simplicity of operation with due regard for scalability and network efficiency.

PGM has no notion of group membership. It simply provides reliable multicast data delivery within a transmit window advanced by a source according to a purely local strategy. Reliable delivery is provided within a source's transmit window from the time a receiver joins the group until it departs. PGM guarantees that a receiver in the group either receives all data packets from transmissions and repairs, or is able to detect unrecoverable data packet loss. PGM supports any number of sources within a multicast group, each fully identified by a globally unique Transport Session Identifier (TSI), but since these sources/sessions operate entirely independently of each other, this specification is phrased in terms of a single source and extends without modification to multiple sources.

More specifically, PGM is not intended for use with applications that depend either upon acknowledged delivery to a known group of recipients, or upon total ordering amongst multiple sources.

Rather, PGM is best suited to those applications in which members may join and leave at any time, and that are either insensitive to unrecoverable data packet loss or are prepared to resort to application recovery in the event. Through its optional extensions, PGM provides specific mechanisms to support applications as disparate as stock and news updates, data conferencing, low-delay real-time video transfer, and bulk data transfer.

In the following text, transport-layer originators of PGM data packets are referred to as sources, transport-layer consumers of PGM data packets are referred to as receivers, and network-layer entities in the intervening network are referred to as network elements.

Unless otherwise specified, the term "repair" will be used to indicate both the actual retransmission of a copy of a missing packet or the transmission of an FEC repair packet.

Terminology

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 RFC 2119 [14] and indicate requirement levels for compliant PGM implementations.

1.1. Summary of Operation

PGM runs over a datagram multicast protocol such as IP multicast [5]. In the normal course of data transfer, a source multicasts sequenced data packets (ODATA), and receivers unicast selective negative acknowledgments (NAKs) for data packets detected to be missing from the expected sequence. Network elements forward NAKs PGM-hop-by-PGM-hop to the source, and confirm each hop by multicasting a NAK confirmation (NCF) in response on the interface on which the NAK was received. Repairs (RDATA) may be provided either by the source itself or by a Designated Local Repairer (DLR) in response to a NAK.

Since NAKs provide the sole mechanism for reliability, PGM is particularly sensitive to their loss. To minimize NAK loss, PGM defines a network-layer hop-by-hop procedure for reliable NAK forwarding.

Upon detection of a missing data packet, a receiver repeatedly unicasts a NAK to the last-hop PGM network element on the distribution tree from the source. A receiver repeats this NAK until it receives a NAK confirmation (NCF) multicast to the group from that PGM network element. That network element responds with an NCF to the first occurrence of the NAK and any further retransmissions of that same NAK from any receiver. In turn, the network element repeatedly forwards the NAK to the upstream PGM network element on the reverse of the distribution path from the source of the original data packet until it also receives an NCF from that network element. Finally, the source itself receives and confirms the NAK by multicasting an NCF to the group.

While NCFs are multicast to the group, they are not propagated by PGM network elements since they act as hop-by-hop confirmations.

To avoid NAK implosion, PGM specifies procedures for subnet-based NAK suppression amongst receivers and NAK elimination within network elements. The usual result is the propagation of just one copy of a given NAK along the reverse of the distribution path from any network with directly connected receivers to a source.

The net effect is that unicast NAKs return from a receiver to a source on the reverse of the path on which ODATA was forwarded, that is, on the reverse of the distribution tree from the source. More specifically, they return through exactly the same sequence of PGM network elements through which ODATA was forwarded, but in reverse. The reasons for handling NAKs this way will become clear in the discussion of constraining repairs, but first it's necessary to describe the mechanisms for establishing the requisite source path state in PGM network elements.

To establish source path state in PGM network elements, the basic data transfer operation is augmented by Source Path Messages (SPMs) from a source, periodically interleaved with ODATA. SPMs function primarily to establish source path state for a given TSI in all PGM network elements on the distribution tree from the source. PGM network elements use this information to address returning unicast NAKs directly to the upstream PGM network element toward the source, and thereby insure that NAKs return from a receiver to a source on the reverse of the distribution path for the TSI.

SPMs are sent by a source at a rate that serves to maintain up-to-date PGM neighbor information. In addition, SPMs complement the role of DATA packets in provoking further NAKs from receivers, and maintaining receive window state in the receivers.

As a further efficiency, PGM specifies procedures for the constraint of repairs by network elements so that they reach only those network segments containing group members that did not receive the original transmission. As NAKs traverse the reverse of the ODATA path (upward), they establish repair state in the network elements which is used in turn to constrain the (downward) forwarding of the corresponding RDATA.

Besides procedures for the source to provide repairs, PGM also specifies options and procedures that permit designated local repairers (DLRs) to announce their availability and to redirect repair requests (NAKs) to themselves rather than to the original source. In addition to these conventional procedures for loss recovery through selective ARQ, Appendix A specifies Forward Error Correction (FEC) procedures for sources to provide and receivers to request general error correcting parity packets rather than selective retransmissions.

Finally, since PGM operates without regular return traffic from receivers, conventional feedback mechanisms for transport flow and congestion control cannot be applied. Appendix B specifies a TCP-friendly, NE-based solution for PGM congestion control, and cites a reference to a TCP-friendly, end-to-end solution for PGM congestion control.

In its basic operation, PGM relies on a purely rate-limited transmission strategy in the source to bound the bandwidth consumed by PGM transport sessions and to define the transmit window maintained by the source.

PGM defines four basic packet types: three that flow downstream (SPMs, DATA, NCFs), and one that flows upstream (NAKs).

1.2. Design Goals and Constraints

PGM has been designed to serve that broad range of multicast applications that have relatively simple reliability requirements, and to do so in a way that realizes the much advertised but often unrealized network efficiencies of multicast data transfer. The usual impediments to realizing these efficiencies are the implosion of negative and positive acknowledgments from receivers to sources, repair latency from the source, and the propagation of repairs to disinterested receivers.

1.2.1. Reliability.

Reliable data delivery across an unreliable network is conventionally achieved through an end-to-end protocol in which a source (implicitly or explicitly) solicits receipt confirmation from a receiver, and the receiver responds positively or negatively. While the frequency of negative acknowledgments is a function of the reliability of the network and the receiver's resources (and so, potentially quite low), the frequency of positive acknowledgments is fixed at at least the rate at which the transmit window is advanced, and usually more often.

Negative acknowledgments primarily determine repairs and reliability. Positive acknowledgments primarily determine transmit buffer management.

When these principles are extended without modification to multicast protocols, the result, at least for positive acknowledgments, is a burden of positive acknowledgments transmitted to the source that quickly threatens to overwhelm it as the number of receivers grows. More succinctly, ACK implosion keeps ACK-based reliable multicast protocols from scaling well.

One of the goals of PGM is to get as strong a definition of reliability as possible from as simple a protocol as possible. ACK implosion can be addressed in a variety of effective but complicated ways, most of which require re-transmit capability from other than the original source.

An alternative is to dispense with positive acknowledgments altogether, and to resort to other strategies for buffer management while retaining negative acknowledgments for repairs and reliability. The approach taken in PGM is to retain negative acknowledgments, but to dispense with positive acknowledgments and resort instead to timeouts at the source to manage transmit resources.

The definition of reliability with PGM is a direct consequence of this design decision. PGM guarantees that a receiver either receives all data packets from transmissions and repairs, or is able to detect unrecoverable data packet loss.

PGM includes strategies for repeatedly provoking NAKs from receivers, and for adding reliability to the NAKs themselves. By reinforcing the NAK mechanism, PGM minimizes the probability that a receiver will detect a missing data packet so late that the packet is unavailable for repair either from the source or from a designated local repairer (DLR). Without ACKs and knowledge of group membership, however, PGM cannot eliminate this possibility.

1.2.2. Group Membership

A second consequence of eliminating ACKs is that knowledge of group membership is neither required nor provided by the protocol. Although a source may receive some PGM packets (NAKs for instance) from some receivers, the identity of the receivers does not figure in the processing of those packets. Group membership MAY change during the course of a PGM transport session without the knowledge of or consequence to the source or the remaining receivers.

1.2.3. Efficiency

While PGM avoids the implosion of positive acknowledgments simply by dispensing with ACKs, the implosion of negative acknowledgments is addressed directly.

Receivers observe a random back-off prior to generating a NAK during which interval the NAK is suppressed (i.e. it is not sent, but the receiver acts as if it had sent it) by the receiver upon receipt of a matching NCF. In addition, PGM network elements eliminate duplicate NAKs received on different interfaces on the same network element.

The combination of these two strategies usually results in the source receiving just a single NAK for any given lost data packet.

Whether a repair is provided from a DLR or the original source, it is important to constrain that repair to only those network segments containing members that negatively acknowledged the original transmission rather than propagating it throughout the group. PGM specifies procedures for network elements to use the pattern of NAKs to define a sub-tree within the group upon which to forward the corresponding repair so that it reaches only those receivers that missed it in the first place.

1.2.4. Simplicity

PGM is designed to achieve the greatest improvement in reliability (as compared to the usual UDP) with the least complexity. As a result, PGM does NOT address conference control, global ordering amongst multiple sources in the group, nor recovery from network partitions.

1.2.5. Operability

PGM is designed to function, albeit with less efficiency, even when some or all of the network elements in the multicast tree have no knowledge of PGM. To that end, all PGM data packets can be conventionally multicast routed by non-PGM network elements with no loss of functionality, but with some inefficiency in the propagation of RDATA and NCFs.

In addition, since NAKs are unicast to the last-hop PGM network element and NCFs are multicast to the group, NAK/NCF operation is also consistent across non-PGM network elements. Note that for NAK suppression to be most effective, receivers should always have a PGM network element as a first hop network element between themselves and every path to every PGM source. If receivers are several hops removed from the first PGM network element, the efficacy of NAK suppression may degrade.

1.3. Options

In addition to the basic data transfer operation described above, PGM specifies several end-to-end options to address specific application requirements. PGM specifies options to support fragmentation, late joining, redirection, Forward Error Correction (FEC), reachability, and session synchronization/termination/reset. Options MAY be appended to PGM data packet headers only by their original transmitters. While they MAY be interpreted by network elements, options are neither added nor removed by network elements.

All options are receiver-significant (i.e., they must be interpreted by receivers). Some options are also network-significant (i.e., they must be interpreted by network elements).

Fragmentation MAY be used in conjunction with data packets to allow a transport-layer entity at the source to break up application-layer data packets into multiple PGM data packets to conform with the maximum transmission unit (MTU) supported by the network layer.

Late joining allows a source to indicate whether or not receivers may request all available repairs when they initially join a particular transport session.

Redirection MAY be used in conjunction with Poll Responses to allow a DLR to respond to normal NCFs or POLLs with a redirecting POLR advertising its own address as an alternative re-transmitter to the original source.

FEC techniques MAY be applied by receivers to use source-provided parity packets rather than selective retransmissions to effect loss recovery.

2. Architectural Description

As an end-to-end transport protocol, PGM specifies packet formats and procedures for sources to transmit and for receivers to receive data. To enhance the efficiency of this data transfer, PGM also specifies packet formats and procedures for network elements to improve the reliability of NAKs and to constrain the propagation of repairs. The division of these functions is described in this section and expanded in detail in the next section.

2.1. Source Functions

Data Transmission

Sources multicast ODATA packets to the group within the transmit window at a given transmit rate.

Source Path State

Sources multicast SPMs to the group, interleaved with ODATA if present, to establish source path state in PGM network elements.

NAK Reliability

Sources multicast NCFs to the group in response to any NAKs they receive.

Repairs

Sources multicast RDATA packets to the group in response to NAKs received for data packets within the transmit window.

Transmit Window Advance

Sources MAY advance the trailing edge of the window according to one of a number of strategies. Implementations MAY support automatic adjustments such as keeping the window at a fixed size in bytes, a fixed number of packets or a fixed real time duration. In addition, they MAY optionally delay window advancement based on NAK-silence for a certain period. Some possible strategies are outlined later in this document.

2.2. Receiver Functions

Source Path State

Receivers use SPMs to determine the last-hop PGM network element for a given TSI to which to direct their NAKs.

Data Reception

Receivers receive ODATA within the transmit window and eliminate any duplicates.

Repair Requests

Receivers unicast NAKs to the last-hop PGM network element (and MAY optionally multicast a NAK with TTL of 1 to the local group) for data packets within the receive window detected to be missing from the expected sequence. A receiver MUST repeatedly transmit a given NAK until it receives a matching NCF.

NAK Suppression

Receivers suppress NAKs for which a matching NCF or NAK is received during the NAK transmit back-off interval.

Receive Window Advance

Receivers immediately advance their receive windows upon receipt of any PGM data packet or SPM within the transmit window that advances the receive window.

2.3. Network Element Functions

Network elements forward ODATA without intervention.

Source Path State

Network elements intercept SPMs and use them to establish source path state for the corresponding TSI before multicast forwarding them in the usual way.

NAK Reliability

Network elements multicast NCFs to the group in response to any NAK they receive. For each NAK received, network elements create repair state recording the transport session identifier, the sequence number of the NAK, and the input interface on which the NAK was received.

Constrained NAK Forwarding

Network elements repeatedly unicast forward only the first copy of any NAK they receive to the upstream PGM network element on the distribution path for the TSI until they receive an NCF in response. In addition, they MAY optionally multicast this NAK upstream with TTL of 1.

Nota Bene: Once confirmed by an NCF, network elements discard NAK packets; NAKs are NOT retained in network elements beyond this forwarding operation, but state about the reception of them is stored.

NAK Elimination

Network elements discard exact duplicates of any NAK for which they already have repair state (i.e., that has been forwarded either by themselves or a neighboring PGM network element), and respond with a matching NCF.

Constrained RDATA Forwarding

Network elements use NAKs to maintain repair state consisting of a list of interfaces upon which a given NAK was received, and they forward the corresponding RDATA only on these interfaces.

NAK Anticipation

If a network element hears an upstream NCF (i.e., on the upstream interface for the distribution tree for the TSI), it establishes repair state without outgoing interfaces in anticipation of responding to and eliminating duplicates of the NAK that may arrive from downstream.

3. Terms and Concepts

Before proceeding from the preceding overview to the detail in the subsequent Procedures, this section presents some concepts and definitions that make that detail more intelligible.

3.1. Transport Session Identifiers

Every PGM packet is identified by a:

TSI transport session identifier

TSIs MUST be globally unique, and only one source at a time may act as the source for a transport session. (Note that repairers do not change the TSI in any RDATA they transmit). TSIs are composed of the concatenation of a globally unique source identifier (GSI) and a source-assigned data-source port.

Since all PGM packets originated by receivers are in response to PGM packets originated by a source, receivers simply echo the TSI heard from the source in any corresponding packets they originate.

Since all PGM packets originated by network elements are in response to PGM packets originated by a receiver, network elements simply echo the TSI heard from the receiver in any corresponding packets they originate.

3.2. Sequence Numbers

PGM uses a circular sequence number space from 0 through ((2**32) - 1) to identify and order ODATA packets. Sources MUST number ODATA packets in unit increments in the order in which the corresponding application data is submitted for transmission. Within a transmit or

receive window (defined below), a sequence number x is "less" or "older" than sequence number y if it numbers an ODATA packet preceding ODATA packet y, and a sequence number y is "greater" or "more recent" than sequence number x if it numbers an ODATA packet subsequent to ODATA packet x.

3.3. Transmit Window

The description of the operation of PGM rests fundamentally on the definition of the source-maintained transmit window. This definition in turn is derived directly from the amount of transmitted data (in seconds) a source retains for repair (TXW_SECS), and the maximum transmit rate (in bytes/second) maintained by a source to regulate its bandwidth utilization (TXW_MAX_RTE).

In terms of sequence numbers, the transmit window is the range of sequence numbers consumed by the source for sequentially numbering and transmitting the most recent TXW_SECS of ODATA packets. The trailing (or left) edge of the transmit window (TXW_TRAIL) is defined as the sequence number of the oldest data packet available for repair from a source. The leading (or right) edge of the transmit window (TXW_LEAD) is defined as the sequence number of the most recent data packet a source has transmitted.

The size of the transmit window in sequence numbers (TXW_SQNS) (i.e., the difference between the leading and trailing edges plus one) MUST be no greater than half the PGM sequence number space less one.

When TXW_TRAIL is equal to TXW_LEAD, the transmit window size is one. When TXW_TRAIL is equal to TXW_LEAD plus one, the transmit window size is empty.

3.4. Receive Window

The receive window at the receivers is determined entirely by PGM packets from the source. That is, a receiver simply obeys what the source tells it in terms of window state and advancement.

For a given transport session identified by a TSI, a receiver maintains:

RXW_TRAIL — the sequence number defining the trailing edge of the receive window, the sequence number (known from data packets and SPMs) of the oldest data packet available for repair from the source

RXW_LEAD the sequence number defining the leading edge of the receive window, the greatest sequence number of any received data packet within the transmit window

The receive window is the range of sequence numbers a receiver is expected to use to identify receivable ODATA.

A data packet is described as being "in" the receive window if its sequence number is in the receive window.

The receive window is advanced by the receiver when it receives an SPM or ODATA packet within the transmit window that increments RXW_TRAIL. Receivers also advance their receive windows upon receipt of any PGM data packet within the receive window that advances the receive window.

3.5. Source Path State

To establish the repair state required to constrain RDATA, it's essential that NAKs return from a receiver to a source on the reverse of the distribution tree from the source. That is, they must return through the same sequence of PGM network elements through which the ODATA was forwarded, but in reverse. There are two reasons for this, the less obvious one being by far the more important.

The first and obvious reason is that RDATA is forwarded on the same path as ODATA and so repair state must be established on this path if it is to constrain the propagation of RDATA.

The second and less obvious reason is that in the absence of repair state, PGM network elements do NOT forward RDATA, so the default behavior is to discard repairs. If repair state is not properly established for interfaces on which ODATA went missing, then receivers on those interfaces will continue to NAK for lost data and ultimately experience unrecoverable data loss.

The principle function of SPMs is to provide the source path state required for PGM network elements to forward NAKs from one PGM network element to the next on the reverse of the distribution tree for the TSI, establishing repair state each step of the way. This source path state is simply the address of the upstream PGM network element on the reverse of the distribution tree for the TSI. That upstream PGM network element may be more than one subnet hop away. SPMs establish the identity of the upstream PGM network element on the distribution tree for each TSI in each group in each PGM network element, a sort of virtual PGM topology. So although NAKs are unicast addressed, they are NOT unicast routed by PGM network elements in the conventional sense. Instead PGM network elements use

the source path state established by SPMs to direct NAKs PGM-hop-by-PGM-hop toward the source. The idea is to constrain NAKs to the pure PGM topology spanning the more heterogeneous underlying topology of both PGM and non-PGM network elements.

The result is repair state in every PGM network element between the receiver and the source so that the corresponding RDATA is never discarded by a PGM network element for lack of repair state.

SPMs also maintain transmit window state in receivers by advertising the trailing and leading edges of the transmit window (SPM_TRAIL and SPM_LEAD). In the absence of data, SPMs MAY be used to close the transmit window in time by advancing the transmit window until SPM_TRAIL is equal to SPM_LEAD plus one.

3.6. Packet Contents

This section just provides enough short-hand to make the Procedures intelligible. For the full details of packet contents, please refer to Packet Formats below.

3.6.1. Source Path Messages

3.6.1.1. SPMs

SPMs are transmitted by sources to establish source-path state in PGM network elements, and to provide transmit-window state in receivers.

SPMs are multicast to the group and contain:

SPM_TSI the source-assigned TSI for the session to which the SPM corresponds

SPM_SQN a sequence number assigned sequentially by the source in unit increments and scoped by SPM_TSI

Nota Bene: this is an entirely separate sequence than is used to number ODATA and RDATA.

SPM_TRAIL the sequence number defining the trailing edge of the source's transmit window (TXW_TRAIL)

SPM_LEAD the sequence number defining the leading edge of the source's transmit window (TXW_LEAD)

SPM_PATH the network-layer address (NLA) of the interface on the PGM network element on which the SPM is forwarded

3.6.2. Data Packets

3.6.2.1. ODATA - Original Data

ODATA packets are transmitted by sources to send application data to receivers.

ODATA packets are multicast to the group and contain:

OD_TSI	the globally unique source-assigned TSI
OD_TRAIL	the sequence number defining the trailing edge of the source's transmit window (TXW_TRAIL) OD_TRAIL makes the protocol more robust in the face of lost SPMs. By including the trailing edge of the transmit window on every data packet, receivers that have missed any SPMs that advanced the transmit window can still detect the case, recover the application, and potentially re-synchronize to the transport session.
OD_SQN	a sequence number assigned sequentially by the source in unit increments and scoped by OD_TSI

3.6.2.2. RDATA - Repair Data

RDATA packets are repair packets transmitted by sources or DLRs in response to NAKs.

RDATA packets are multicast to the group and contain:

RD_TSI	OD_TSI of the ODATA packet for which this is a repair
RD_TRAIL	the sequence number defining the trailing edge of the source's transmit window (TXW_TRAIL). This is updated to the most current value when the repair is sent, so it is not necessarily the same as OD_TRAIL of the ODATA packet for which this is a repair
RD_SQN	OD_SQN of the ODATA packet for which this is a repair

3.6.3. Negative Acknowledgments

3.6.3.1. NAKs - Negative Acknowledgments

NAKs are transmitted by receivers to request repairs for missing data packets.

NAKs are unicast (PGM-hop-by-PGM-hop) to the source and contain:

NAK_TSI	OD_TSI of the ODATA packet for which a repair is requested
NAK_SQN	OD_SQN of the ODATA packet for which a repair is requested
NAK_SRC	the unicast NLA of the original source of the missing ODATA.
NAK_GRP	the multicast group NLA

3.6.3.2. NNAKs - Null Negative Acknowledgments

NNAKs are transmitted by a DLR that receives NAKs redirected to it by either receivers or network elements to provide flow-control feedback to a source.

NNAKs are unicast (PGM-hop-by-PGM-hop) to the source and contain:

NNAK_TSI	NAK_TSI of the corresponding re-directed NAK.
NNAK_SQN	NAK_SQN of the corresponding re-directed NAK.
NNAK_SRC	NAK_SRC of the corresponding re-directed NAK.
NNAK_GRP	NAK_GRP of the corresponding re-directed NAK.

3.6.4. Negative Acknowledgment Confirmations

3.6.4.1. NCFs - NAK confirmations

NCFs are transmitted by network elements and sources in response to NAKs.

NCFs are multicast to the group and contain:

NCF_TSI	NAK_TSI of the NAK being confirmed
NCF_SQN	NAK_SQN of the NAK being confirmed
NCF_SRC	NAK_SRC of the NAK being confirmed
NCF_GRP	NAK_GRP of the NAK being confirmed

3.6.5. Option Encodings

OPT_LENGTH	0x00	Option's Length
OPT_FRAGMENT	0x01	Fragmentation
OPT_NAK_LIST	0x02	List of NAK entries
OPT_JOIN	0x03	Late Joining
OPT_REDIRECT	0x07	Redirect
OPT_SYN	0x0D	Synchronization
OPT_FIN	0x0E	Session Fin receivers, conventional feedbackish
OPT_RST	0x0F	Session Reset
OPT_PARITY_PRM	0x08	Forward Error Correction Parameters
OPT_PARITY_GRP	0x09	Forward Error Correction Group Number
OPT_CURR_TGSIZE	0x0A	Forward Error Correction Group Size
OPT_CR	0x10	Congestion Report
OPT_CRQST	0x11	Congestion Report Request
OPT_NAK_BO_IVL	0x04	NAK Back-Off Interval
OPT_NAK_BO_RNG	0x05	NAK Back-Off Range
OPT_NBR_UNREACH	0x0B	Neighbor Unreachable
OPT_PATH_NLA	0x0C	Path NLA
OPT_INVALID	0x7F	Option invalidated

4. Procedures - General

Since SPMs, NCFs, and RDATA must be treated conditionally by PGM network elements, they must be distinguished from other packets in the chosen multicast network protocol if PGM network elements are to extract them from the usual switching path.

The most obvious way for network elements to achieve this is to examine every packet in the network for the PGM transport protocol and packet types. However, the overhead of this approach is costly for high-performance, multi-protocol network elements. An alternative, and a requirement for PGM over IP multicast, is that SPMs, NCFs, and RDATA MUST be transmitted with the IP Router Alert Option [6]. This option gives network elements a network-layer indication that a packet should be extracted from IP switching for more detailed processing.

5. Procedures - Sources

5.1. Data Transmission

Since PGM relies on a purely rate-limited transmission strategy in the source to bound the bandwidth consumed by PGM transport sessions, an assortment of techniques is assembled here to make that strategy as conservative and robust as possible. These techniques are the minimum REQUIRED of a PGM source.

5.1.1. Maximum Cumulative Transmit Rate

A source MUST number ODATA packets in the order in which they are submitted for transmission by the application. A source MUST transmit ODATA packets in sequence and only within the transmit window beginning with TXW_TRAIL at no greater a rate than TXW_MAX_RTE.

TXW_MAX_RTE is typically the maximum cumulative transmit rate of SPM, ODATA, and RDATA. Different transmission strategies MAY define TXW_MAX_RTE as appropriate for the implementation.

5.1.2. Transmit Rate Regulation

To regulate its transmit rate, a source MUST use a token bucket scheme or any other traffic management scheme that yields equivalent behavior. A token bucket [7] is characterized by a continually sustainable data rate (the token rate) and the extent to which the data rate may exceed the token rate for short periods of time (the token bucket size). Over any arbitrarily chosen interval, the number of bytes the source may transmit MUST NOT exceed the token bucket size plus the product of the token rate and the chosen interval.

In addition, a source MUST bound the maximum rate at which successive packets may be transmitted using a leaky bucket scheme drained at a maximum transmit rate, or equivalent mechanism.

5.1.3. Outgoing Packet Ordering

To preserve the logic of PGM's transmit window, a source MUST strictly prioritize sending of pending NCFs first, pending SPMs second, and only send ODATA or RDATA when no NCFs or SPMs are pending. The priority of RDATA versus ODATA is application dependent. The sender MAY implement weighted bandwidth sharing between RDATA and ODATA. Note that strict prioritization of RDATA over ODATA may stall progress of ODATA if there are receivers that keep generating NAKs so as to always have RDATA pending (e.g. a steady stream of late joiners with OPT_JOIN). Strictly prioritizing ODATA over RDATA may lead to a larger portion of receivers getting unrecoverable losses.

5.1.4. Ambient SPMs

Interleaved with ODATA and RDATA, a source MUST transmit SPMs at a rate at least sufficient to maintain current source path state in PGM network elements. Note that source path state in network elements does not track underlying changes in the distribution tree from a source until an SPM traverses the altered distribution tree. The consequence is that NAKs may go unconfirmed both at receivers and amongst network elements while changes in the underlying distribution tree take place.

5.1.5. Heartbeat SPMs

In the absence of data to transmit, a source SHOULD transmit SPMs at a decaying rate in order to assist early detection of lost data, to maintain current source path state in PGM network elements, and to maintain current receive window state in the receivers.

In this scheme [8], a source maintains an inter-heartbeat timer IHB_TMR which times the interval between the most recent packet (ODATA, RDATA, or SPM) transmission and the next heartbeat transmission. IHB_TMR is initialized to a minimum interval IHB_MIN after the transmission of any data packet. If IHB_TMR expires, the source transmits a heartbeat SPM and initializes IHB_TMR to double its previous value. The transmission of consecutive heartbeat SPMs doubles IHB each time up to a maximum interval IHB_MAX. The transmission of any data packet initializes IHB_TMR to IHB_MIN once again. The effect is to provoke prompt detection of missing packets in the absence of data to transmit, and to do so with minimal bandwidth overhead.

5.1.6. Ambient and Heartbeat SPMs

Ambient and heartbeat SPMs are described as driven by separate timers in this specification to highlight their contrasting functions. Ambient SPMs are driven by a count-down timer that expires regularly while heartbeat SPMs are driven by a count-down timer that keeps being reset by data, and the interval of which changes once it begins to expire. The ambient SPM timer is just counting down in real-time while the heartbeat timer is measuring the inter-data-packet interval.

In the presence of data, no heartbeat SPMs will be transmitted since the transmission of data keeps setting the IHB_TMR back to its initial value. At the same time however, ambient SPMs MUST be interleaved into the data as a matter of course, not necessarily as a heartbeat mechanism. This ambient transmission of SPMs is REQUIRED to keep the distribution tree information in the network current and to allow new receivers to synchronize with the session.

An implementation SHOULD de-couple ambient and heartbeat SPM timers sufficiently to permit them to be configured independently of each other.

5.2. Negative Acknowledgment Confirmation

A source MUST immediately multicast an NCF in response to any NAK it receives. The NCF is REQUIRED since the alternative of responding immediately with RDATA would not allow other PGM network elements on the same subnet to do NAK anticipation, nor would it allow DLRs on the same subnet to provide repairs. A source SHOULD be able to detect a NAK storm and adopt countermeasure to protect the network against a denial of service. A possible countermeasure is to send the first NCF immediately in response to a NAK and then delay the generation of further NCFs (for identical NAKs) by a small interval, so that identical NCFs are rate-limited, without affecting the ability to suppress NAKs.

5.3. Repairs

After multicasting an NCF in response to a NAK, a source MUST then multicast RDATA (while respecting TXW_MAX_RTE) in response to any NAK it receives for data packets within the transmit window.

In the interest of increasing the efficiency of a particular RDATA packet, a source MAY delay RDATA transmission to accommodate the arrival of NAKs from the whole loss neighborhood. This delay SHOULD not exceed twice the greatest propagation delay in the loss neighborhood.

6. Procedures - Receivers

6.1. Data Reception

Initial data reception

A receiver SHOULD initiate data reception beginning with the first data packet it receives within the advertised transmit window. This packet's sequence number (ODATA_SQN) temporarily defines the trailing edge of the transmit window from the receiver's perspective. That is, it is assigned to RXW_TRAIL_INIT within the receiver, and until the trailing edge sequence number advertised in subsequent packets (SPMs or ODATA or RDATA) increments past RXW_TRAIL_INIT, the receiver MUST only request repairs for sequence numbers subsequent to RXW_TRAIL_INIT. Thereafter, it MAY request repairs anywhere in the transmit window. This temporary restriction on repair requests prevents receivers from requesting a potentially large amount of history when they first begin to receive a given PGM transport session.

Note that the JOIN option, discussed later, MAY be used to provide a different value for RXW_TRAIL_INIT.

Receiving and discarding data packets

Within a given transport session, a receiver MUST accept any ODATA or RDATA packets within the receive window. A receiver MUST discard any data packet that duplicates one already received in the transmit window. A receiver MUST discard any data packet outside of the receive window.

Contiguous data

Contiguous data is comprised of those data packets within the receive window that have been received and are in the range from RXW_TRAIL up to (but not including) the first missing sequence number in the receive window. The most recently received data packet of contiguous data defines the leading edge of contiguous data.

As its default mode of operation, a receiver MUST deliver only contiguous data packets to the application, and it MUST do so in the order defined by those data packets' sequence numbers. This provides applications with a reliable ordered data flow.

Non contiguous data

PGM receiver implementations MAY optionally provide a mode of operation in which data is delivered to an application in the order received. However, the implementation MUST only deliver complete application protocol data units (APDUs) to the application. That is, APDUs that have been fragmented into different TPDUs MUST be reassembled before delivery to the application.

6.2. Source Path Messages

Receivers MUST receive and sequence SPMs for any TSI they are receiving. An SPM is in sequence if its sequence number is greater than that of the most recent in-sequence SPM and within half the PGM number space. Out-of-sequence SPMs MUST be discarded.

For each TSI, receivers MUST use the most recent SPM to determine the NLA of the upstream PGM network element for use in NAK addressing. A receiver MUST NOT initiate repair requests until it has received at least one SPM for the corresponding TSI.

Since SPMs require per-hop processing, it is likely that they will be forwarded at a slower rate than data, and that they will arrive out of sync with the data stream. In this case, the window information that the SPMs carry will be out of date. Receivers SHOULD expect this to be the case and SHOULD detect it by comparing the packet lead and trail values with the values the receivers have stored for lead and trail. If the SPM packet values are less, they SHOULD be ignored, but the rest of the packet SHOULD be processed as normal.

6.3. Data Recovery by Negative Acknowledgment

Detecting missing data packets

Receivers MUST detect gaps in the expected data sequence in the following manners:

- by comparing the sequence number on the most recently received ODATA or RDATA packet with the leading edge of contiguous data

- by comparing SPM_LEAD of the most recently received SPM with the leading edge of contiguous data

In both cases, if the receiver has not received all intervening data packets, it MAY initiate selective NAK generation for each missing sequence number.

In addition, a receiver may detect a single missing data packet by receiving an NCF or multicast NAK for a data packet within the transmit window which it has not received. In this case it MAY initiate selective NAK generation for the said sequence number.

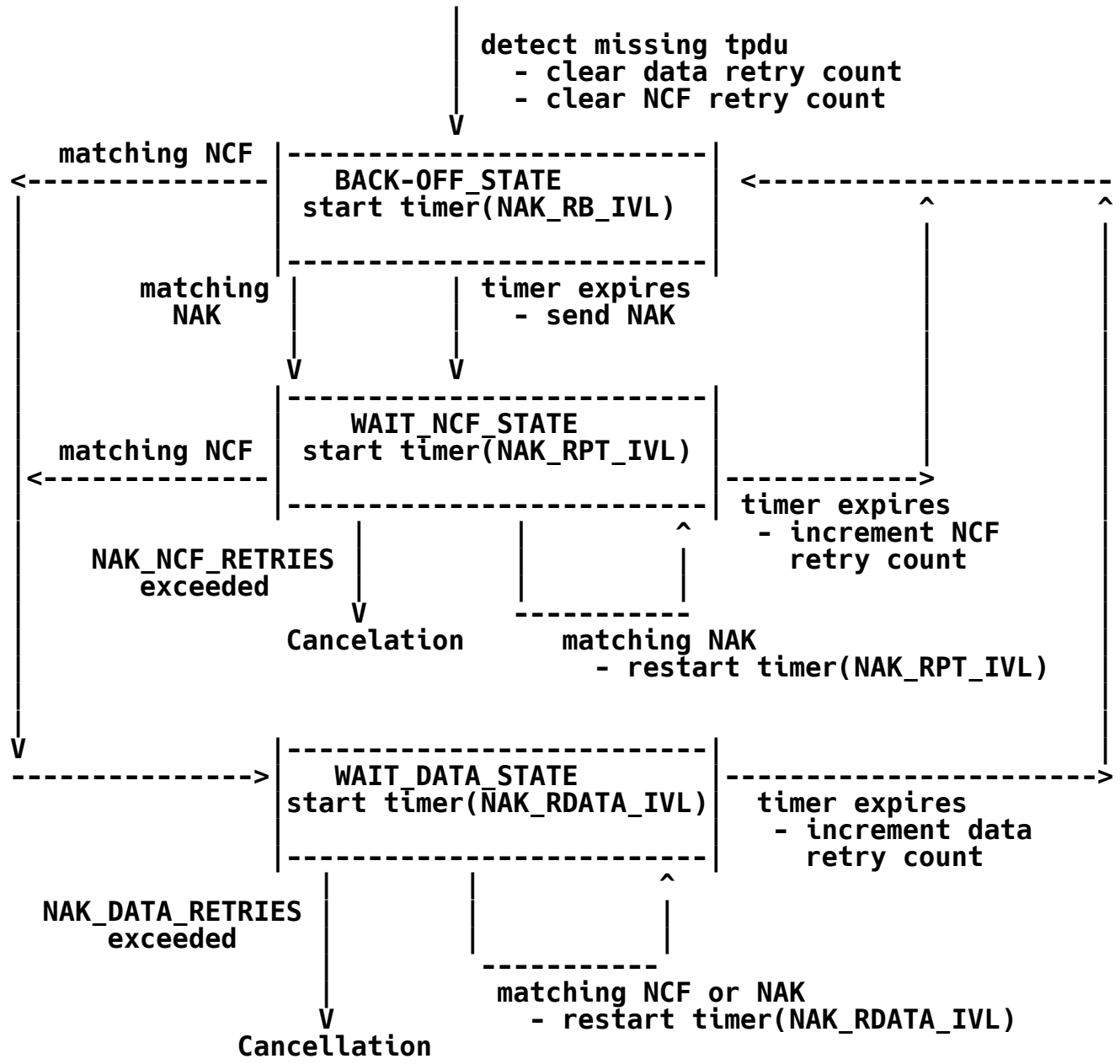
In all cases, receivers SHOULD temper the initiation of NAK generation to account for simple mis-ordering introduced by the network. A possible mechanism to achieve this is to assume loss only after the reception of N packets with sequence numbers higher than those of the (assumed) lost packets. A possible value for N is 2. This method SHOULD be complemented with a timeout based mechanism that handles the loss of the last packet before a pause in the transmission of the data stream. The leading edge field in SPMs SHOULD also be taken into account in the loss detection algorithm.

Generating NAKs

NAK generation follows the detection of a missing data packet and is the cycle of:

- waiting for a random period of time (NAK_RB_IVL) while listening for matching NCFs or NAKs
- transmitting a NAK if a matching NCF or NAK is not heard
- waiting a period (NAK_RPT_IVL) for a matching NCF and recommencing NAK generation if the matching NCF is not received
- waiting a period (NAK_RDATA_IVL) for data and recommencing NAK generation if the matching data is not received

The entire generation process can be summarized by the following state machine:



In any state, receipt of matching RDATA or ODATA completes data recovery and successful exit from the state machine. State transition stops any running timers.

In any state, if the trailing edge of the window moves beyond the sequence number, data recovery for that sequence number terminates.

During NAK_RB_IVL a NAK is said to be pending. When awaiting data or an NCF, a NAK is said to be outstanding.

Backing off NAK transmission

Before transmitting a NAK, a receiver MUST wait some interval NAK_RB_IVL chosen randomly over some time period NAK_BO_IVL. During this period, receipt of a matching NAK or a matching NCF will suspend NAK generation. NAK_RB_IVL is counted down from the time a missing data packet is detected.

A value for NAK_BO_IVL learned from OPT_NAK_BO_IVL (see 16.4.1 below) MUST NOT be used by a receiver (i.e., the receiver MUST NOT NAK) unless either NAK_BO_IVL_SQN is zero, or the receiver has seen POLL_RND == 0 for POLL_SQN =< NAK_BO_IVL_SQN within half the sequence number space.

When a parity NAK (Appendix A, FEC) is being generated, the back-off interval SHOULD be inversely biased with respect to the number of parity packets requested. This way NAKs requesting larger numbers of parity packets are likely to be sent first and thus suppress other NAKs. A NAK for a given transmission group suppresses another NAK for the same transmission group only if it is requesting an equal or larger number of parity packets.

When a receiver has to transmit a sequence of NAKs, it SHOULD transmit the NAKs in order from oldest to most recent.

Suspending NAK generation

Suspending NAK generation just means waiting for either NAK_RB_IVL, NAK_RPT_IVL or NAK_RDATA_IVL to pass. A receiver MUST suspend NAK generation if a duplicate of the NAK is already pending from this receiver or the NAK is already outstanding from this or another receiver.

NAK suppression

A receiver MUST suppress NAK generation and wait at least NAK_RDATA_IVL before recommencing NAK generation if it hears a matching NCF or NAK during NAK_RB_IVL. A matching NCF must match NCF_TSI with NAK_TSI, and NCF_SQN with NAK_SQN.

Transmitting a NAK

Upon expiry of NAK_RB_IVL, a receiver MUST unicast a NAK to the upstream PGM network element for the TSI specifying the transport session identifier and missing sequence number. In addition, it MAY

multicast a NAK with TTL of 1 to the group, if the PGM parent is not directly connected. It also records both the address of the source of the corresponding ODATA and the address of the group in the NAK header.

It MUST repeat the NAK at a rate governed by NAK_RPT_IVL up to NAK_NCF_RETRIES times while waiting for a matching NCF. It MUST then wait NAK_RDATA_IVL before recommencing NAK generation. If it hears a matching NCF or NAK during NAK_RDATA_IVL, it MUST wait anew for NAK_RDATA_IVL before recommencing NAK generation (i.e. matching NCFs and NAKs restart NAK_RDATA_IVL).

Completion of NAK generation

NAK generation is complete only upon the receipt of the matching RDATA (or even ODATA) packet at any time during NAK generation.

Cancellation of NAK generation

NAK generation is cancelled upon the advancing of the receive window so as to exclude the matching sequence number of a pending or outstanding NAK, or NAK_DATA_RETRIES / NAK_NCF_RETRIES being exceeded. Cancellation of NAK generation indicates unrecoverable data loss.

Receiving NCFs and multicast NAKs

A receiver MUST discard any NCFs or NAKs it hears for data packets outside the transmit window or for data packets it has received. Otherwise they are treated as appropriate for the current repair state.

7. Procedures - Network Elements

7.1. Source Path State

Upon receipt of an in-sequence SPM, a network element records the Source Path Address SPM_PATH with the multicast routing information for the TSI. If the receiving network element is on the same subnet as the forwarding network element, this address will be the same as the address of the immediately upstream network element on the distribution tree for the TSI. If, however, non-PGM network elements intervene between the forwarding and the receiving network elements, this address will be the address of the first PGM network element across the intervening network elements.

The network element then forwards the SPM on each outgoing interface for that TSI. As it does so, it encodes the network address of the outgoing interface in SPM_PATH in each copy of the SPM it forwards.

7.2. NAK Confirmation

Network elements MUST immediately transmit an NCF in response to any unicast NAK they receive. The NCF MUST be multicast to the group on the interface on which the NAK was received.

> Nota Bene: In order to avoid creating multicast routing state for PGM network elements across non-PGM-capable clouds, the network-header source address of NCFs transmitted by network elements MUST be set to the ODATA source's NLA, not the network element's NLA as might be expected.

Network elements should be able to detect a NAK storm and adopt counter-measure to protect the network against a denial of service. A possible countermeasure is to send the first NCF immediately in response to a NAK and then delay the generation of further NCFs (for identical NAKs) by a small interval, so that identical NCFs are rate-limited, without affecting the ability to suppress NAKs.

Simultaneously, network elements MUST establish repair state for the NAK if such state does not already exist, and add the interface on which the NAK was received to the corresponding repair interface list if the interface is not already listed.

7.3. Constrained NAK Forwarding

The NAK forwarding procedures for network elements are quite similar to those for receivers, but three important differences should be noted.

First, network elements do NOT back off before forwarding a NAK (i.e., there is no NAK_BO_IVL) since the resulting delay of the NAK would compound with each hop. Note that NAK arrivals will be randomized by the receivers from which they originate, and this factor in conjunction with NAK anticipation and elimination will combine to forestall NAK storms on subnets with a dense network element population.

Second, network elements do NOT retry confirmed NAKs if RDATA is not seen; they simply discard the repair state and rely on receivers to re-request the repair. This approach keeps the repair state in the network elements relatively ephemeral and responsive to underlying routing changes.

Third, note that ODATA does NOT cancel NAK forwarding in network elements since it is switched by network elements without transport-layer intervention.

> Nota Bene: Once confirmed by an NCF, network elements discard NAK packets; they are NOT retained in network elements beyond this forwarding operation.

NAK forwarding requires that a network element listen to NCFs for the same transport session. NAK forwarding also requires that a network element observe two time out intervals for any given NAK (i.e., per NAK_TSI and NAK_SQN): NAK_RPT_IVL and NAK_RDATA_IVL.

The NAK repeat interval NAK_RPT_IVL, limits the length of time for which a network element will repeat a NAK while waiting for a corresponding NCF. NAK_RPT_IVL is counted down from the transmission of a NAK. Expiry of NAK_RPT_IVL cancels NAK forwarding (due to missing NCF).

The NAK RDATA interval NAK_RDATA_IVL, limits the length of time for which a network element will wait for the corresponding RDATA. NAK_RDATA_IVL is counted down from the time a matching NCF is received. Expiry of NAK_RDATA_IVL causes the network element to discard the corresponding repair state (due to missing RDATA).

During NAK_RPT_IVL, a NAK is said to be pending. During NAK_RDATA_IVL, a NAK is said to be outstanding.

A Network element MUST forward NAKs only to the upstream PGM network element for the TSI.

A network element MUST repeat a NAK at a rate of NAK_RPT_RTE for an interval of NAK_RPT_IVL until it receives a matching NCF. A matching NCF must match NCF_TSI with NAK_TSI, and NCF_SQN with NAK_SQN.

Upon reception of the corresponding NCF, network elements MUST wait at least NAK_RDATA_IVL for the corresponding RDATA. Receipt of the corresponding RDATA at any time during NAK forwarding cancels NAK forwarding and tears down the corresponding repair state in the network element.

7.4. NAK elimination

Two NAKs duplicate each other if they bear the same NAK_TSI and NAK_SQN. Network elements MUST discard all duplicates of a NAK that is pending.

Once a NAK is outstanding, network elements MUST discard all duplicates of that NAK for NAK_ELIM_IVL. Upon expiry of NAK_ELIM_IVL, network elements MUST suspend NAK elimination for that TSI/SQN until the first duplicate of that NAK is seen after the expiry of NAK_ELIM_IVL. This duplicate MUST be forwarded in the usual manner. Once this duplicate NAK is outstanding, network elements MUST once again discard all duplicates of that NAK for NAK_ELIM_IVL, and so on. NAK_RDATA_IVL MUST be reset each time a NAK for the corresponding TSI/SQN is confirmed (i.e., each time NAK_ELIM_IVL is reset). NAK_ELIM_IVL MUST be some small fraction of NAK_RDATA_IVL.

NAK_ELIM_IVL acts to balance implosion prevention against repair state liveness. That is, it results in the elimination of all but at most one NAK per NAK_ELIM_IVL thereby allowing repeated NAKs to keep the repair state alive in the PGM network elements.

7.5. NAK Anticipation

An unsolicited NCF is one that is received by a network element when the network element has no corresponding pending or outstanding NAK. Network elements MUST process unsolicited NCFs differently depending on the interface on which they are received.

If the interface on which an NCF is received is the same interface the network element would use to reach the upstream PGM network element, the network element simply establishes repair state for NCF_TSI and NCF_SQN without adding the interface to the repair interface list, and discards the NCF. If the repair state already exists, the network element restarts the NAK_RDATA_IVL and NAK_ELIM_IVL timers and discards the NCF.

If the interface on which an NCF is received is not the same interface the network element would use to reach the upstream PGM network element, the network element does not establish repair state and just discards the NCF.

Anticipated NAKs permit the elimination of any subsequent matching NAKs from downstream. Upon establishing anticipated repair state, network elements MUST eliminate subsequent NAKs only for a period of NAK_ELIM_IVL. Upon expiry of NAK_ELIM_IVL, network elements MUST suspend NAK elimination for that TSI/SQN until the first duplicate of that NAK is seen after the expiry of NAK_ELIM_IVL. This duplicate MUST be forwarded in the usual manner. Once this duplicate NAK is outstanding, network elements MUST once again discard all duplicates of that NAK for NAK_ELIM_IVL, and so on. NAK_RDATA_IVL MUST be reset

each time a NAK for the corresponding TSI/SQN is confirmed (i.e., each time NAK_ELIM_IVL is reset). NAK_ELIM_IVL must be some small fraction of NAK_RDATA_IVL.

7.6. NAK Shedding

Network elements MAY implement local procedures for withholding NAK confirmations for receivers detected to be reporting excessive loss. The result of these procedures would ultimately be unrecoverable data loss in the receiver.

7.7. Addressing NAKs

A PGM network element uses the source and group addresses (NLAs) contained in the transport header to find the state for the corresponding TSI, looks up the corresponding upstream PGM network element's address, uses it to re-address the (unicast) NAK, and unicasts it on the upstream interface for the distribution tree for the TSI.

7.8. Constrained RDATA Forwarding

Network elements MUST maintain repair state for each interface on which a given NAK is received at least once. Network elements MUST then use this list of interfaces to constrain the forwarding of the corresponding RDATA packet only to those interfaces in the list. An RDATA packet corresponds to a NAK if it matches NAK_TSI and NAK_SQN.

Network elements MUST maintain this repair state only until either the corresponding RDATA is received and forwarded, or NAK_RDATA_IVL passes after forwarding the most recent instance of a given NAK. Thereafter, the corresponding repair state MUST be discarded.

Network elements SHOULD discard and not forward RDATA packets for which they have no repair state. Note that the consequence of this procedure is that, while it constrains repairs to the interested subset of the network, loss of repair state precipitates further NAKs from neglected receivers.

8. Packet Formats

All of the packet formats described in this section are transport-layer headers that MUST immediately follow the network-layer header in the packet. Only data packet headers (ODATA and RDATA) may be followed in the packet by application data. For each packet type, the network-header source and destination addresses are specified in

addition to the format and contents of the transport layer header. Recall from General Procedures that, for PGM over IP multicast, SPMs, NCFs, and RDATA MUST also bear the IP Router Alert Option.

For PGM over IP, the IP protocol number is 113.

In all packets the descriptions of Data-Source Port, Data-Destination Port, Type, Options, Checksum, Global Source ID (GSI), and Transport Service Data Unit (TSDU) Length are:

Data-Source Port:

A random port number generated by the source. This port number MUST be unique within the source. Source Port together with Global Source ID forms the TSI.

Data-Destination Port:

A globally well-known port number assigned to the given PGM application.

Type:

The high-order two bits of the Type field encode a version number, 0x0 in this instance. The low-order nibble of the type field encodes the specific packet type. The intervening two bits (the low-order two bits of the high-order nibble) are reserved and MUST be zero.

Within the low-order nibble of the Type field:

values in the range 0x0 through 0x3 represent SPM-like packets (i.e., session-specific, sourced by a source, periodic),

values in the range 0x4 through 0x7 represent DATA-like packets (i.e., data and repairs),

values in the range 0x8 through 0xB represent NAK-like packets (i.e., hop-by-hop reliable NAK forwarding procedures),

and values in the range 0xC through 0xF represent SPMR-like packets (i.e., session-specific, sourced by a receiver, asynchronous).

Options:

This field encodes binary indications of the presence and significance of any options. It also directly encodes some options.

bit 0 set => One or more Option Extensions are present

bit 1 set => One or more Options are network-significant

Note that this bit is clear when OPT_FRAGMENT and/or OPT_JOIN are the only options present.

bit 6 set => Packet is a parity packet for a transmission group of variable sized packets (OPT_VAR_PKTLEN). Only present when OPT_PARITY is also present.

bit 7 set => Packet is a parity packet (OPT_PARITY)

Bits are numbered here from left (0 = MSB) to right (7 = LSB).

All the other options (option extensions) are encoded in extensions to the PGM header.

Checksum:

This field is the usual 1's complement of the 1's complement sum of the entire PGM packet including header.

The checksum does not include a network-layer pseudo header for compatibility with network address translation. If the computed checksum is zero, it is transmitted as all ones. A value of zero in this field means the transmitter generated no checksum.

Note that if any entity between a source and a receiver modifies the PGM header for any reason, it MUST either recompute the checksum or clear it. The checksum is mandatory on data packets (ODATA and RDATA).

Global Source ID:

A globally unique source identifier. This ID MUST NOT change throughout the duration of the transport session. A RECOMMENDED identifier is the low-order 48 bits of the MD5 [9] signature of the DNS name of the source. Global Source ID together with Data-Source Port forms the TSI.

TSDU Length:

The length in octets of the transport data unit exclusive of the transport header.

Note that those who require the TPDU length must obtain it from sum of the transport header length (TH) and the TSDU length. TH length is the sum of the size of the particular PGM packet header (type_specific_size) plus the length of any options that might be present.

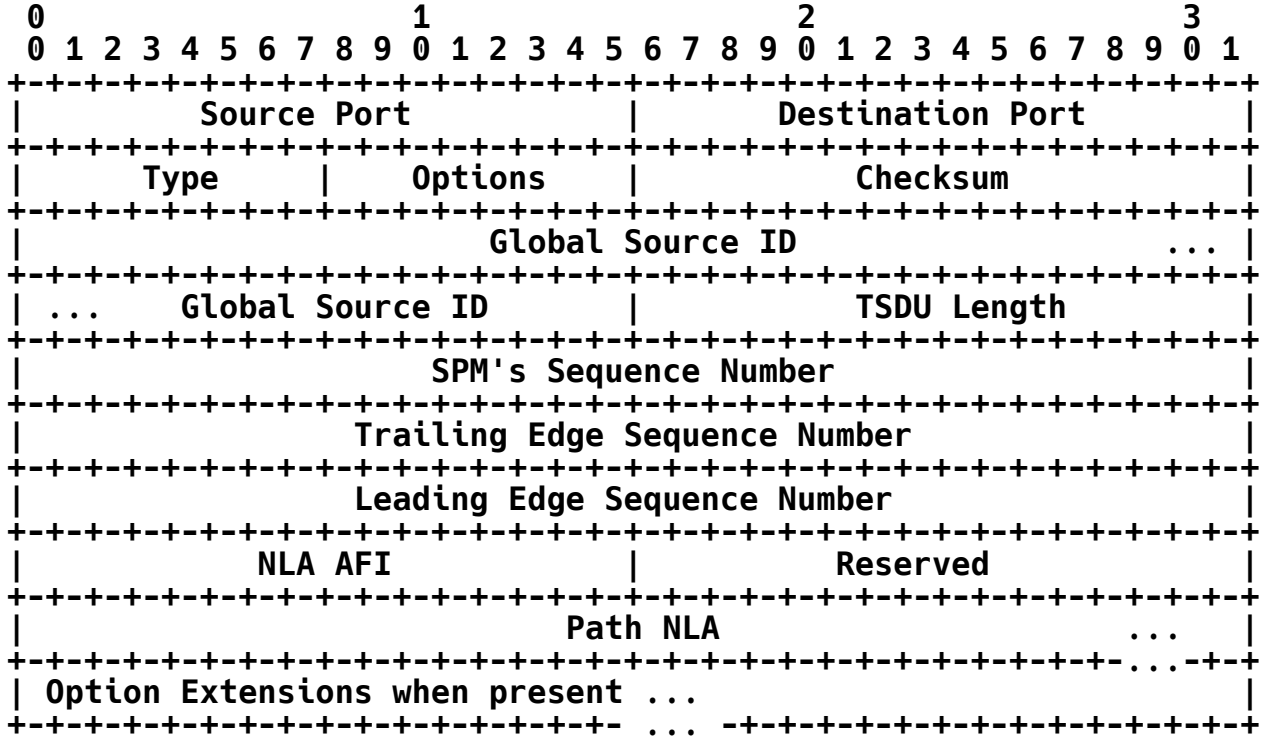
Address Family Indicators (AFIs) are as specified in [10].

8.1. Source Path Messages

SPMs are sent by a source to establish source path state in network elements and to provide transmit window state to receivers.

The network-header source address of an SPM is the unicast NLA of the entity that originates the SPM.

The network-header destination address of an SPM is a multicast group NLA.



Source Port:

SPM_SPORT

Data-Source Port, together with SPM_GSI forms SPM_TSI

Destination Port:

SPM_DPORT

Data-Destination Port

Type:

SPM_TYPE = 0x00

Global Source ID:

SPM_GSI

Together with SPM_SPORT forms SPM_TSI

SPM's Sequence Number

SPM_SQN

The sequence number assigned to the SPM by the source.

Trailing Edge Sequence Number:

SPM_TRAIL

The sequence number defining the current trailing edge of the source's transmit window (TXW_TRAIL).

Leading Edge Sequence Number:

SPM_LEAD

The sequence number defining the current leading edge of the source's transmit window (TXW_LEAD).

If SPM_TRAIL == 0 and SPM_LEAD == 0x80000000, this indicates that no window information is present in the packet.

Path NLA:

SPM_PATH

The NLA of the interface on the network element on which this SPM was forwarded. Initialized by a source to the source's NLA, rewritten by each PGM network element upon forwarding.

8.2. Data Packets

Data packets carry application data from a source or a repairer to receivers.

ODATA:

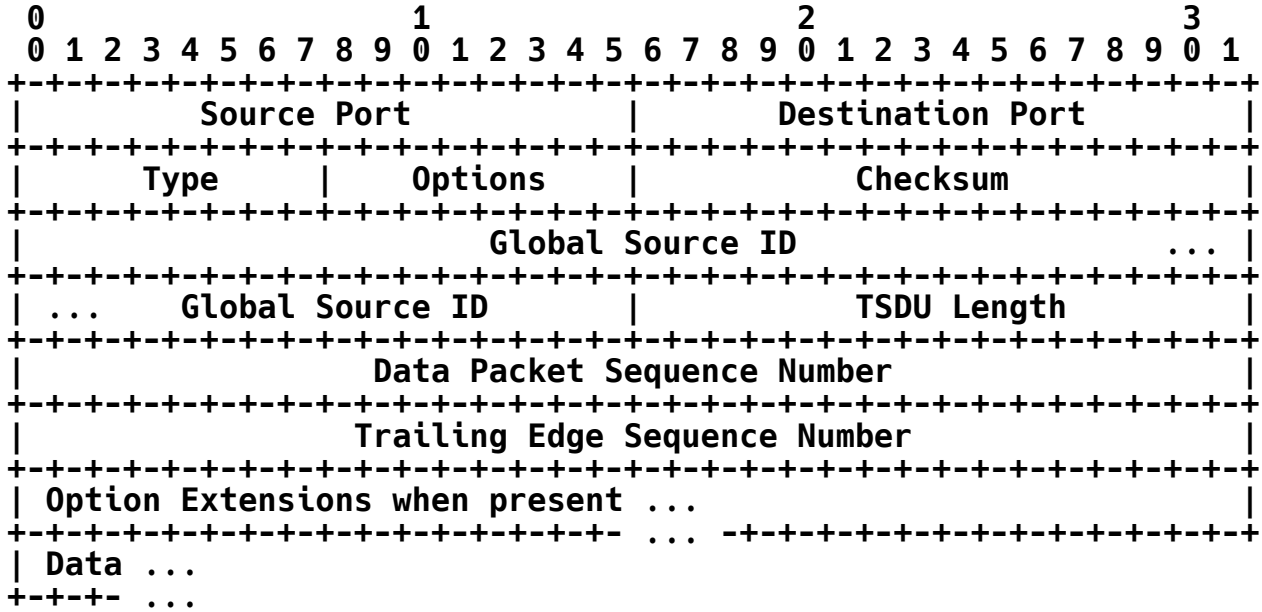
Original data packets transmitted by a source.

RDATA:

Repairs transmitted by a source or by a designated local repairer (DLR) in response to a NAK.

The network-header source address of a data packet is the unicast NLA of the entity that originates the data packet.

The network-header destination address of a data packet is a multicast group NLA.



Source Port:

OD_SPORT, RD_SPORT

Data-Source Port, together with Global Source ID forms:

OD_TSI, RD_TSI

Destination Port:

OD_DPORT, RD_DPORT

Data-Destination Port

Type:

OD_TYPE = 0x04 RD_TYPE = 0x05

Global Source ID:

OD_GSI, RD_GSI

Together with Source Port forms:

OD_TSI, RD_TSI

Data Packet Sequence Number:

OD_SQN, RD_SQN

The sequence number originally assigned to the ODATA packet by the source.

Trailing Edge Sequence Number:

OD_TRAIL, RD_TRAIL

The sequence number defining the current trailing edge of the source's transmit window (TXW_TRAIL). In RDATA, this MAY not be the same as OD_TRAIL of the ODATA packet for which it is a repair.

Data:

Application data.

8.3. Negative Acknowledgments and Confirmations

NAK:

Negative Acknowledgments are sent by receivers to request the repair of an ODATA packet detected to be missing from the expected sequence.

N-NAK:

Null Negative Acknowledgments are sent by DLRs to provide flow control feedback to the source of ODATA for which the DLR has provided the corresponding RDATA.

The network-header source address of a NAK is the unicast NLA of the entity that originates the NAK. The network-header source address of NAK is rewritten by each PGM network element with its own.

The network-header destination address of a NAK is initialized by the originator of the NAK (a receiver) to the unicast NLA of the upstream PGM network element known from SPMs. The network-header destination address of a NAK is rewritten by each PGM network element with the unicast NLA of the upstream PGM network element to which this NAK is forwarded. On the final hop, the network-header destination address of a NAK is rewritten by the PGM network element with the unicast NLA of the original source or the unicast NLA of a DLR.

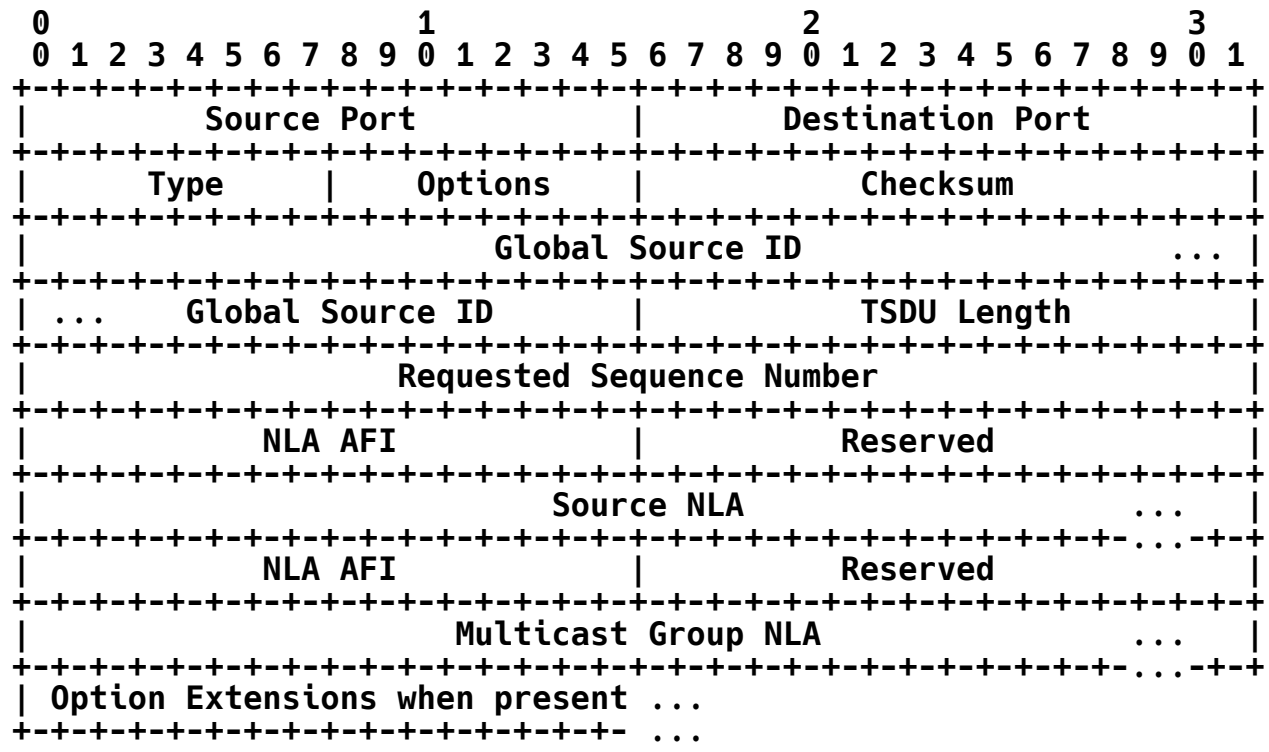
NCF:

NAK Confirmations are sent by network elements and sources to confirm the receipt of a NAK.

The network-header source address of an NCF is the ODATA source's NLA, not the network element's NLA as might be expected.

The network-header destination address of an NCF is a multicast group NLA.

Note that in NAKs and N-NAKs, unlike the other packets, the field SPORT contains the Data-Destination port and the field DPORT contains the Data-Source port. As a general rule, the content of SPORT/DPORT is determined by the direction of the flow: in packets which travel down-stream SPORT is the port number chosen in the data source (Data-Source Port) and DPORT is the data destination port number (Data-Destination Port). The opposite holds for packets which travel upstream. This makes DPORT the protocol endpoint in the recipient host, regardless of the direction of the packet.



Source Port:

NAK_SPORT, NNAK_SPORT

Data-Destination Port

NCF_SPORT

Data-Source Port, together with Global Source ID forms NCF_TSI

Destination Port:

NAK_DPORT, NNAK_DPORT

Data-Source Port, together with Global Source ID forms:

NAK_TSI, NNAK_TSI

NCF_DPORT

Data-Destination Port

Type:

NAK_TYPE = 0x08 NNAK_TYPE = 0x09

NCF_TYPE = 0x0A

Global Source ID:

NAK_GSI, NNAK_GSI, NCF_GSI

Together with Data-Source Port forms

NAK_TSI, NNAK_TSI, NCF_TSI

Requested Sequence Number:

NAK_SQN, NNAK_SQN

NAK_SQN is the sequence number of the ODATA packet for which a repair is requested.

NNAK_SQN is the sequence number of the RDATA packet for which a repair has been provided by a DLR.

NCF_SQN

NCF_SQN is NAK_SQN from the NAK being confirmed.

Source NLA:

NAK_SRC, NNAK_SRC, NCF_SRC

The unicast NLA of the original source of the missing ODATA.

Multicast Group NLA:

NAK_GRP, NNAK_GRP, NCF_GRP

The multicast group NLA. NCFs MAY bear OPT_REDIRECT and/or OPT_NAK_LIST

9. Options

PGM specifies several end-to-end options to address specific application requirements. PGM specifies options to support fragmentation, late joining, and redirection.

Options MAY be appended to PGM data packet headers only by their original transmitters. While they MAY be interpreted by network elements, options are neither added nor removed by network elements.

Options are all in the TLV style, or Type, Length, Value. The Type field is contained in the first byte, where bit 0 is the OPT_END bit, followed by 7 bits of type. The OPT_END bit MUST be set in the last option in the option list, whichever that might be. The Length field is the total length of the option in bytes, and directly follows the Type field. Following the Length field are 5 reserved bits, the OP_ENCODED flag, the 2 Option Extensibility bits OPX and the OP_ENCODED_NULL flag. Last are 7 bits designated for option specific information which may be defined on a per-option basis. If not defined for a particular option, they MUST be set to 0.

The Option Extensibility bits dictate the desired treatment of an option if it is unknown to the network element processing it.

Nota Bene: Only network elements pay any attention to these bits.

The OPX bits are defined as follows:

00 - Ignore the option

01 - Invalidate the option by changing the type to OPT_INVALID = 0x7F

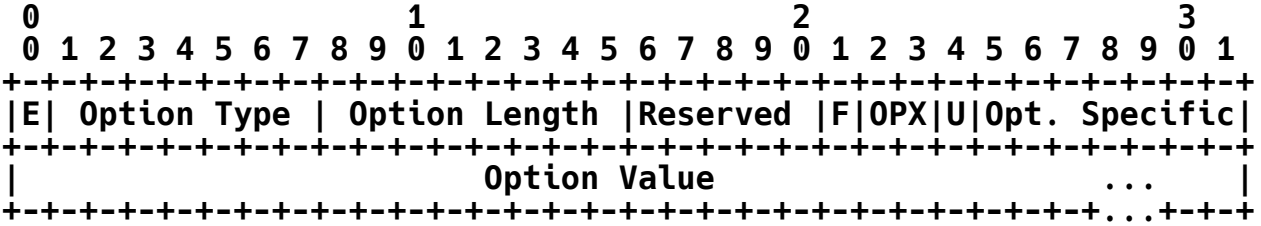
10 - Discard the packet

11 - Unsupported, and reserved for future use

Some options present in data packet (ODATA and RDATA) are strictly associated with the packet content (PGM payload), OPT_FRAGMENT being an example. These options must be preserved even when the data packet that would normally contain them is not received, but its the payload is recovered though the use of FEC. PGM specifies a mechanism to accomplish this that uses the F (OP_ENCODED) and U (OP_ENCODED_NULL) bits in the option common header. OP_ENCODED and OP_ENCODED_NULL MUST be normally set to zero except when the option is used in FEC packets to preserve original options. See Appendix A for details.

There is a limit of 16 options per packet.

General Option Format



9.1. Option extension length - OPT_LENGTH

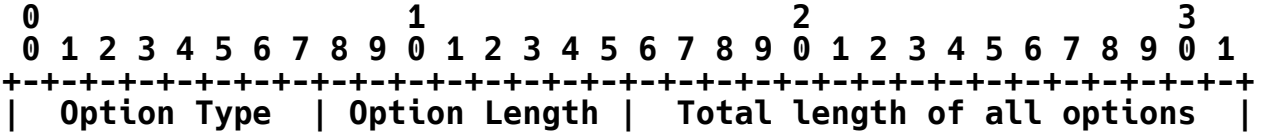
When option extensions are appended to the standard PGM header, the extensions MUST be preceded by an option extension length field specifying the total length of all option extensions.

In addition, the presence of the options MUST be encoded in the Options field of the standard PGM header before the Checksum is computed.

All network-significant options MUST be appended before any exclusively receiver-significant options.

To provide an indication of the end of option extensions, OPT_END (0x80) MUST be set in the Option Type field of the trailing option extension.

9.1.1. OPT_LENGTH - Packet Extension Format



Option Type = 0x00

Option Length = 4 octets

Total length of all options

The total length in octets of all option extensions including OPT_LENGTH.

OPT_LENGTH is NOT network-significant.

9.2. Fragmentation Option - OPT_FRAGMENT

Fragmentation allows transport-layer entities at a source to break up application protocol data units (APDUs) into multiple PGM data packets (TPDUs) to conform with the MTU supported by the network layer. The fragmentation option MAY be applied to ODATA and RDATA packets only.

Architecturally, the accumulation of TSDUs into APDUs is applied to TPDUs that have already been received, duplicate eliminated, and contiguously sequenced by the receiver. Thus APDUs MAY be reassembled across increments of the transmit window.

9.2.1. OPT_FRAGMENT - Packet Extension Contents

OPT_FRAG_OFF the offset of the fragment from the beginning of the APDU

OPT_FRAG_LEN the total length of the original APDU

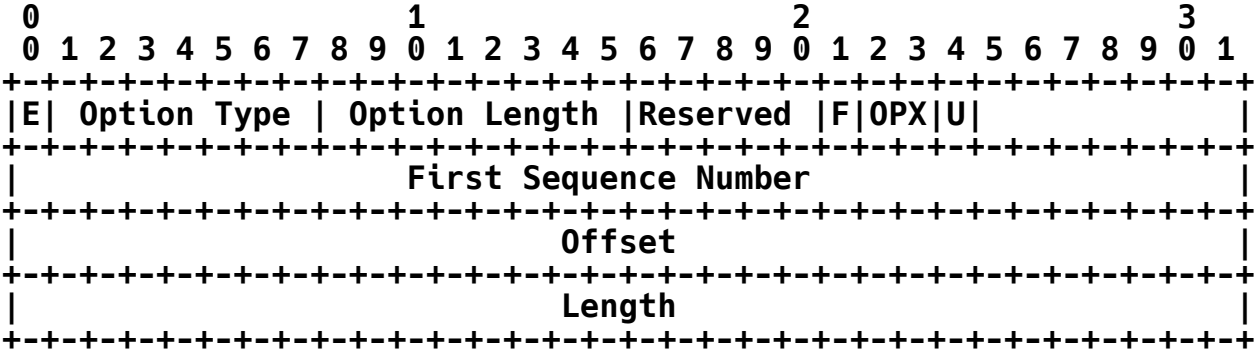
9.2.2. OPT_FRAGMENT - Procedures - Sources

A source fragments APDUs into a contiguous series of fragments no larger than the MTU supported by the network layer. A source sequentially and uniquely assigns OD_SQNs to these fragments in the order in which they occur in the APDU. A source then sets OPT_FRAG_OFF to the value of the offset of the fragment in the original APDU (where the first byte of the APDU is at offset 0, and OPT_FRAG_OFF numbers the first byte in the fragment), and set OPT_FRAG_LEN to the value of the total length of the original APDU.

9.2.3. OPT_FRAGMENT - Procedures - Receivers

Receivers detect and accumulate fragmented packets until they have received an entire contiguous sequence of packets comprising an APDU. This sequence begins with the fragment bearing OPT_FRAG_OFF of 0, and terminates with the fragment whose length added to its OPT_FRAG_OFF is OPT_FRAG_LEN.

9.2.4. OPT_FRAGMENT - Packet Extension Format



Option Type = 0x01

Option Length = 12 octets

First Sequence Number

Sequence Number of the PGM DATA/RDATA packet containing the first fragment of the APDU.

Offset

The byte offset of the fragment from the beginning of the APDU (OPT_FRAG_OFF).

Length

The total length of the original APDU (OPT_FRAG_LEN).

OPT_FRAGMENT is NOT network-significant.

9.3. NAK List Option - OPT_NAK_LIST

The NAK List option MAY be used in conjunction with NAKs to allow receivers to request transmission for more than one sequence number with a single NAK packet. The option is limited to 62 listed NAK entries. The NAK list MUST be unique and duplicate free. It MUST be ordered, and MUST consist of either a list of selective or a list of parity NAKs. In general, network elements, sources and receivers must process a NAK list as if they had received individual NAKs for each sequence number in the list. The procedures for each are outlined in detail earlier in this document. Clarifications and differences are detailed here.

9.3.1. OPT_NAK_LIST - Packet Extensions Contents

A list of sequence numbers for which retransmission is requested.

9.3.2. OPT_NAK_LIST - Procedures - Receivers

Receivers MAY append the NAK List option to a NAK to indicate that they wish retransmission of a number of RDATA.

Receivers SHOULD proceed to back off NAK transmission in a manner consistent with the procedures outlined for single sequence number NAKs. Note that the repair of each separate sequence number will be completed upon receipt of a separate RDATA packet.

Reception of an NCF or multicast NAK containing the NAK List option suspends generation of NAKs for all sequence numbers within the NAK list, as well as the sequence number within the NAK header.

9.3.3. OPT_NAK_LIST - Procedures - Network Elements

Network elements MUST immediately respond to a NAK with an identical NCF containing the same NAK list as the NAK itself.

Network elements MUST forward a NAK containing a NAK List option if any one sequence number specified by the NAK (including that in the main NAK header) is not currently outstanding. That is, it MUST forward the NAK, if any one sequence number does not have an elimination timer running for it. The NAK must be forwarded intact.

Network elements MUST eliminate a NAK containing the NAK list option only if all sequence numbers specified by the NAK (including that in the main NAK header) are outstanding. That is, they are all running an elimination timer.

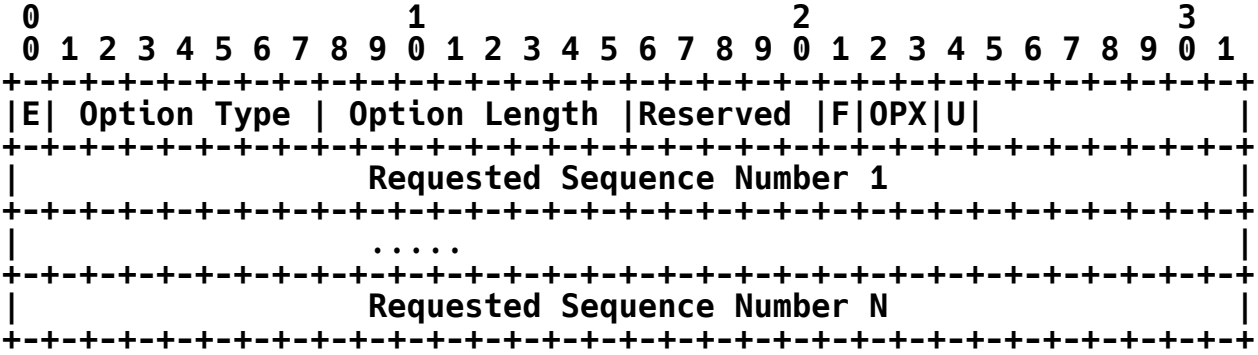
Upon receipt of an unsolicited NCF containing the NAK list option, a network element MUST anticipate data for every sequence number specified by the NAK as if it had received an NCF for every sequence number specified by the NAK.

9.3.4. OPT_NAK_LIST - Procedures - Sources

A source MUST immediately respond to a NAK with an identical NCF containing the same NAK list as the NAK itself.

It MUST then multicast RDATA (while respecting TXW_MAX_RTE) for every requested sequence number.

9.3.5. OPT_NAK_LIST - Packet Extension Format



Option Type = 0x02

Option Length = 4 + (4 * number of SQNs) octets

Requested Sequence Number

A list of up to 62 additional sequence numbers to which the NAK applies.

OPT_NAK_LIST is network-significant.

9.4. Late Joining Option - OPT_JOIN

Late joining allows a source to bound the amount of repair history receivers may request when they initially join a particular transport session.

This option indicates that receivers that join a transport session in progress MAY request repair of all data as far back as the given minimum sequence number from the time they join the transport session. The default is for receivers to receive data only from the first packet they receive and onward.

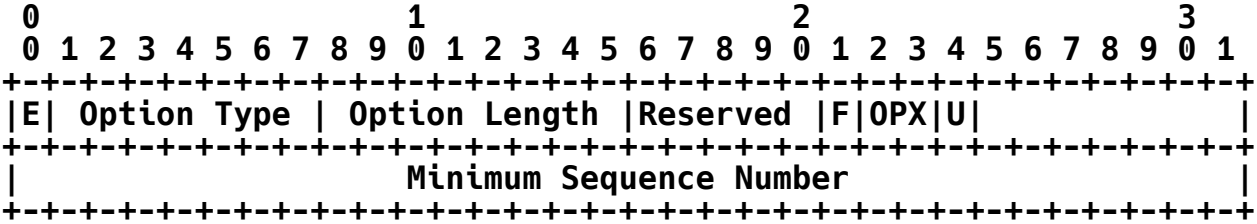
9.4.1. OPT_JOIN - Packet Extensions Contents

OPT_JOIN_MIN the minimum sequence number for repair

9.4.2. OPT_JOIN - Procedures - Receivers

If a PGM packet (ODATA, RDATA, or SPM) bears OPT_JOIN, a receiver MAY initialize the trailing edge of the receive window (RXW_TRAIL_INIT) to the given Minimum Sequence Number and proceeds with normal data reception.

9.4.3. OPT_JOIN - Packet Extension Format



Option Type = 0x03

Option Length = 8 octets

Minimum Sequence Number

The minimum sequence number defining the initial trailing edge of the receive window for a late joining receiver.

OPT_JOIN is NOT network-significant.

9.5. Redirect Option - OPT_REDIRECT

Redirection MAY be used by a designated local repairer (DLR) to advertise its own address as an alternative to the original source, for requesting repairs.

These procedures allow a PGM Network Element to use a DLR that is one PGM hop from it either upstream or downstream in the multicast distribution tree. The former are referred to as upstream DLRs. The latter are referred to as off-tree DLRs. Off-Tree because even though they are downstream of the point of loss, they might not lie on the subtree affected by the loss.

A DLR MUST receive any PGM sessions for which it wishes to provide retransmissions. A DLR SHOULD respond to NCFs or POLLs sourced by its PGM parent with a redirecting POLR response packet containing an OPT_REDIRECT which provides its own network layer address. Recipients of redirecting POLRs MAY then direct NAKs for subsequent ODATA sequence numbers to the DLR rather than to the original source. In addition, DLRs that receive redirected NAKs for which they have RDATA MUST send a NULL NAK to provide flow control to the original source without also provoking a repair from that source.

9.5.1. OPT_REDIRECT - Packet Extensions Contents

OPT_REDIR_NLA the DLR's own unicast network-layer address to which recipients of the redirecting POLR MAY direct subsequent NAKs for the corresponding TSI.

9.5.2. OPT_REDIRECT - Procedures - DLRs

A DLR MUST receive any PGM sessions for which it wishes to provide a source of repairs. In addition to acting as an ordinary PGM receiver, a DLR MAY then respond to NCFs or relevant POLLs sourced by parent network elements (or even by the source itself) by sending a POLR containing an OPT_REDIRECT providing its own network-layer address.

If a DLR can provide FEC repairs it MUST denote this by setting OPT_PARITY in the PGM header of its POLR response.

9.5.2.1. Upstream DLRs

If the NCF completes NAK transmission initiated by the DLR itself, the DLR MUST NOT send a redirecting POLR.

When a DLR receives an NCF from its upstream PGM parent, it SHOULD send a redirecting POLR, multicast to the group. The DLR SHOULD record that it is acting as an upstream DLR for the said session. Note that this POLR MUST have both the data source's source address and the router alert option in its network header.

An upstream DLR MUST act as an ordinary PGM source in responding to any NAK it receives (i.e., directed to it). That is, it SHOULD respond first with a normal NCF and then RDATA as usual. In addition, an upstream DLR that receives redirected NAKs for which it has RDATA MUST send a NULL NAK to provide flow control to the original source. If it cannot provide the RDATA it forwards the NAK to the upstream PGM neighbor as usual.

> Nota Bene: In order to propagate on exactly the same distribution tree as ODATA, RDATA and POLR packets transmitted by DLRs MUST bear the ODATA source's NLA as the network-header source address, not the DLR's NLA as might be expected.

9.5.2.2. Off-Tree DLRs

A DLR that receives a POLL with sub-type PGM_POLL_DLR MUST respond with a unicast redirecting POLR if it provides the appropriate service. The DLR SHOULD respond using the rules outlined for polling in Appendix D of this text. If the DLR responds, it SHOULD record that it is acting as an off-tree DLR for the said session.

An off-tree DLR acts in a special way in responding to any NAK it receives (i.e., directed to it). It MUST respond to a NAK directed to it from its parent by unicasting an NCF and RDATA to its parent. The parent will then forward the RDATA down the distribution tree. The DLR uses its own and the parent's NLA addresses in the network header for the source and destination respectively. The unicast NCF and RDATA packets SHOULD not have the router alert option. In all other ways the RDATA header should be "as if" the packet had come from the source.

Again, an off-tree DLR that receives redirected NAKs for which it has RDATA MUST originate a NULL NAK to provide flow control to the original source. It MUST originate the NULL NAK before originating the RDATA. This must be done to reduce the state held in the network element.

If it cannot provide the RDATA for a given NAK, an off-tree DLR SHOULD confirm the NAK with a unicast NCF as normal, then immediately send a NAK for the said data packet back to its parent.

9.5.2.3. Simultaneous Upstream and Off-Tree DLR operation

Note that it is possible for a DLR to provide service to its parent and to downstream network elements simultaneously. A downstream loss coupled with a loss for the same data on some other part of the distribution tree served by its parent could cause this. In this case it may provide both upstream and off-tree functionality simultaneously.

Note that a DLR differentiates between NAKs from an NE downstream or from its parent by comparing the network-header source address of the NAK with it's upstream PGM parent's NLA. The DLR knows the parent's NLA from the session's SPM messages.

9.5.3. OPT_REDIRECT - Procedures - Network Elements

9.5.3.1. Discovering DLRs

When a PGM router receives notification of a loss via a NAK, it SHOULD first try to use a known DLR to recover the loss. If such a DLR is not known it SHOULD initiate DLR discovery. DLR discovery may occur in two ways. If there are upstream DLRs, the NAK transmitted by this router to its PGM parent will trigger their discovery, via a redirecting POLR. Also, a network element SHOULD initiate a search for off-tree DLRs using the PGM polling mechanism, and the sub-type PGM_POLL_DLR.

If a DLR can provide FEC repairs it will denote this by setting OPT_PARITY in the PGM header of its POLR response. A network element SHOULD only direct parity NAKs to a DLR that can provide FEC repairs.

9.5.3.2. Redirected Repair

When it can, a network element SHOULD use upstream DLRs.

Upon receiving a redirecting POLR, network elements SHOULD record the redirecting information for the TSI, and SHOULD redirect subsequent NAKs for the same TSI to the network address provided in the redirecting POLR rather than to the PGM neighbor known via the SPMs. Note, however, that a redirecting POLR is NOT regarded as matching the NAK that provoked it, so it does not complete the transmission of that NAK. Only a normal matching NCF can complete the transmission of a NAK.

For subsequent NAKs, if the network element has recorded redirection information for the corresponding TSI, it MAY change the destination network address of those NAKs and attempt to transmit them to the DLR. No NAK for a specific SQN SHOULD be sent to an off-tree DLR if a NAK for the SQN has been seen on the interface associated with the DLR. Instead the NAK SHOULD be forwarded upstream. Subsequent NAKs for different SQNs MAY be forwarded to the said DLR (again assuming no NAK for them has been seen on the interface to the DLR).

If a corresponding NCF is not received from the DLR within NAK_RPT_IVL, the network element MUST discard the redirecting information for the TSI and re-attempt to forward the NAK towards the PGM upstream neighbor.

If a NAK is received from the DLR for a requested SQN, the network element MUST discard the redirecting information for the SQN and re-attempt to forward the NAK towards the PGM upstream neighbor. The network element MAY still direct NAKs for different SQNs to the DLR.

RDATA and NCFs from upstream DLRs will flow down the distribution tree. However, RDATA and NCFs from off-tree DLRs will be unicast to the network element. The network element will terminate the NCF, but MUST put the source's NLA and the group address into the network header and MUST add router alert before forwarding the RDATA packet to the distribution subtree.

NULL NAKs from an off-tree DLR for an RDATA packet requested from that off-tree DLR MUST always be forwarded upstream. The network element can assume that these will arrive before the matching RDATA. Other NULL NAKs are forwarded only if matching repair state has not already been created. Network elements MUST NOT confirm or retry NULL NAKs and they MUST NOT add the receiving interface to the repair state. If a NULL NAK is used to initially create repair state, this fact must be recorded so that any subsequent non-NULL NAK will not be eliminated, but rather will be forwarded to provoke an actual repair. State created by a NULL NAK exists only for NAK_ELIM_IVL.

9.5.4. OPT_REDIRECT - Procedures - Receivers

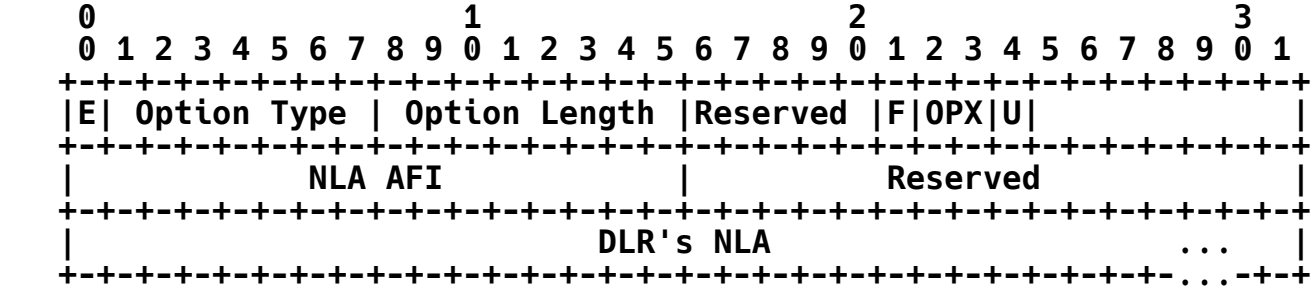
These procedures are intended to be applied in instances where a receiver's first hop router on the reverse path to the source is not a PGM Network Element. So, receivers MUST ignore a redirecting POLR from a DLR on the same IP subnet that the receiver resides on, since this is likely to suffer identical loss to the receiver and so be useless. Therefore, these procedures are entirely OPTIONAL. A receiver MAY choose to ignore all redirecting POLRs since in cases where its first hop router on the reverse path is PGM capable, it would ignore them anyway. Also, note that receivers will never learn of off-tree DLRs.

Upon receiving a redirecting POLR, receivers SHOULD record the redirecting information for the TSI, and MAY redirect subsequent NAKs for the same TSI to the network address provided in the redirecting POLR rather than to the PGM neighbor for the corresponding ODATA for which the receiver is requesting repair. Note, however, that a redirecting POLR is NOT regarded as matching the NAK that provoked it, so it does not complete the transmission of that NAK. Only a normal matching NCF can complete the transmission of a NAK.

For subsequent NAKs, if the receiver has recorded redirection information for the corresponding TSI, it MAY change the destination network address of those NAKs and attempt to transmit them to the

DLR. If a corresponding NCF is not received within NAK_RPT_IVL, the receiver MUST discard the redirecting information for the TSI and re-attempt to forward the NAK to the PGM neighbor for the original source of the missing ODATA.

9.5.5. OPT_REDIRECT - Packet Extension Format



Option Type = 0x07

Option Length = 4 + NLA length

DLR's NLA

The DLR's own unicast network address to which recipients of the redirecting POLR may direct subsequent NAKs.

OPT_REDIRECT is network-significant.

9.6. OPT_SYN - Synchronization Option

The SYN option indicates the starting data packet for a session. It must only appear in ODATA or RDATA packets.

The SYN option MAY be used to provide a useful abstraction to applications that can simplify application design by providing stream start notification. It MAY also be used to let a late joiner to a session know that it is indeed late (i.e. it would not see the SYN option).

9.6.1. OPT_SYN - Procedures - Receivers

Procedures for receivers are implementation dependent. A receiver MAY use the SYN to provide its applications with abstractions of the data stream.

9.6.2. OPT_SYN - Procedures - Sources

Sources MAY include OPT_SYN in the first data for a session. That is, they MAY include the option in:

the first ODATA sent on a session by a PGM source

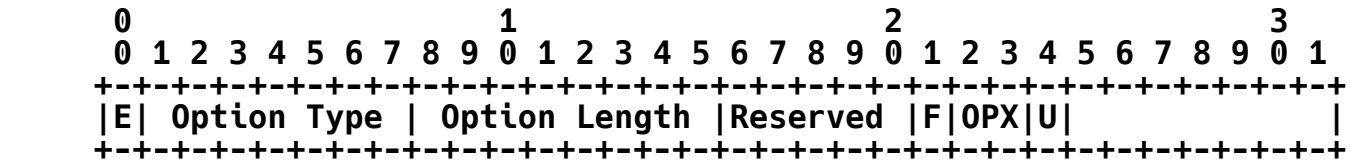
any RDATA sent as a result of loss of this ODATA packet

all FEC packets for the first transmission group; in this case it is interpreted as the first packet having the SYN

9.6.3. OPT_SYN - Procedures - DLRs

In an identical manner to sources, DLRs MUST provide OPT_SYN in any retransmitted data that is at the start of a session.

9.6.4. OPT_SYN - Packet Extension Format



Option Type = 0x0D

Option Length = 4

OPT_SYN is NOT network-significant.

9.7. OPT_FIN - Session Finish Option

This FIN option indicates the last data packet for a session and an orderly close down.

The FIN option MAY be used to provide an abstraction to applications that can simplify application design by providing stream end notification.

This option MAY be present in the last data packet or transmission group for a session. The FIN PGM option MUST appear in every SPM sent after the last ODATA for a session. The SPM_LEAD sequence number in an SPM with the FIN option indicates the last known data successfully transmitted for the session.

9.7.1. OPT_FIN - Procedures - Receivers

A receiver SHOULD use receipt of a FIN to let it know that it can tear down its data structures for the said session once a suitable time period has expired (TXW_SECS). It MAY still try to solicit retransmissions within the existing transmit window.

Other than this, procedures for receivers are implementation dependent. A receiver MAY use the FIN to provide its applications with abstractions of the data stream and to inform its applications that the session is ending.

9.7.2. OPT_FIN - Procedures - Sources

Sources MUST include OPT_FIN in every SPM sent after it has been determined that the application has closed gracefully. If a source is aware at the time of transmission that it is ending a session the source MAY include OPT_FIN in,

the last ODATA

any associated RDATAs for the last data

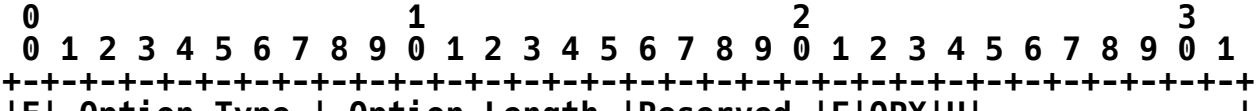
FEC packets for the last transmission group; in this case it is interpreted as the last packet having the FIN

When a source detects that it needs to send an OPT_FIN it SHOULD immediately send it. This is done either by appending it to the last data packet or transmission group or by immediately sending an SPM and resetting the SPM heartbeat timer (i.e. it does not wait for a timer to expire before sending the SPM). After sending an OPT_FIN, the session SHOULD not close and stop sending SPMs until after a time period equal to TXW_SECS.

9.7.3. OPT_FIN - Procedures - DLRs

In an identical manner to sources, DLRs MUST provide OPT_FIN in any retransmitted data that is at the end of a session.

9.7.4. OPT_FIN - Packet Extension Format



Option Type = 0x0E

Option Length = 4

OPT_FIN is NOT network-significant.

9.8. OPT_RST - Session Reset Option

The RST option MAY appear in every SPM sent after an unrecoverable error is identified by the source. This acts to notify the receivers that the session is being aborted. This option MAY appear only in SPMs. The SPM_LEAD sequence number in an SPM with the RST option indicates the last known data successfully transmitted for the session.

9.8.1. OPT_RST - Procedures - Receivers

Receivers SHOULD treat the reception of OPT_RST in an SPM as an abort of the session.

A receiver that receives an SPM with an OPT_RST with the N bit set SHOULD not send any more NAKs for the said session towards the source. If the N bit (see 9.8.5) is not set, the receiver MAY continue to try to solicit retransmit data within the current transmit window.

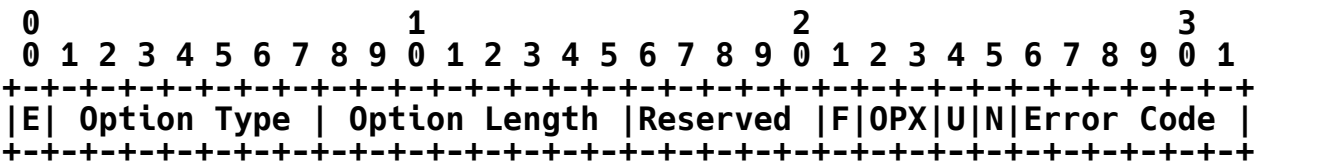
9.8.2. OPT_RST - Procedures - Sources

Sources SHOULD include OPT_RST in every SPM sent after it has been determined that an unrecoverable error condition has occurred. The N bit of the OPT_RST SHOULD only be sent if the source has determined that it cannot process NAKs for the session. The cause of the OPT_RST is set to an implementation specific value. If the error code is unknown, then the value of 0x00 is used. When a source detects that it needs to send an OPT_RST it SHOULD immediately send it. This is done by immediately sending an SPM and resetting the SPM heartbeat timer (i.e. it does not wait for a timer to expire before sending the SPM). After sending an OPT_RST, the session SHOULD not close and stop sending SPMs until after a time period equal to TXW_SECS.

9.8.3. OPT_RST - Procedures - DLRs

None.

9.8.4. OPT_RST - Packet Extension Format



Option Type = 0x0F

Option Length = 4

N bit

The N bit is set to 1 to indicate that NAKs for previous ODATA will go unanswered from the source. The application will tell the source to turn this bit on or off.

Error Code

The 6 bit error code field is used to forward an error code down to the receivers from the source.

The value of 0x00 indicates an unknown reset reason. Any other value indicates the application purposely aborted and gave a reason (the error code value) that may have meaning to the end receiver application. These values are entirely application dependent.

OPT_RST is NOT network-significant.

10. Security Considerations

In addition to the usual problems of end-to-end authentication, PGM is vulnerable to a number of security risks that are specific to the mechanisms it uses to establish source path state, to establish repair state, to forward NAKs, to identify DLRs, and to distribute repairs. These mechanisms expose PGM network elements themselves to security risks since network elements not only switch but also interpret SPMs, NAKs, NCFs, and RDATA, all of which may legitimately be transmitted by PGM sources, receivers, and DLRs. Short of full authentication of all neighboring sources, receivers, DLRs, and network elements, the protocol is not impervious to abuse.

So putting aside the problems of rogue PGM network elements for the moment, there are enough potential security risks to network elements associated with sources, receivers, and DLRs alone. These risks include denial of service through the exhausting of both CPU bandwidth and memory, as well as loss of (repair) data connectivity through the muddling of repair state.

False SPMs may cause PGM network elements to mis-direct NAKs intended for the legitimate source with the result that the requested RDATA would not be forthcoming.

False NAKs may cause PGM network elements to establish spurious repair state that will expire only upon time-out and could lead to memory exhaustion in the meantime.

False NCFs may cause PGM network elements to suspend NAK forwarding prematurely (or to mis-direct NAKs in the case of redirecting POLRs) resulting eventually in loss of RDATA.

False RDATA may cause PGM network elements to tear down legitimate repair state resulting eventually in loss of legitimate RDATA.

The development of precautions for network elements to protect themselves against incidental or unsophisticated versions of these attacks is work outside of this spec and includes:

- Damping of jitter in the value of either the network-header source address of SPMs or the path NLA in SPMs. While the network-header source address is expected to change seldom, the path NLA is expected to change occasionally as a consequence of changes in underlying multicast routing information.

The extension of NAK shedding procedures to control the volume, not just the rate, of confirmed NAKs. In either case, these procedures assist network elements in surviving NAK attacks at the expense of maintaining service. More efficiently, network elements may use the knowledge of TSIs and their associated transmit windows gleaned from SPMs to control the proliferation of repair state.

A three-way handshake between network elements and DLRs that would permit a network element to ascertain with greater confidence that an alleged DLR is identified by the alleged network-header source address, and is PGM conversant.

11. Appendix A - Forward Error Correction

11.1. Introduction

The following procedures incorporate packet-level Reed Solomon Erasure correcting techniques as described in [11] and [12] into PGM. This approach to Forward Error Correction (FEC) is based upon the computation of h parity packets from k data packets for a total of n packets such that a receiver can reconstruct the k data packets out of any k of the n packets. The original k data packets are referred to as the Transmission Group, and the total n packets as the FEC Block.

These procedures permit any combination of pro-active FEC or on-demand FEC with conventional ARQ (selective retransmission) within a given TSI to provide any flavor of layered or integrated FEC. The two approaches can be used by the same or different receivers in a single transport session without conflict. Once provided by a source, the actual use of FEC or selective retransmission for loss recovery in the session is entirely at the discretion of the receivers. Note however that receivers SHOULD NOT ask for selective retransmissions when FEC is available, nevertheless sources MUST provide selective retransmissions in response to selective NAKs from the leading partial transmission group (i.e. the most recent transmission group, which is not yet full). For any group that is full, the source SHOULD provide FEC on demand in response to a selective NAK.

Pro-active FEC refers to the technique of computing parity packets at transmission time and transmitting them as a matter of course following the data packets. Pro-active FEC is RECOMMENDED for providing loss recovery over simplex or asymmetric multicast channels over which returning repair requests is either impossible or costly. It provides increased reliability at the expense of bandwidth.

On-demand FEC refers to the technique of computing parity packets at repair time and transmitting them only upon demand (i.e., receiver-based loss detection and repair request). On-demand FEC is RECOMMENDED for providing loss recovery of uncorrelated loss in very large receiver populations in which the probability of any single packet being lost is substantial. It provides equivalent reliability to selective NAKs (ARQ) at no more and typically less expense of bandwidth.

Selective NAKs are NAKs that request the retransmission of specific packets by sequence number corresponding to the sequence number of any data packets detected to be missing from the expected sequence (conventional ARQ). Selective NAKs can be used for recovering losses

occurring in leading partial transmission groups, i.e. in the most recent transmission group, which is not yet full. The RECOMMENDED way of handling partial transmission groups, however, is for the data source to use variable-size transmission groups (see below).

Parity NAKs are NAKs that request the transmission of a specific number of parity packets by count corresponding to the count of the number of data packets detected to be missing from a group of k data packets (on-demand FEC).

The objective of these procedures is to incorporate these FEC techniques into PGM so that:

sources MAY provide parity packets either pro-actively or on-demand, interchangeably within the same TSI,

receivers MAY use either selective or parity NAKs interchangeably within the same TSI (however, in a session where on-demand parity is available receivers SHOULD only use parity NAKs).

network elements maintain repair state based on either selective or parity NAKs in the same data structure, altering only search, RDATA constraint, and deletion algorithms in either case,

and only OPTION additions to the basic packet formats are REQUIRED.

11.2. Overview

Advertising FEC parameters in the transport session

Sources add OPT_PARITY_PRM to SPMs to provide session-specific parameters such as the number of packets (TGSIZE == k) in a transmission group. This option lets receivers know how many packets there are in a transmission group, and it lets network elements sort repair state by transmission group number. This option includes an indication of whether pro-active and/or on-demand parity is available from the source.

Distinguishing parity packets from data packets

Sources send pro-active parity packets as ODATA (NEs do not forward RDATA unless a repair state is present) and on-demand parity packets as RDATA. A source MUST add OPT_PARITY to the ODATA/RDATA packet header of parity packets to permit network elements and receivers to distinguish them from data packets.

Data and parity packet numbering

Parity packets MUST be calculated over a fixed number k of data packets known as the Transmission Group. Grouping of packets into transmission groups effectively partitions a packet sequence number into a high-order portion (TG_SQN) specifying the transmission group (TG), and a low-order portion (PKT_SQN) specifying the packet number (PKT-NUM in the range 0 through k-1) within that group. From an implementation point of view, it's handy if k, the TG size, is a power of 2. If so, then TG_SQN and PKT_SQN can be mapped side-by-side into the 32 bit SQN. log2(TGSIZE) is then the size in bits of PKT_SQN.

This mapping does not reduce the effective sequence number space since parity packets marked with OPT_PARITY allow the sequence space (PKT_SQN) to be completely reused in order to number the h parity packets, as long as h is not greater than k.

In the case where h is greater than k, a source MUST add OPT_PARITY_GRP to any parity packet numbered j greater than k-1, specifying the number m of the group of k parity packets to which the packet belongs, where m is just the quotient from the integer division of j by k. Correspondingly, PKT-NUM for such parity packets is just j modulo k. In other words, when a source needs to generate more parity packets than there were original data packets (perhaps because of a particularly lossy line such that a receiver lost not only the original data but some of the parity RDATA as well), use the OPT_PARITY_GRP option in order to number and identify the transmission group of the extra packets that would exceed the normal sequential number space.

Note that parity NAKs (and consequently their corresponding parity NCFs) MUST also contain the OPT_PARITY flag in the options field of the fixed header, and that in these packets, PKT_SQN MUST contain PKT_CNT, the number of missing packets, rather than PKT_NUM, the SQN of a specific missing packet. More on all this later.

Variable Transmission Group Size

The transmission group size advertised in the OPT_PARITY_PRM option on SPMs MUST be a power of 2 and constant for the duration of the session. However, the actual transmission group size used MAY not be constant for the duration of the session, and MAY not be a power of 2. When a TG size different from the one advertised in OPT_PARITY_PRM is used, the TG size advertised in OPT_PARITY_PRM MUST be interpreted as specifying the maximum effective size of the TG.

When the actual TG size is not a power of 2 or is smaller than the max TG size, there will be sparse utilization of the sequence number space since some of the sequence numbers that would have been consumed in numbering a maximum sized TG will not be assigned to packets in the smaller TG. The start of the next transmission group will always begin on the boundary of the maximum TG size as though each of the sequence numbers had been utilized.

When the source decides to use a smaller group size than that advertised in OPT_PARITY_PRM, it appends OPT_CURR_TGSIZE to the last data packet (ODATA) in the truncated transmission group. This lets the receiver know that it should not expect any more packets in this transmission group, and that it may start requesting repairs for any missing packets. If the last data packet itself went missing, the receiver will detect the end of the group when it receives a parity packet for the group, an SPM with SPM_LEAD equal to OD_SQN of the last data packet, or the first packet of the next group, whichever comes first. In addition, any parity packet from this TG will also carry the OPT_CURR_TGSIZE option as will any SPM sent with SPM_LEAD equal to OD_SQN of the last data packet.

Variable TSDU length

If a non constant TSDU length is used within a given transmission group, the size of parity packets in the corresponding FEC block MUST be equal to the size of the largest original data packet in the block. Parity packets MUST be computed by padding the original packets with zeros up to the size of the largest data packet. Note that original data packets are transmitted without padding.

Receivers using a combination of original packets and FEC packets to rebuild missing packets MUST pad the original packets in the same way as the source does. The receiver MUST then feed the padded original packets plus the parity packets to the FEC decoder. The decoder produces the original packets padded with zeros up to the size of the largest original packet in the group. In order for the receiver to eliminate the padding on the reconstructed data packets, the original size of the packet MUST be known, and this is accomplished as follows:

The source, along with the packet payloads, encodes the TSDU length and appends the 2-byte encoded length to the padded FEC packets.

Receivers pad the original packets that they received to the largest original packet size and then append the TSDU length to the padded packets. They then pass them and the FEC packets to the FEC decoder.

The decoder produces padded original packets with their original TSDU length appended. Receivers MUST now use this length to get rid of the padding.

A source that transmits variable size packets MUST take into account the fact that FEC packets will have a size equal to the maximum size of the original packets plus the size of the length field (2 bytes).

If a fixed packet size is used within a transmission group, the encoded length is not appended to the parity packets. The presence of the fixed header option flag OPT_VAR_PKTLEN in parity packets allows receivers to distinguish between transmission groups with variable sized packets and fixed-size ones, and behave accordingly.

Payload-specific options

Some options present in data packet (ODATA and RDATA) are strictly associated with the packet content (PGM payload), OPT_FRAGMENT being an example. These options must be preserved even when the data packet that would normally contain them is not received, but its the payload is recovered though the use of FEC.

To achieve this, PGM encodes the content of these options in special options that are inserted in parity packets. Two flags present in the the option common-header are used for this process: bit F (OP_ENCODED) and bit U (OP_ENCODED_NULL).

Whenever at least one of the original packets of a TG contains a payload-specific option of a given type, the source MUST include an encoded version of that option type in all the parity packets it transmits. The encoded option is computed by applying FEC encoding to the whole option with the exception of the first three bytes of the option common-header (E, Option Type, Option Length, OP_ENCODED and OPX fields). The type, length and OPX of the encoded option are the same as the type, length and OPX in the original options. OP_ENCODED is set to 1 (all original option have OP_ENCODED = 0).

The encoding is performed using the same process that is used to compute the payload of the parity packet. i.e. the FEC encoder is fed with one copy of that option type for each original packet in the TG. If one (or more) original packet of the TG does not contain that option type, an all zeroes option is used for the encoding process. To be able to distinguish this "dummy" option from valid options with all-zeroes payload, OP_ENCODED_NULL is used. OP_ENCODED_NULL is set to 0 in all the original options, but the value of 1 is used in the encoding process if the option did not exist in the original packet. On the receiver side, all option with OP_ENCODED_NULL equal to 1 are discarded after decoding.

When a receiver recovers a missing packet using FEC repair packets, it MUST also recover payload-specific options, if any. The presence of these can be unequivocally detected through the presence of encoded options in parity packets (encoded options have OP_ENCODED set to 1). Receivers apply FEC-recovery to encoded options and possibly original options, as they do to recover packet payloads. The FEC decoding is applied to the whole option with the exception of the first three bytes of the option common-header (E, Option Type, Option Length, OP_ENCODED and OPX fields). Each decoded option is associated with the relative payload, unless OP_ENCODED_NULL turns out to be 1, in which case the decoded option is discarded.

The decoding MUST be performed using the 1st occurrence of a given option type in original/parity packets. If one or more original packets do not contain that option type, an option of the same type with zero value must be used. This option MUST have OP_ENCODED_NULL equal to 1.

11.3. Packet Contents

This section just provides enough short-hand to make the Procedures intelligible. For the full details of packet contents, please refer to Packet Formats below.

OPT_PARITY	indicated in pro-active (ODATA) and on-demand (RDATA) parity packets to distinguish them from data packets. This option is directly encoded in the "Option" field of the fixed PGM header
OPT_VAR_PKTLEN	MAY be present in pro-active (ODATA) and on-demand (RDATA) parity packets to indicate that the corresponding transmission group is composed of variable size data packets. This option is directly encoded in the "Option" field of the fixed PGM header
OPT_PARITY_PRM	appended by sources to SPMs to specify session-specific parameters such as the transmission group size and the availability of pro-active and/or on-demand parity from the source
OPT_PARITY_GRP	the number of the group (greater than 0) of h parity packets to which the parity packet belongs when more than k parity packets are provided by the source

OPT_CURR_TGSIZE appended by sources to the last data packet and any parity packets in a variable sized transmission group to indicate to the receiver the actual size of a transmission group. May also be appended to certain SPMs

11.3.1. Parity NAKs

NAK_TG_SQN the high-order portion of NAK_SQN specifying the transmission group for which parity packets are requested

NAK_PKT_CNT the low-order portion of NAK_SQN specifying the number of missing data packets for which parity packets are requested

Nota Bene: NAK_PKT_CNT (and NCF_PKT_CNT) are 0-based counters, meaning that NAK_PKT_CNT = 0 means that 1 FEC RDATA is being requested, and in general NAK_PKT_CNT = k - 1 means that k FEC RDATA are being requested.

11.3.2. Parity NCFs

NCF_TG_SQN the high-order portion of NCF_SQN specifying the transmission group for which parity packets were requested

NCF_PKT_CNT the low-order portion of NCF_SQN specifying the number of missing data packets for which parity packets were requested

Nota Bene: NCF_PKT_CNT (and NAK_PKT_CNT) are 0-based counters, meaning that NAK_PKT_CNT = 0 means that 1 FEC RDATA is being requested, and in general NAK_PKT_CNT = k - 1 means that k FEC RDATA are being requested.

11.3.3. On-demand Parity

RDATA_TG_SQN the high-order portion of RDATA_SQN specifying the transmission group to which the parity packet belongs

RDATA_PKT_SQN the low-order portion of RDATA_SQN specifying the parity packet sequence number within the transmission group

11.3.4. Pro-active Parity

ODATA_TG_SQN	the high-order portion of ODATA_SQN specifying the transmission group to which the parity packet belongs
ODATA_PKT_SQN	the low-order portion of ODATA_SQN specifying the parity packet sequence number within the transmission group

11.4. Procedures - Sources

If a source elects to provide parity for a given transport session, it MUST first provide the transmission group size PARITY_PRM_TGS in the OPT_PARITY_PRM option of its SPMs. This becomes the maximum effective transmission group size in the event that the source elects to send smaller size transmission groups. If a source elects to provide proactive parity for a given transport session, it MUST set PARITY_PRM_PRO in the OPT_PARITY_PRM option of its SPMs. If a source elects to provide on-demand parity for a given transport session, it MUST set PARITY_PRM_OND in the OPT_PARITY_PRM option of its SPMs.

A source MUST send any pro-active parity packets for a given transmission group only after it has first sent all of the corresponding k data packets in that group. Pro-active parity packets MUST be sent as ODATA with OPT_PARITY in the fixed header.

If a source elects to provide on-demand parity, it MUST respond to a parity NAK for a transmission group with a parity NCF. The source MUST complete the transmission of the k original data packets and the proactive parity packets, possibly scheduled, before starting the transmission of on-demand parity packets. Subsequently, the source MUST send the number of parity packets requested by that parity NAK. On-demand parity packets MUST be sent as RDATA with OPT_PARITY in the fixed header. Previously transmitted pro-active parity packets cannot be reused as on-demand parity packets, these MUST be computed with new, previously unused, indexes.

In either case, the source MUST provide selective retransmissions only in response to selective NAKs from the leading partial transmission group. For any group that is full, the source SHOULD provide FEC on demand in response to a selective retransmission request.

In the absence of data to transmit, a source SHOULD prematurely terminate the current transmission group by including OPT_CURR_TGSIZE to the last data packet or to any proactive parity packets provided.

If the last data packet has already been transmitted and there is no provision for sending proactive parity packets, an SPM with OPT_CURR_TGSIZE SHOULD be sent.

A source consolidates requests for on-demand parity in the same transmission group according to the following procedures. If the number of pending (i.e., unsent) parity packets from a previous request for on-demand parity packets is equal to or greater than NAK_PKT_CNT in a subsequent NAK, that subsequent NAK MUST be confirmed but MAY otherwise be ignored. If the number of pending (i.e., unsent) parity packets from a previous request for on-demand parity packets is less than NAK_PKT_CNT in a subsequent NAK, that subsequent NAK MUST be confirmed but the source need only increase the number of pending parity packets to NAK_PKT_CNT.

When a source provides parity packets relative to a transmission group with variable sized packets, it MUST compute parity packets by padding the smaller original packets with zeroes out to the size of the largest of the original packets. The source MUST also append the encoded TSDU lengths at the end of any padding or directly to the end of the largest packet, and add the OPT_VAR_PKTLEN option as specified in the overview description.

When a source provides variable sized transmission groups, it SHOULD append the OPT_CURR_TGSIZE option to the last data packet in the shortened group, and it MUST append the OPT_CURR_TGSIZE option to any parity packets it sends within that group. In case the the last data packet is sent before a determination has been made to shorten the group and there is no provision for sending proactive parity packets, an SPM with OPT_CURR_TGSIZE SHOULD be sent. The source MUST also add OPT_CURR_TGSIZE to any SPM that it sends with SPM_LEAD equal to OD_SQN of the last data packet.

A receiver MUST NAK for the entire number of packets missing based on the maximum TG size, even if it already knows that the actual TG size is smaller. The source MUST take this into account and compute the number of packets effectively needed as the difference between NAK_PKT_CNT and an offset computed as the difference between the max TG size and the effective TG size.

11.5. Procedures - Receivers

If a receiver elects to make use of parity packets for loss recovery, it MUST first learn the transmission group size PARITY_PRM_TGS from OPT_PARITY_PRM in the SPMs for the TSI. The transmission group size is used by a receiver to determine the sequence number boundaries between transmission groups.

Thereafter, if PARITY_PRM_PRO is also set in the SPMs for the TSI, a receiver SHOULD use any pro-active parity packets it receives for loss recovery, and if PARITY_PRM_OND is also set in the SPMs for the TSI, it MAY solicit on-demand parity packets upon loss detection. If PARITY_PRM_OND is set, a receiver MUST NOT send selective NAKs, except in partial transmission groups if the source does not use the variable transmission-group size option. Parity packets are ODATA (pro-active) or RDATA (on-demand) packets distinguished by OPT_PARITY which lets receivers know that ODATA/RDATA_TG_SQN identifies the group of PARITY_PRM_TGS packets to which the parity may be applied for loss recovery in the corresponding transmission group, and that ODATA/RDATA_PKT_SQN is being reused to number the parity packets within that group. Receivers order parity packets and eliminate duplicates within a transmission group based on ODATA/RDATA_PKT_SQN and on OPT_PARITY_GRP if present.

To solicit on-demand parity packets, a receiver MUST send parity NAKs upon loss detection. For the purposes of soliciting on-demand parity, loss detection occurs at transmission group boundaries, i.e. upon receipt of the last data packet in a transmission group, upon receipt of any data packet in any subsequent transmission group, or upon receipt of any parity packet in the current or a subsequent transmission group.

A parity NAK is simply a NAK with OPT_PARITY and NAK_PKT_CNT set to the count of the number of packets detected to be missing from the transmission group specified by NAK_TG_SQN. Note that this constrains the receiver to request no more parity packets than there are data packets in the transmission group.

A receiver SHOULD bias the value of NAK_BO_IVL for parity NAKs inversely proportional to NAK_PKT_CNT so that NAKs for larger losses are likely to be scheduled ahead of NAKs for smaller losses in the same receiver population.

A confirming NCF for a parity NAK is a parity NCF with NCF_PKT_CNT equal to or greater than that specified by the parity NAK.

A receiver's NAK_RDATA_IVL timer is not cancelled until all requested parity packets have been received.

In the absence of data (detected from SPMs bearing SPM_LEAD equal to RXW_LEAD) on non-transmission-group boundaries, receivers MAY resort to selective NAKs for any missing packets in that partial transmission group.

When a receiver handles parity packets belonging to a transmission group with variable sized packets, (detected from the presence of the OPT_VAR_PKTLEN option in the parity packets), it MUST decode them as specified in the overview description and use the decoded TSDU length to get rid of the padding in the decoded packet.

If the source was using a variable sized transmission group via the OPT_CURR_TGSIZE, the receiver might learn this before having requested (and received) any retransmission. The above happens if it sees OPT_CURR_TGSIZE in the last data packet of the TG, in any proactive parity packet or in a SPM. If the receivers learns this and determines that it has missed one or more packets in the shortened transmission group, it MAY then NAK for them without waiting for the start of the next transmission group. Otherwise it will start NAKing at the start of the next transmission group.

In both cases, the receiver MUST NAK for the number of packets missing assuming that the size of the transmission group is the maximum effective transmission group. In other words, the receivers cannot exploit the fact that it might already know that the transmission group was smaller but MUST always NAK for the number of packets it believes are missing, plus the number of packets required to bring the total packets up to the maximum effective transmission group size.

After the first parity packet has been delivered to the receiver, the actual TG size is known to him, either because already known or because discovered via OPT_CURR_TGSIZE contained in the parity packet. Hence the receiver can decode the whole group as soon as the minimum number of parity packets needed is received.

11.6. Procedures - Network Elements

Pro-active parity packets (ODATA with OPT_PARITY) are switched by network elements without transport-layer intervention.

On-demand parity packets (RDATA with OPT_PARITY) necessitate modified request, confirmation and repair constraint procedures for network elements. In the context of these procedures, repair state is maintained per NAK_TSI and NAK_TG_SQN, and in addition to recording the interfaces on which corresponding NAKs have been received, records the largest value of NAK_PKT_CNT seen in corresponding NAKs on each interface. This value is referred to as the known packet count. The largest of the known packet counts recorded for any interface in the repair state for the transmit group or carried by an NCF is referred to as the largest known packet count.

Upon receipt of a parity NAK, a network element responds with the corresponding parity NCF. The corresponding parity NCF is just an NCF formed in the usual way (i.e., a multicast copy of the NAK with the packet type changed), but with the addition of OPT_PARITY and with NCF_PKT_CNT set to the larger of NAK_PKT_CNT and the known packet count for the receiving interface. The network element then creates repair state in the usual way with the following modifications.

If repair state for the receiving interface does not exist, the network element MUST create it and additionally record NAK_PKT_CNT from the parity NAK as the known packet count for the receiving interface.

If repair state for the receiving interface already exists, the network element MUST eliminate the NAK only if NAK_ELIM_IVL has not expired and NAK_PKT_CNT is equal to or less than the largest known packet count. If NAK_PKT_CNT is greater than the known packet count for the receiving interface, the network element MUST update the latter with the larger NAK_PKT_CNT.

Upon either adding a new interface or updating the known packet count for an existing interface, the network element MUST determine if NAK_PKT_CNT is greater than the largest known packet count. If so or if NAK_ELIM_IVL has expired, the network element MUST forward the parity NAK in the usual way with a value of NAK_PKT_CNT equal to the largest known packet count.

Upon receipt of an on-demand parity packet, a network element MUST locate existing repair state for the corresponding RDATA_TSI and RDATA_TG_SQN. If no such repair state exists, the network element MUST discard the RDATA as usual.

If corresponding repair state exists, the largest known packet count MUST be decremented by one, then the network element MUST forward the RDATA on all interfaces in the existing repair state, and decrement the known packet count by one for each. Any interfaces whose known packet count is thereby reduced to zero MUST be deleted from the repair state. If the number of interfaces is thereby reduced to zero, the repair state itself MUST be deleted.

Upon reception of a parity NCF, network elements MUST cancel pending NAK retransmission only if NCF_PKT_CNT is greater or equal to the largest known packet count. Network elements MUST use parity NCFs to anticipate NAKs in the usual way with the addition of recording NCF_PKT_CNT from the parity NCF as the largest known packet count with the anticipated state so that any subsequent NAKs received with NAK_PKT_CNT equal to or less than NCF_PKT_CNT will be eliminated, and

any with NAK_PKT_CNT greater than NCF_PKT_CNT will be forwarded. Network elements which receive a parity NCF with NCF_PKT_CNT larger than the largest known packet count MUST also use it to anticipate NAKs, increasing the largest known packet count to reflect NCF_PKT_CNT (partial anticipation).

Parity NNAKs follow the usual elimination procedures with the exception that NNAKs are eliminated only if existing NAK state has a NAK_PKT_CNT greater than NNAK_PKT_CNT.

Network elements must take extra precaution when the source is using a variable sized transmission group. Network elements learn that the source is using a TG size smaller than the maximum from OPT_CURR_TGSIZE in parity RDATAs or in SPMs. When this happens, they compute a TG size offset as the difference between the maximum TG size and the actual TG size advertised by OPT_CURR_TGSIZE. Upon reception of parity RDATA, the TG size offset is used to update the repair state as follows:

Any interface whose known packet count is reduced to the TG size offset is deleted from the repair state.

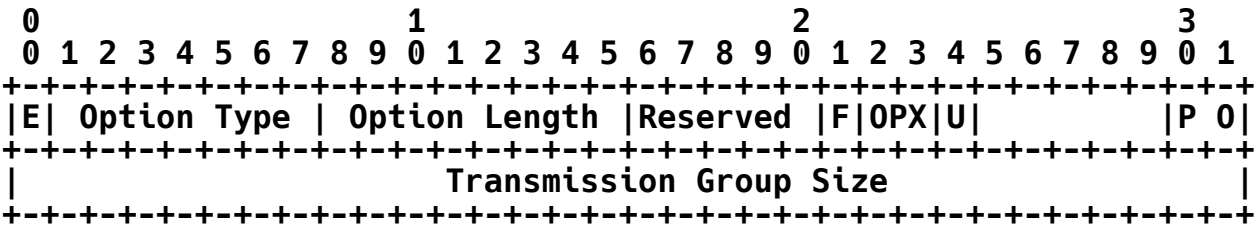
This replaces the normal rule for deleting interfaces that applies when the TG size is equal to the maximum TG size.

11.7. Procedures - DLRs

A DLR with the ability to provide FEC repairs MUST indicate this by setting the OPT_PARITY bit in the redirecting POLR. It MUST then process any redirected FEC NAKs in the usual way.

11.8. Packet Formats

11.8.1. OPT_PARITY_PRM - Packet Extension Format



Option Type = 0x08

Option Length = 8 octets

P-bit (PARITY_PRM_PRO)

Indicates when set that the source is providing pro-active parity packets.

O-bit (PARITY_PRM_OND)

Indicates when set that the source is providing on-demand parity packets.

At least one of PARITY_PRM_PRO and PARITY_PRM_OND MUST be set.

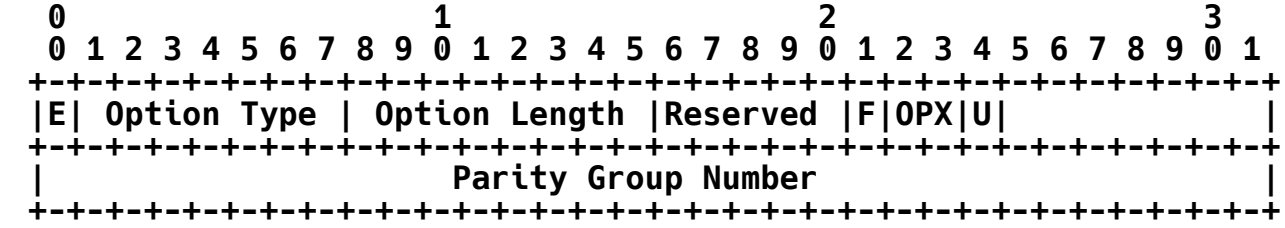
Transmission Group Size (PARITY_PRM_TGS)

The number of data packets in the transmission group over which the parity packets are calculated. If a variable transmission group size is being used, then this becomes the maximum effective transmission group size across the session.

OPT_PARITY_PRM MAY be appended only to SPMs.

OPT_PARITY_PRM is network-significant.

11.8.2. OPT_PARITY_GRP - Packet Extension Format



Option Type = 0x09

Option Length = 8 octets

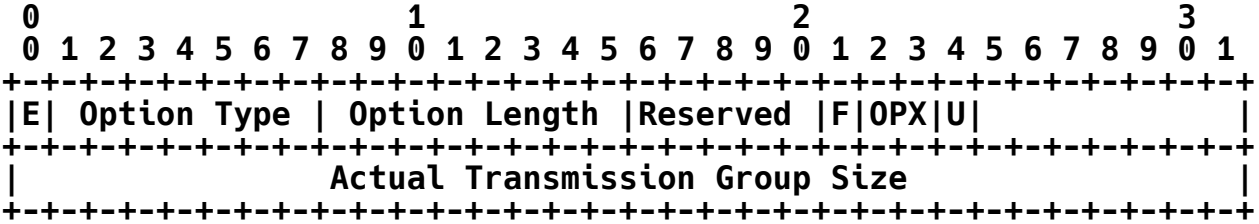
Parity Group Number (PRM_GROUP)

The number of the group of k parity packets amongst the h parity packets within the transmission group to which the parity packet belongs, where the first k parity packets are in group zero. PRM_GROUP MUST NOT be zero.

OPT_PARITY_GRP MAY be appended only to parity packets.

OPT_PARITY_GRP is NOT network-significant.

11.8.3. OPT_CURR_TGSIZE - Packet Extension Format



Option Type = 0x0A

Option Length = 8 octets

Actual Transmission Group Size (PRM_ATGSIZE)

The actual number of data packets in this transmission group. This MUST be less than or equal to the maximum transmission group size PARITY_PRM_TGS in OPT_PARITY_PRM.

OPT_CURR_TGSIZE MAY be appended to data and parity packets (ODATA or RDATA) and to SPMs.

OPT_CURR_TGSIZE is network-significant except when appended to ODATA.

12. Appendix B - Support for Congestion Control

12.1. Introduction

A source MUST implement strategies for congestion avoidance, aimed at providing overall network stability, fairness among competing PGM flows, and some degree of fairness towards coexisting TCP flows [13]. In order to do this, the source must be provided with feedback on the status of the network in terms of traffic load. This appendix specifies NE procedures that provide such feedback to the source in a scalable way. (An alternative TCP-friendly scheme for congestion control that does not require NE support can be found in [16]).

The procedures specified in this section enable the collection and selective forwarding of three types of feedback to the source:

- Worst link load as measured in network elements.
- Worst end-to-end path load as measured in network elements.
- Worst end-to-end path load as reported by receivers.

This specification defines in detail NE procedures, receivers procedures and packet formats. It also defines basic procedures in receivers for generating congestion reports. This specification does not define the procedures used by PGM sources to adapt their transmission rates in response of congestion reports. Those procedures depend upon the specific congestion control scheme.

PGM defines a header option that PGM receivers may append to NAKs (OPT_CR). OPT_CR carries congestion reports in NAKs that propagate upstream towards the source.

During the process of hop-by-hop reverse NAK forwarding, NEs examine OPT_CR and possibly modify its contents prior to forwarding the NAK upstream. Forwarding CRs also has the side effect of creating congestion report state in the NE. The presence of OPT_CR and its contents also influences the normal NAK suppression rules. Both the modification performed on the congestion report and the additional suppression rules depend on the content of the congestion report and on the congestion report state recorded in the NE as detailed below.

OPT_CR contains the following fields:

OPT_CR_NE_WL Reports the load in the worst link as detected though NE internal measurements

OPT_CR_NE_WP Reports the load in the worst end-to-end path as detected though NE internal measurements

OPT_CR_RX_WP Reports the load in the worst end-to-end path as detected by receivers

A load report is either a packet drop rate (as measured at an NE's interfaces) or a packet loss rate (as measured in receivers). Its value is linearly encoded in the range 0-0xFFFF, where 0xFFFF represents a 100% loss/drop rate. Receivers that send a NAK bearing OPT_CR determine which of the three report fields are being reported.

OPT_CR also contains the following fields:

OPT_CR_NEL A bit indicating that OPT_CR_NE_WL is being reported.

OPT_CR_NEP A bit indicating that OPT_CR_NE_WP is being reported.

OPT_CR_RXP A bit indicating that OPT_CR_RX_WP is being reported.

OPT_CR_LEAD A SQN in the ODATA space that serves as a temporal reference for the load report values. This is initialized by receivers with the leading edge of the transmit window as known at the moment of transmitting the NAK. This value MAY be advanced in NEs that modify the content of OPT_CR.

OPT_CR_RCVR The identity of the receiver that generated the worst OPT_CR_RX_WP.

The complete format of the option is specified later.

12.2. NE-Based Worst Link Report

To permit network elements to report worst link, receivers append OPT_CR to a NAK with bit OPT_CR_NEL set and OPT_CR_NE_WL set to zero. NEs receiving NAKs that contain OPT_CR_NE_WL process the option and update per-TSI state related to it as described below. The ultimate result of the NEs' actions ensures that when a NAK leaves a sub-tree, OPT_CR_NE_WL contains a congestion report that reflects the load of the worst link in that sub-tree. To achieve this, NEs rewrite OPT_CR_NE_WL with the worst value among the loads measured on the local (outgoing) links for the session and the congestion reports received from those links.

Note that the mechanism described in this sub-section does not permit the monitoring of the load on (outgoing) links at non-PGM-capable multicast routers. For this reason, NE-Based Worst Link Reports SHOULD be used in pure PGM topologies only. Otherwise, this mechanism might fail in detecting congestion. To overcome this limitation PGM sources MAY use a heuristic that combines NE-Based Worst Link Reports and Receiver-Based Reports.

12.3. NE-Based Worst Path Report

To permit network elements to report a worst path, receivers append OPT_CR to a NAK with bit OPT_CR_NEP set and OPT_CR_NE_WP set to zero. The processing of this field is similar to that of OPT_CR_NE_WL with the difference that, on the reception of a NAK, the value of OPT_CR_NE_WP is adjusted with the load measured on the interface on which the NAK was received according to the following formula:

OPT_CR_NE_WP = if_load + OPT_CR_NE_WP * (100% - if_loss_rate)

The worst among the adjusted OPT_CR_NE_WP is then written in the outgoing NAK. This results in a hop-by-hop accumulation of link loss rates into a path loss rate.

As with OPT_CR_NE_WL, the congestion report in OPT_CR_NE_WP may be invalid if the multicast distribution tree includes non-PGM-capable routers.

12.4. Receiver-Based Worst Report

To report a packet loss rate, receivers append OPT_CR to a NAK with bit OPT_CR_RXP set and OPT_CR_RX_WP set to the packet loss rate. NEs receiving NAKs that contain OPT_CR_RX_WP process the option and update per-TSI state related to it as described below. The ultimate result of the NEs' actions ensures that when a NAK leaves a sub-tree, OPT_CR_RX_WP contains a congestion report that reflects the load of the worst receiver in that sub-tree. To achieve this, NEs rewrite OTP_CR_RE_WP with the worst value among the congestion reports received on its outgoing links for the session. In addition to this, OPT_CR_RCVR MUST contain the NLA of the receiver that originally measured the value of OTP_CR_RE_WP being forwarded.

12.5. Procedures - Receivers

To enable the generation of any type of congestion report, receivers MUST insert OPT_CR in each NAK they generate and provide the corresponding field (OPT_CR_NE_WL, OPT_CR_NE_WP, OPT_CR_RX_WP). The specific fields to be reported will be advertised to receivers in OPT_CRQST on the session's SPMs. Receivers MUST provide only those options requested in OPT_CRQST.

Receivers MUST initialize OPT_CR_NE_WL and OPT_CR_NE_WP to 0 and they MUST initialize OPT_CR_RCVR to their NLA. At the moment of sending the NAK, they MUST also initialize OPT_CR_LEAD to the leading edge of the transmission window.

Additionally, if a receiver generates a NAK with OPT_CR with OPT_CR_RX_WP, it MUST initialize OPT_CR_RX_WP to the proper value, internally computed.

12.6. Procedures - Network Elements

Network elements start processing each OPT_CR by selecting a reference SQN in the ODATA space. The reference SQN selected is the highest SQN known to the NE. Usually this is OPT_CR_LEAD contained in the NAK received.

They use the selected SQN to age the value of load measurement as follows:

- locally measured load values (e.g. interface loads) are considered up-to-date

- load values carried in OPT_CR are considered up-to-date and are not aged so as to be independent of variance in round-trip times from the network element to the receivers

- old load values recorded in the NE are exponentially aged according to the difference between the selected reference SQN and the reference SQN associated with the old load value.

The exponential aging is computed so that a recorded value gets scaled down by a factor exp(-1/2) each time the expected inter-NAK time elapses. Hence the aging formula must include the current loss rate as follows:

```
aged_loss_rate = loss_rate * exp( - SQN_difference * loss_rate /
2)
```

Note that the quantity 1/loss_rate is the expected SQN_lag between two NAKs, hence the formula above can also be read as:

```
aged_loss_rate = loss_rate * exp( - 1/2 * SQN_difference /
SQN_lag)
```

which equates to (loss_rate * exp(-1/2)) when the SQN_difference is equal to expected SQN_lag between two NAKs.

All the subsequent computations refer to the aged load values.

Network elements process OPT_CR by handling the three possible types of congestion reports independently.

For each congestion report in an incoming NAK, a new value is computed to be used in the outgoing NAK:

- The new value for OPT_CR_NE_WL is the maximum of the load measured on the outgoing interfaces for the session, the value of OPT_CR_NE_WL of the incoming NAK, and the value previously sent upstream (recorded in the NE). All these values are as obtained after the aging process.

- The new value for OPT_CR_NE_WP is the maximum of the value previously sent upstream (after aging) and the value of OPT_CR_NE_WP in the incoming NAK adjusted with the load on the interface upon which the NAK was received (as described above).

- The new value for OPT_CR_RX_WP is the maximum of the value previously sent upstream (after aging) and the value of OPT_CR_RX_WP in the incoming NAK.

- If OPT_CR_RX_WP was selected from the incoming NAK, the new value for OPT_CR_RCVR is the one in the incoming NAK. Otherwise it is the value previously sent upstream.

- The new value for OPT_CR_LEAD is the reference SQN selected for the aging procedure.

12.6.1. Overriding Normal Suppression Rules

Normal suppression rules hold to determine if a NAK should be forwarded upstream or not. However if any of the outgoing congestion reports has changed by more than 5% relative to the one previously sent upstream, this new NAK is not suppressed.

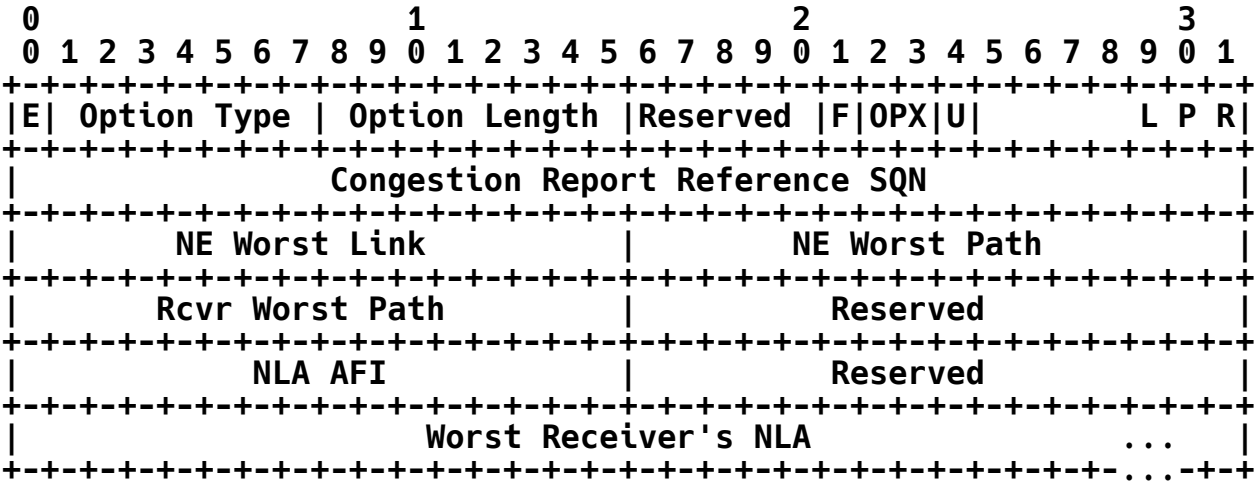
12.6.2. Link Load Measurement

PGM routers monitor the load on all their outgoing links and record it in the form of per-interface loss rate statistics. "load" MUST be interpreted as the percentage of the packets meant to be forwarded on the interface that were dropped. Load statistics refer to the aggregate traffic on the links and not to PGM traffic only.

This document does not specify the algorithm to be used to collect such statistics, but requires that such algorithm provide both accuracy and responsiveness in the measurement process. As far as accuracy is concerned, the expected measurement error SHOULD be upper-limited (e.g. less than than 10%). As far as responsiveness is concerned, the measured load SHOULD converge to the actual value in a limited time (e.g. converge to 90% of the actual value in less than 200 milliseconds), when the instantaneous offered load changes. Whenever both requirements cannot be met at the same time, accuracy SHOULD be traded for responsiveness.

12.7. Packet Formats

12.7.1. OPT_CR - Packet Extension Format



Option Type = 0x10

Option Length = 20 octets + NLA length

L OPT_CR_NEL bit : set indicates OPT_CR_NE_WL is being reported

P OPT_CR_NEP bit : set indicates OPT_CR_NE_WP is being reported

R OPT_CR_RXP bit : set indicates OPT_CR_RX_WP is being reported

Congestion Report Reference SQN (OPT_CR_LEAD).

A SQN in the ODATA space that serves as a temporal reference point for the load report values.

NE Worst Link (OPT_CR_NE_WL).

Reports the load in the worst link as detected though NE internal measurements

NE Worst Path (OPT_CR_NE_WP).

Reports the load in the worst end-to-end path as detected though NE internal measurements

Rcvr Worst Path (OPT_CR_RX_WP).

Reports the load in the worst end-to-end path as detected by receivers

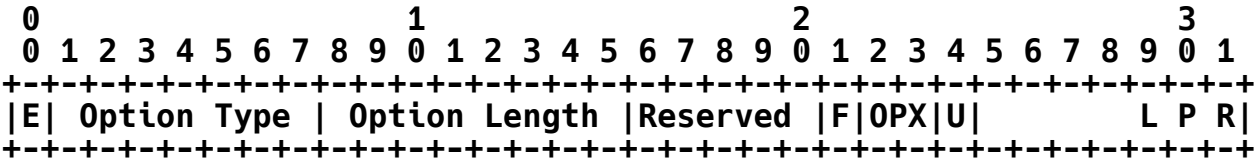
Worst Receiver's NLA (OPT_CR_RCVR).

The unicast address of the receiver that generated the worst OPT_CR_RX_WP.

OPT_CR MAY be appended only to NAKs.

OPT-CR is network-significant.

12.7.2. OPT_CRQST - Packet Extension Format



Option Type = 0x11

Option Length = 4 octets

L OPT_CRQST_NEL bit : set indicates OPT_CR_NE_WL is being requested

P OPT_CRQST_NEP bit : set indicates OPT_CR_NE_WP is being requested

R OPT_CRQST_RXP bit : set indicates OPT_CR_RX_WP is being requested

OPT_CRQST MAY be appended only to SPMs.

OPT-CRQST is network-significant.

13. Appendix C - SPM Requests

13.1. Introduction

SPM Requests (SPMRs) MAY be used to solicit an SPM from a source in a non-implosive way. The typical application is for late-joining receivers to solicit SPMs directly from a source in order to be able to NAK for missing packets without having to wait for a regularly scheduled SPM from that source.

13.2. Overview

Allowing for SPMR implosion protection procedures, a receiver MAY unicast an SPMR to a source to solicit the most current session, window, and path state from that source any time after the receiver has joined the group. A receiver may learn the TSI and source to which to direct the SPMR from any other PGM packet it receives in the group, or by any other means such as from local configuration or directory services. The receiver MUST use the usual SPM procedures to glean the unicast address to which it should direct its NAKs from the solicited SPM.

13.3. Packet Contents

This section just provides enough short-hand to make the Procedures intelligible. For the full details of packet contents, please refer to Packet Formats below.

13.3.1. SPM Requests

SPMRs are transmitted by receivers to solicit SPMs from a source.

SPMs are unicast to a source and contain:

SPMR_TSI	the source-assigned TSI for the session to which the SPMR corresponds

13.4. Procedures - Sources

A source MUST respond immediately to an SPMR with the corresponding SPM rate limited to once per IHB_MIN per TSI. The corresponding SPM matches SPM_TSI to SPMR_TSI and SPM_DPORT to SPMR_DPORT.

13.5. Procedures - Receivers

To moderate the potentially implosive behavior of SPMRs at least on a densely populated subnet, receivers MUST use the following back-off and suppression procedure based on multicasting the SPMR with a TTL of 1 ahead of and in addition to unicasting the SPMR to the source. The role of the multicast SPMR is to suppress the transmission of identical SPMRs from the subnet.

More specifically, before unicasting a given SPMR, receivers MUST choose a random delay on SPMR_BO_IVL (~250 msecs) during which they listen for a multicast of an identical SPMR. If a receiver does not see a matching multicast SPMR within its chosen random interval, it MUST first multicast its own SPMR to the group with a TTL of 1 before then unicasting its own SPMR to the source. If a receiver does see a

matching multicast SPMR within its chosen random interval, it MUST refrain from unicasting its SPMR and wait instead for the corresponding SPM.

In addition, receipt of the corresponding SPM within this random interval SHOULD cancel transmission of an SPMR.

In either case, the receiver MUST wait at least SPMR_SPM_IVL before attempting to repeat the SPMR by choosing another delay on SPMR_BO_IVL and repeating the procedure above.

The corresponding SPMR matches SPMR_TSI to SPMR_TSI and SPMR_DPORT to SPMR_DPORT. The corresponding SPM matches SPM_TSI to SPMR_TSI and SPM_DPORT to SPMR_DPORT.

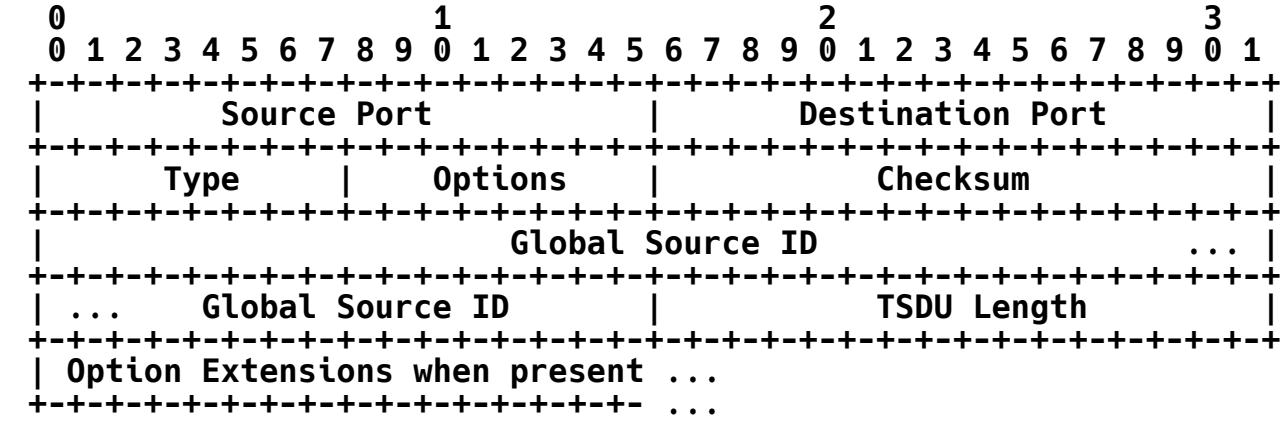
13.6. SPM Requests

SPMR:

SPM Requests are sent by receivers to request the immediate transmission of an SPM for the given TSI from a source.

The network-header source address of an SPMR is the unicast NLA of the entity that originates the SPMR.

The network-header destination address of an SPMR is the unicast NLA of the source from which the corresponding SPM is requested.



Source Port:

SPMR_SPORT

Data-Destination Port

Destination Port:

SPMR_DPORT

Data-Source Port, together with Global Source ID forms SPMR_TSI

Type:

SPMR_TYPE = 0x0C

Global Source ID:

SPMR_GSI

Together with Source Port forms

SPMR_TSI

14. Appendix D - Poll Mechanism

14.1. Introduction

These procedures provide PGM network elements and sources with the ability to poll their downstream PGM neighbors to solicit replies in an implosion-controlled way.

Both general polls and specific polls are possible. The former provide a PGM (parent) node with a way to check if there are any PGM (children) nodes connected to it, both network elements and receivers, and to estimate their number. The latter may be used by PGM parent nodes to search for nodes with specific properties among its PGM children. An example of application for this is DLR discovery.

Polling is implemented using two additional PGM packets:

POLL a Poll Request that PGM parent nodes multicast to the group to perform the poll. Similarly to NCFs, POLL packets stop at the first PGM node they reach, as they are not forwarded by PGM network elements.

POLR a Poll Response that PGM children nodes (either network elements or receivers) use to reply to a Poll Request by addressing it to the NLA of the interface from which the triggering POLL was sent.

The polling mechanism dictates that PGM children nodes that receive a POLL packet reply to it only if certain conditions are satisfied and ignore the POLL otherwise. Two types of condition are possible: a random condition that defines a probability of replying for the polled child, and a deterministic condition. Both the random condition and the deterministic condition are controlled by the polling PGM parent node by specifying the probability of replying and defining the deterministic condition(s) respectively. Random-only poll, deterministic-only poll or a combination of the two are possible.

The random condition in polls allows the prevention of implosion of replies by controlling their number. Given a probability of replying P and assuming that each receiver makes an independent decision, the number of expected replies to a poll is P*N where N is the number of PGM children relative to the polling PGM parent. The polling node can control the number of expected replies by specifying P in the POLL packet.

14.2. Packet Contents

This section just provides enough short-hand to make the Procedures intelligible. For the full details of packet contents, please refer to Packet Formats below.

14.2.1. POLL (Poll Request)

POLL_SQN	a sequence number assigned sequentially by the polling parent in unit increments and scoped by POLL_PATH and the TSI of the session.
POLL_ROUND	a poll round sequence number. Multiple poll rounds are possible within a POLL_SQN.
POLL_S_TYPE	the sub-type of the poll request
POLL_PATH	the network-layer address (NLA) of the interface on the PGM network element or source on which the POLL is transmitted
POLL_BO_IVL	the back-off interval that MUST be used to compute the random back-off time to wait before sending the response to a poll. POLL_BO_IVL is expressed in microseconds.
POLL_RAND	a random string used to implement the randomness in replying

POLL_MASK a bit-mask used to determine the probability of random replies

Poll request MAY also contain options which specify deterministic conditions for the reply. No options are currently defined.

14.2.2. POLR (Poll Response)

POLR_SQN POLL_SQN of the poll request for which this is a reply

POLR_ROUND POLL_ROUND of the poll request for which this is a reply

Poll response MAY also contain options. No options are currently defined.

14.3. Procedures - General

14.3.1. General Polls

General Polls may be used to check for and count PGM children that are 1 PGM hop downstream of an interface of a given node. They have POLL_S_TYPE equal to PGM_POLL_GENERAL. PGM children that receive a general poll decide whether to reply to it only based on the random condition present in the POLL.

To prevent response implosion, PGM parents that initiate a general poll SHOULD establish the probability of replying to the poll, P, so that the expected number of replies is contained. The expected number of replies is N * P, where N is the number of children. To be able to compute this number, PGM parents SHOULD already have a rough estimate of the number of children. If they do not have a recent estimate of this number, they SHOULD send the first poll with a very low probability of replying and increase it in subsequent polls in order to get the desired number of replies.

To prevent poll-response implosion caused by a sudden increase in the children population occurring between two consecutive polls with increasing probability of replying, PGM parents SHOULD use poll rounds. Poll rounds allow PGM parents to "freeze" the size of the children population when they start a poll and to maintain it constant across multiple polls (with the same POLL_SQN but different POLL_ROUND). This works by allowing PGM children to respond to a poll only if its POLL_ROUND is zero or if they have previously received a poll with the same POLL_SQN and POLL_ROUND equal to zero.

In addition to this PGM children MUST observe a random back-off in replying to a poll. This spreads out the replies in time and allows a PGM parent to abort the poll if too many replies are being received. To abort an ongoing poll a PGM parent MUST initiate another poll with different POLL_SQN. PGM children that receive a POLL MUST cancel any pending reply for POLLs with POLL_SQN different from the one of the last POLL received.

For a given poll with probability of replying P, a PGM parent estimates the number of children as M / P, where M is the number of responses received. PGM parents SHOULD keep polling periodically and use some average of the result of recent polls as their estimate for the number of children.

14.3.2. Specific Polls

Specific polls provide a way to search for PGM children that comply to specific requisites. As an example specific poll could be used to search for down-stream DLRs. A specific poll is characterized by a POLL_S_TYPE different from PGM_POLL_GENERAL. PGM children decide whether to reply to a specific poll or not based on the POLL_S_TYPE, on the random condition and on options possibly present in the POLL. The way options should be interpreted is defined by POLL_S_TYPE. The random condition MUST be interpreted as an additional condition to be satisfied. To disable the random condition PGM parents MUST specify a probability of replying P equal to 1.

PGM children MUST ignore a POLL packet if they do not understand POLL_S_TYPE. Some specific POLL_S_TYPE may also require that the children ignore a POLL if they do not fully understand all the PGM options present in the packet.

14.4. Procedures - PGM Parents (Sources or Network Elements)

A PGM parent (source or network element), that wants to poll the first PGM-hop children connected to one of its outgoing interfaces MUST send a POLL packet on that interface with:

POLL_SQN equal to POLL_SQN of the last POLL sent incremented by one. If poll rounds are used, this must be equal to POLL_SQN of the last group of rounds incremented by one.

POLL_ROUND The round of the poll. If the poll has a single round, this must be zero. If the poll has multiple rounds, this must be one plus the last POLL_ROUND for the same POLL_SQN, or zero if this is the first round within this POLL_SQN.

POLL_S_TYPE	the type of the poll. For general poll use PGM_POLL_GENERAL
POLL_PATH	set to the NLA of the outgoing interface
POLL_BO_IVL	set to the wanted reply back-off interval. As far as the choice of this is concerned, using NAK_BO_IVL is usually a conservative option, however a smaller value MAY be used, if the number of expected replies can be determined with a good confidence or if a conservatively low probability of reply (P) is being used (see POLL_MASK next). When the number of expected replies is unknown, a large POLL_BO_IVL SHOULD be used, so that the poll can be effectively aborted if the number of replies being received is too large.
POLL_RAND	MUST be a random string re-computed each time a new poll is sent on a given interface
POLL_MASK	determines the probability of replying, P, according to the relationship P = 1 / (2 ^ B), where B is the number of bits set in POLL_MASK [15]. If this is a deterministic poll, B MUST be 0, i.e. POLL_MASK MUST be a all-zeroes bit-mask.

Nota Bene: POLLs transmitted by network elements MUST bear the ODATA source's network-header source address, not the network element's NLA. POLLs MUST also be transmitted with the IP

Router Alert Option [6], to be allow PGM network element to intercept them.

A PGM parent that has started a poll by sending a POLL packet SHOULD wait at least POLL_BO_IVL before starting another poll. During this interval it SHOULD collect all the valid response (the one with POLR_SQN and POLR_ROUND matching with the outstanding poll) and process them at the end of the collection interval.

A PGM parent SHOULD observe the rules mentioned in the description of general procedures, to prevent implosion of response. These rules should in general be observed both for generic polls and specific polls. The latter however can be performed using deterministic poll (with no implosion prevention) if the expected number of replies is known to be small. A PGM parent that issue a generic poll with the intent of estimating the children population size SHOULD use poll rounds to "freeze" the children that are involved in the measure process. This allows the sender to "open the door wider" across

subsequent rounds (by increasing the probability of response), without fear of being flooded by late joiners. Note the use of rounds has the drawback of introducing additional delay in the estimate of the population size, as the estimate obtained at the end of a round-group refers to the condition present at the time of the first round.

A PGM parent that has started a poll SHOULD monitor the number of replies during the collection phase. If this become too large, the PGM parent SHOULD abort the poll by immediately starting a new poll (different POLL_SQN) and specifying a very low probability of replying.

When polling is being used to estimate the receiver population for the purpose of calculating NAK_BO_IVL, OPT_NAK_BO_IVL (see 16.4.1 below) MUST be appended to SPMs, MAY be appended to NCFs and POLLs, and in all cases MUST have NAK_BO_IVL_SQN set to POLL_SQN of the most recent complete round of polls, and MUST bear that round's corresponding derived value of NAK_BAK_IVL. In this way, OPT_NAK_BO_IVL provides a current value for NAK_BO_IVL at the same time as information is being gathered for the calculation of a future value of NAK_BO_IVL.

14.5. Procedures - PGM Children (Receivers or Network Elements)

PGM receivers and network elements MUST compute a 32-bit random node identifier (RAND_NODE_ID) at startup time. When a PGM child (receiver or network element) receives a POLL it MUST use its RAND_NODE_ID to match POLL_RAND of incoming POLLs. The match is limited to the bits specified by POLL_MASK. If the incoming POLL contain a POLL_MASK made of all zeroes, the match is successful despite the content of POLL_RAND (deterministic reply). If the match fails, then the receiver or network element MUST discard the POLL without any further action, otherwise it MUST check the fields POLL_ROUND, POLL_S_TYPE and any PGM option included in the POLL to determine whether it SHOULD reply to the poll.

If POLL_ROUND is non-zero and the PGM receiver has not received a previous poll with the same POLL_SQN and a zero POLL_ROUND, it MUST discard the poll without further action.

If POLL_S_TYPE is equal to PGM_POLL_GENERAL, the PGM child MUST schedule a reply to the POLL despite the presence of PGM options on the POLL packet.

If POLL_S_TYPE is different from PGM_POLL_GENERAL, the decision on whether a reply should be scheduled depends on the actual type and on the options possibly present in the POLL.

If POLL_S_TYPE is unknown to the recipient of the POLL, it MUST NOT reply and ignore the poll. Currently the only POLL_S_TYPE defined are PGM_POLL_GENERAL and PGM_POLL_DLR.

If a PGM receiver or network element has decided to reply to a POLL, it MUST schedule the transmission of a single POLR at a random time in the future. The random delay is chosen in the interval [0, POLL_BO_IVL]. POLL_BO_IVL is the one contained in the POLL received. When this timer expires, it MUST send a POLR using POLL_PATH of the received POLL as destination address. POLR_SQN MUST be equal to POLL_SQN and POLR_ROUND must be equal to POLL_ROUND. The POLR MAY contain PGM options according to the semantic of POLL_S_TYPE or the semantic of PGM options possibly present in the POLL. If POLL_S_TYPE is PGM_POLL_GENERAL no option is REQUIRED.

A PGM receiver or network element MUST cancel any pending transmission of POLRs if a new POLL is received with POLL_SQN different from POLR_SQN of the poll that scheduled POLRs.

14.6. Constant Definition

The POLL_S_TYPE values currently defined are:

PGM_POLL_GENERAL	0
PGM_POLL_DLR	1

14.7. Packet Formats

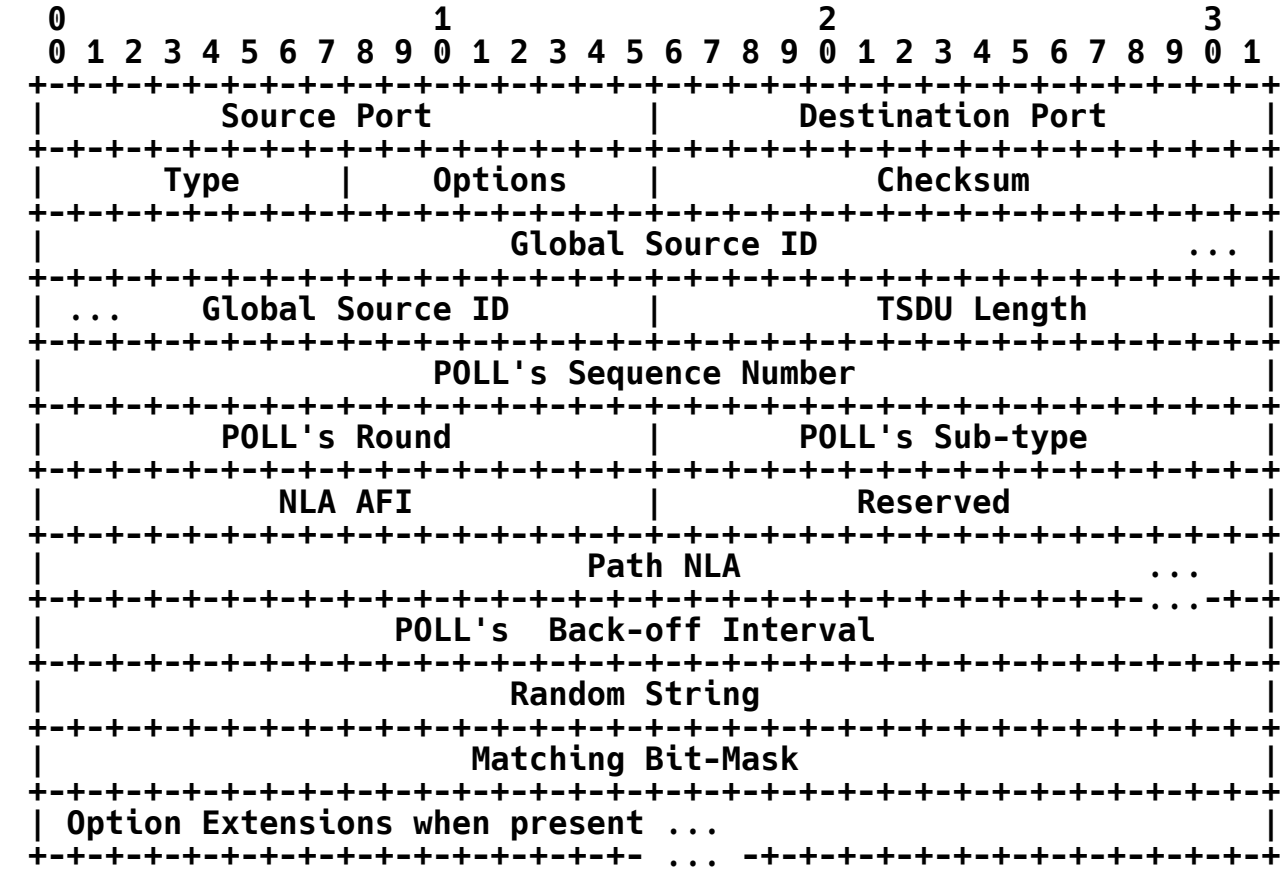
The packet formats described in this section are transport-layer headers that MUST immediately follow the network-layer header in the packet.

The descriptions of Data-Source Port, Data-Destination Port, Options, Checksum, Global Source ID (GSI), and TSDU Length are those provided in Section 8.

14.7.1. Poll Request

POLL are sent by PGM parents (sources or network elements) to initiate a poll among their first PGM-hop children.

POLLs are sent to the ODATA multicast group. The network-header source address of a POLL is the ODATA source's NLA. POLL MUST be transmitted with the IP Router Alert Option.



Source Port:

POLL_SPORT

Data-Source Port, together with POLL_GSI forms POLL_TSI

Destination Port:

POLL_DPORT

Data-Destination Port

Type:

POLL_TYPE = 0x01

Global Source ID:

POLL_GSI

Together with POLL_SPORT forms POLL_TSI

POLL's Sequence Number

POLL_SQN

The sequence number assigned to the POLL by the originator.

POLL's Round

POLL_ROUND

The round number within the poll sequence number.

POLL's Sub-type

POLL_S_TYPE

The sub-type of the poll request.

Path NLA:

POLL_PATH

The NLA of the interface on the source or network element on which this POLL was forwarded.

POLL's Back-off Interval

POLL_BO_IVL

The back-off interval used to compute a random back-off for the reply, expressed in microseconds.

Random String

POLL_RAND

A random string used to implement the random condition in replying.

Matching Bit-Mask

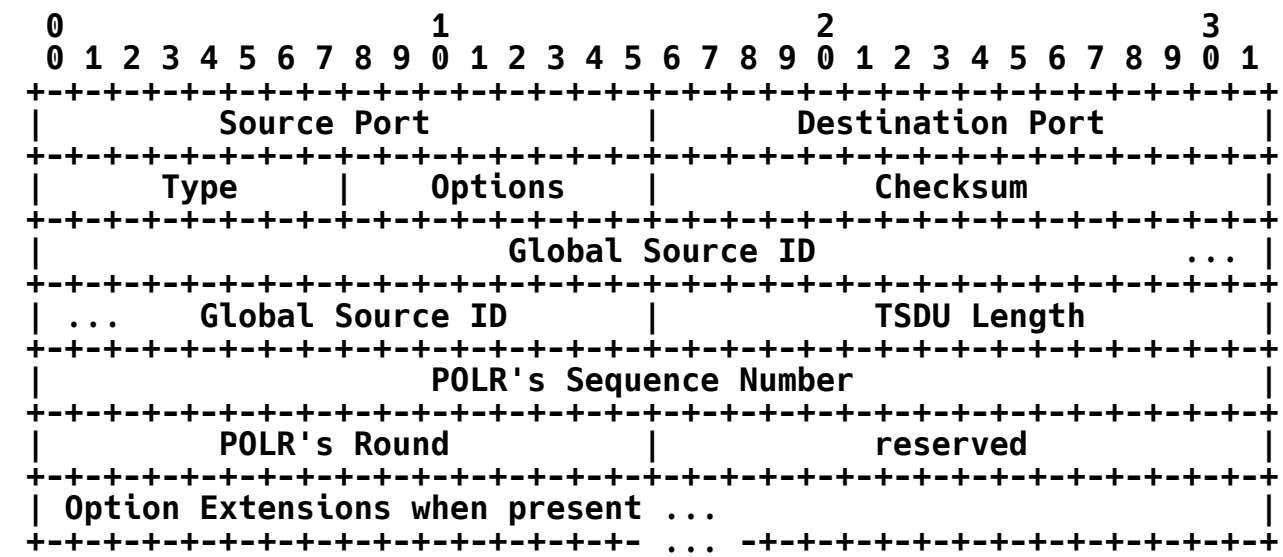
POLL_MASK

A bit-mask used to determine the probability of random replies.

14.7.2. Poll Response

POLR are sent by PGM children (receivers or network elements) to reply to a POLL.

The network-header source address of a POLR is the unicast NLA of the entity that originates the POLR. The network-header destination address of a POLR is initialized by the originator of the POLL to the unicast NLA of the upstream PGM element (source or network element) known from the POLL that triggered the POLR.



Source Port:

POLR_SPORT

Data-Destination Port

Destination Port:

POLR_DPORT

Data-Source Port, together with Global Source ID forms POLR_TSI

Type:

POLR_TYPE = 0x02

Global Source ID:

POLR_GSI

Together with POLR_DPORT forms POLR_TSI

POLR's Sequence Number

POLR_SQN

The sequence number (POLL_SQN) of the POLL packet for which this is a reply.

POLR's Round

POLR_ROUND

The round number (POLL_ROUND) of the POLL packet for which this is a reply.

15. Appendix E - Implosion Prevention

15.1. Introduction

These procedures are intended to prevent NAK implosion and to limit its extent in case of the loss of all or part of the suppressing multicast distribution tree. They also provide a means to adaptively tune the NAK back-off interval, NAK_BO_IVL.

The PGM virtual topology is established and refreshed by SPMs. Between one SPM and the next, PGM nodes may have an out-of-date view of the PGM topology due to multicast routing changes, flapping, or a link/router failure. If any of the above happens relative to a PGM parent node, a potential NAK implosion problem arises because the parent node is unable to suppress the generation of duplicate NAKs as it cannot reach its children using NCFs. The procedures described below introduce an alternative way of performing suppression in this case. They also attempt to prevent implosion by adaptively tuning NAK_BO_IVL.

15.2. Tuning NAK_BO_IVL

Sources and network elements continuously monitor the number of duplicated NAKs received and use this observation to tune the NAK back-off interval (NAK_BO_IVL) for the first PGM-hop receivers connected to them. Receivers learn the current value of NAK_BO_IVL through OPT_NAK_BO_IVL appended to NCFs or SPMs.

15.2.1. Procedures - Sources and Network Elements

For each TSI, sources and network elements advertise the value of NAK_BO_IVL that their first PGM-hop receivers should use. They advertise a separate value on all the outgoing interfaces for the TSI and keep track of the last values advertised.

For each interface and TSI, sources and network elements count the number of NAKs received for a specific repair state (i.e., per sequence number per TSI) from the time the interface was first added to the repair state list until the time the repair state is discarded. Then they use this number to tune the current value of NAK_BO_IVL as follows:

- Increase the current value NAK_BO_IVL when the first duplicate NAK is received for a given SQN on a particular interface.

Decrease the value of NAK_BO_IVL if no duplicate NAKs are received on a particular interface for the last NAK_PROBE_NUM measurements where each measurement corresponds to the creation of a new repair state.

An upper and lower limit are defined for the possible value of NAK_BO_IVL at any time. These are NAK_BO_IVL_MAX and NAK_BO_IVL_MIN respectively. The initial value that should be used as a starting point to tune NAK_BO_IVL is NAK_BO_IVL_DEFAULT. The policies RECOMMENDED for increasing and decreasing NAK_BO_IVL are multiplying by two and dividing by two respectively.

Sources and network elements advertise the current value of NAK_BO_IVL through the OPT_NAK_BO_IVL that they append to NCFs. They MAY also append OPT_NAK_BO_IVL to outgoing SPMs.

In order to avoid forwarding the NAK_BO_IVL advertised by the parent, network elements must be able to recognize OPT_NAK_BO_IVL. Network elements that receive SPMs containing OPT_NAK_BO_IVL MUST either remove the option or over-write its content (NAK_BO_IVL) with the current value of NAK_BO_IVL for the outgoing interface(s), before forwarding the SPMs.

Sources MAY advertise the value of NAK_BO_IVL_MAX and NAK_BO_IVL_MIN to the session by appending a OPT_NAK_BO_RNG to SPMs.

15.2.2. Procedures - Receivers

Receivers learn the value of NAK_BO_IVL to use through the option OPT_NAK_BO_IVL, when this is present in NCFs or SPMs. A value for NAK_BO_IVL learned from OPT_NAK_BO_IVL MUST NOT be used by a receiver unless either NAK_BO_IVL_SQN is zero, or the receiver has seen POLL_RND == 0 for POLL_SQN =< NAK_BO_IVL_SQN within half the sequence number space. The initial value of NAK_BO_IVL is set to NAK_BO_IVL_DEFAULT.

Receivers that receive an SPM containing OPT_NAK_BO_RNG MUST use its content to set the local values of NAK_BO_IVL_MAX and NAK_BO_IVL_MIN.

15.2.3. Adjusting NAK_BO_IVL in the absence of NAKs

Monitoring the number of duplicate NAKs provides a means to track indirectly the change in the size of first PGM-hop receiver population and adjust NAK_BO_IVL accordingly. Note that the number of duplicate NAKs for a given SQN is related to the number of first PGM-hop children that scheduled (or forwarded) a NAK and not to the absolute number of first PGM-hop children. This mechanism, however, does not work in the absence of packet loss, hence a large number of duplicate NAKs is possible after a period without NAKs, if many new receivers have joined the session in the meanwhile. To address this issue, PGM Sources and network elements SHOULD periodically poll the number of first PGM-hop children using the "general poll" procedures described in Appendix D. If the result of the polls shows that the population size has increased significantly during a period without NAKs, they SHOULD increase NAK_BO_IVL as a safety measure.

15.3. Containing Implosion in the Presence of Network Failures

15.3.1. Detecting Network Failures

In some cases PGM (parent) network elements can promptly detect the loss of all or part of the suppressing multicast distribution tree (due to network failures or route changes) by checking their multicast connectivity, when they receive NAKs. In some other cases this is not possible as the connectivity problem might occur at some other non-PGM node downstream or might take time to reflect in the multicast routing table. To address these latter cases, PGM uses a simple heuristic: a failure is assumed for a TSI when the count of duplicated NAKs received for a repair state reaches the value DUP_NAK_MAX in one of the interfaces.

15.3.2. Containing Implosion

When a PGM source or network element detects or assumes a failure for which it looses multicast connectivity to down-stream PGM agents (either receivers or other network elements), it sends unicast NCFs to them in response to NAKs. Downstream PGM network elements which receive unicast NCFs and have multicast connectivity to the multicast session send special SPMs to prevent further NAKs until a regular SPM sent by the source refreshes the PGM tree.

Procedures - Sources and Network Elements

PGM sources or network elements which detect or assume a failure that prevents them from reaching down-stream PGM agents through multicast NCFs revert to confirming NAKs through unicast NCFs for a given TSI on a given interface. If the PGM agent is the source itself, than it MUST generate an SPM for the TSI, in addition to sending the unicast NCF.

Network elements MUST keep using unicast NCFs until they receive a regular SPM from the source.

When a unicast NCF is sent for the reasons described above, it MUST contain the OPT_NBR_UNREACH option and the OPT_PATH_NLA option. OPT_NBR_UNREACH indicates that the sender is unable to use multicast to reach downstream PGM agents. OPT_PATH_NLA carries the network layer address of the NCF sender, namely the NLA of the interface leading to the unreachable subtree.

When a PGM network element receives an NCF containing the OPT_NBR_UNREACH option, it MUST ignore it if OPT_PATH_NLA specifies an upstream neighbour different from the one currently known to be the upstream neighbor for the TSI. Assuming the network element matches the OPT_PATH_NLA of the upstream neighbour address, it MUST stop forwarding NAKs for the TSI until it receives a regular SPM for the TSI. In addition, it MUST also generate a special SPM to prevent downstream receivers from sending more NAKs. This special SPM MUST contain the OPT_NBR_UNREACH option and SHOULD have a SPM_SQN equal to SPM_SQN of the last regular SPM forwarded. The OPT_NBR_UNREACH option invalidates the windowing information in SPMs (SPM_TRAIL and SPM_LEAD). The PGM network element that adds the OPT_NBR_UNREACH option SHOULD invalidate the windowing information by setting SPM_TRAIL to 0 and SPM_LEAD to 0x80000000.

PGM network elements which receive an SPM containing the OPT_NBR_UNREACH option and whose SPM_PATH matches the currently known PGM parent, MUST forward them in the normal way and MUST stop

forwarding NAKs for the TSI until they receive a regular SPM for the TSI. If the SPM_PATH does not match the currently known PGM parent, the SPM containing the OPT_NBR_UNREACH option MUST be ignored.

Procedures - Receivers

PGM receivers which receive either an NCF or an SPM containing the OPT_NBR_UNREACH option MUST stop sending NAKs until a regular SPM is received for the TSI.

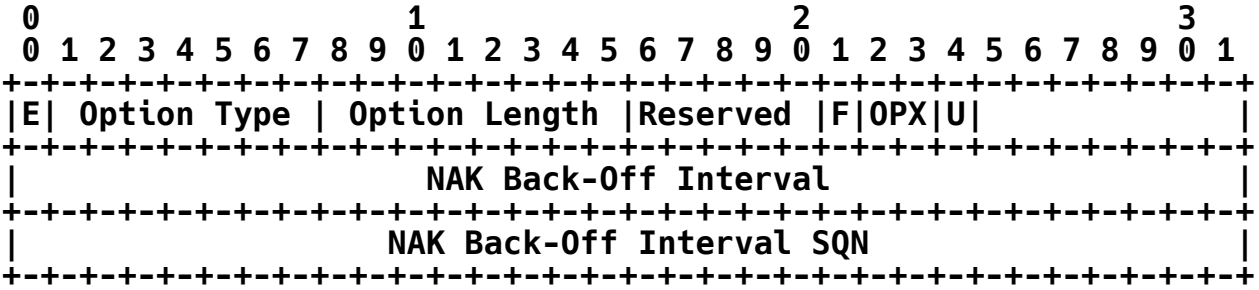
On reception of a unicast NCF containing the OPT_NBR_UNREACH option receivers MUST generate a multicast copy of the packet with TTL set to one on the RPF interface for the data source. This will prevent other receivers in the same subnet from generating NAKs.

Receivers MUST ignore windowing information in SPMs which contain the OPT_NBR_UNREACH option.

Receivers MUST ignore NCFs containing the OPT_NBR_UNREACH option if the OPT_PATH_NLA specifies a neighbour different than the one currently know to be the PGM parent neighbour. Similarly receivers MUST ignore SPMs containing the OPT_NBR_UNREACH option if SPM_PATH does not match the current PGM parent.

15.4. Packet Formats

15.4.1. OPT_NAK_BO_IVL - Packet Extension Format



Option Type = 0x04

NAK Back-Off Interval

The value of NAK-generation Back-Off Interval in microseconds.

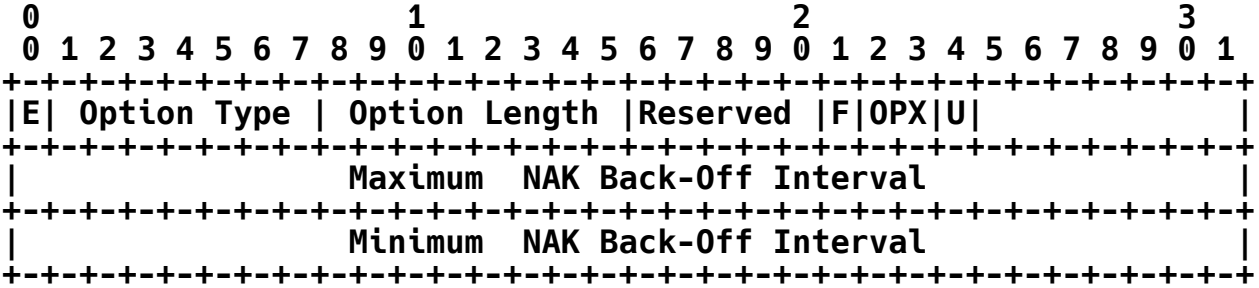
NAK Back-Off Interval Sequence Number

The POLL_SQN to which this value of NAK_BO_IVL corresponds. Zero is reserved and means NAK_BO_IVL is NOT being determined through polling (see Appendix D) and may be used immediately. Otherwise, NAK_BO_IVL MUST NOT be used unless the receiver has also seen POLL_ROUND = 0 for POLL_SQN =< NAK_BO_IVL_SQN within half the sequence number space.

OPT_NAK_BO_IVL MAY be appended to NCFs, SPMs, or POLLs.

OPT_NAK_BO_IVL is network-significant.

15.4.2. OPT_NAK_BO_RNG - Packet Extension Format



Option Type = 0x05

Maximum NAK Back-Off Interval

The maximum value of NAK-generation Back-Off Interval in microseconds.

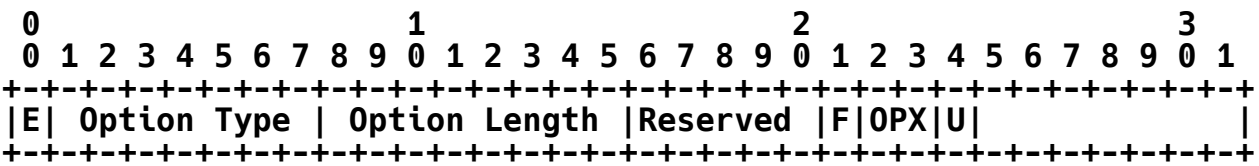
Minimum NAK Back-Off Interval

The minimum value of NAK-generation Back-Off Interval in microseconds.

OPT_NAK_BO_RNG MAY be appended to SPMs.

OPT_NAK_BO_RNG is network-significant.

15.4.3. OPT_NBR_UNREACH - Packet Extension Format



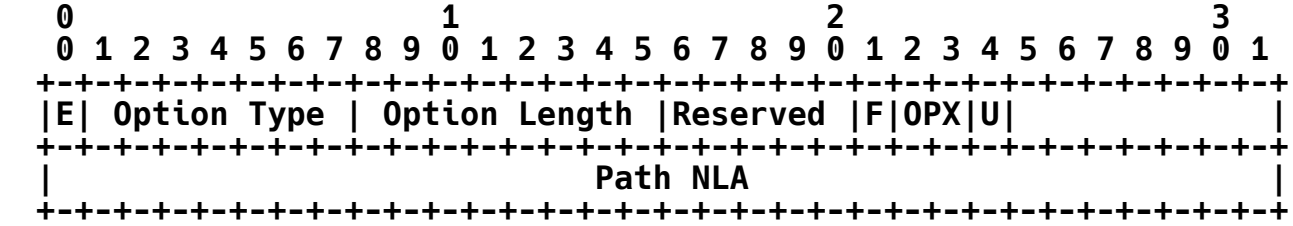
Option Type = 0x0B

When present in SPMs, it invalidates the windowing information.

OPT_NBR_UNREACH MAY be appended to SPMs and NCFs.

OPT_NBR_UNREACH is network-significant.

15.4.4. OPT_PATH_NLA - Packet Extension Format



Option Type = 0x0C

Path NLA

The NLA of the interface on the originating PGM network element that it uses to send multicast SPMs to the recipient of the packet containing this option.

OPT_PATH_NLA MAY be appended to NCFs.

OPT_PATH_NLA is network-significant.

16. Appendix F - Transmit Window Example

Nota Bene: The concept of and all references to the increment window (TXW_INC) and the window increment (TXW_ADV_SECS) throughout this document are for illustrative purposes only. They provide the shorthand with which to describe the concept of advancing the transmit window without also implying any particular implementation or policy of advancement.

The size of the transmit window in seconds is simply TXW_SECS. The size of the transmit window in bytes (TXW_BYTES) is (TXW_MAX_RTE * TXW_SECS). The size of the transmit window in sequence numbers (TXW_SQNS) is (TXW_BYTES / bytes-per-packet).

The fraction of the transmit window size (in seconds of data) by which the transmit window is advanced (TXW_ADV_SECS) is called the window increment. The trailing (oldest) such fraction of the transmit window itself is called the increment window.

In terms of sequence numbers, the increment window is the range of sequence numbers that will be the first to be expired from the transmit window. The trailing (or left) edge of the increment window is just TXW_TRAIL, the trailing (or left) edge of the transmit window. The leading (or right) edge of the increment window (TXW_INC) is defined as one less than the sequence number of the first data packet transmitted by the source TXW_ADV_SECS after transmitting TXW_TRAIL.

A data packet is described as being "in" the transmit or increment window, respectively, if its sequence number is in the range defined by the transmit or increment window, respectively.

The transmit window is advanced across the increment window by the source when it increments TXW_TRAIL to TXW_INC. When the transmit window is advanced across the increment window, the increment window is emptied (i.e., TXW_TRAIL is momentarily equal to TXW_INC), begins to refill immediately as transmission proceeds, is full again TXW_ADV_SECS later (i.e., TXW_TRAIL is separated from TXW_INC by TXW_ADV_SECS of data), at which point the transmit window is advanced again, and so on.

16.1. Advancing across the Increment Window

In anticipation of advancing the transmit window, the source starts a timer TXW_ADV_IVL_TMR which runs for time period TXW_ADV_IVL. TXW_ADV_IVL has a value in the range (0, TXW_ADV_SECS). The value MAY be configurable or MAY be determined statically by the strategy used for advancing the transmit window.

When TXW_ADV_IVL_TMR is running, a source MAY reset TXW_ADV_IVL_TMR if NAKs are received for packets in the increment window. In addition, a source MAY transmit RDATA in the increment window with priority over other data within the transmit window.

When TXW_ADV_IVL_TMR expires, a source SHOULD advance the trailing edge of the transmit window from TXW_TRAIL to TXW_INC.

Once the transmit window is advanced across the increment window, SPM_TRAIL, OD_TRAIL and RD_TRAIL are set to the new value of TXW_TRAIL in all subsequent transmitted packets, until the next window advancement.

PGM does not constrain the strategies that a source may use for advancing the transmit window. The source MAY implement any scheme or number of schemes. Three suggested strategies are outlined here.

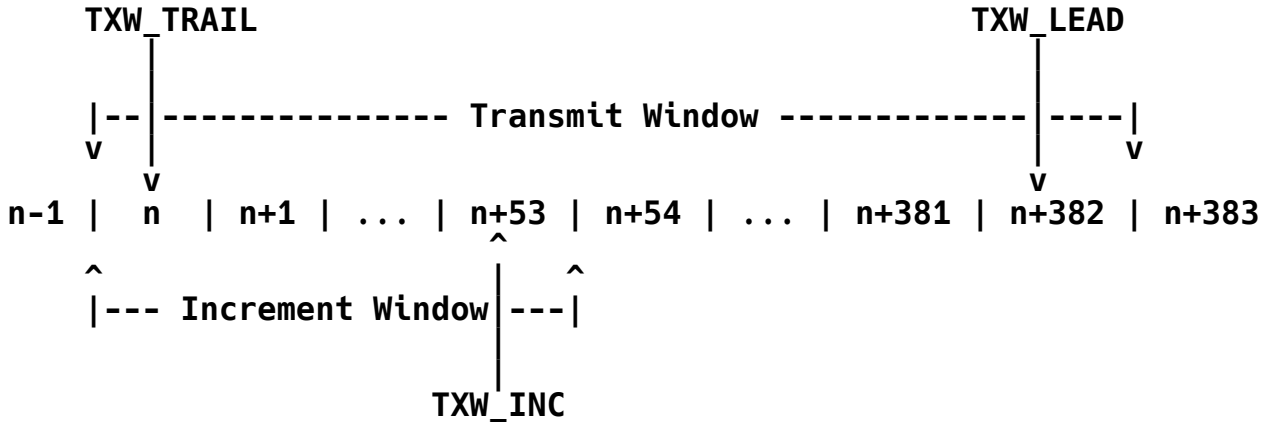
Consider the following example:

Assuming a constant transmit rate of 128kbps and a constant data packet size of 1500 bytes, if a source maintains the past 30 seconds of data for repair and increments its transmit window in 5 second increments, then

TXW_MAX_RTE = 16kBps
TXW_ADV_SECS = 5 seconds,
TXW_SECS = 35 seconds,
TXW_BYTES = 560kB,
TXW_SQNS = 383 (rounded up),

and the size of the increment window in sequence numbers (TXW_MAX_RTE * TXW_ADV_SECS / 1500) = 54 (rounded down).

Continuing this example, the following is a diagram of the transmit window and the increment window therein in terms of sequence numbers.



So the values of the sequence numbers defining these windows are:

TXW_TRAIL = n
TXW_INC = n+53
TXW_LEAD = n+382

Nota Bene: In this example the window sizes in terms of sequence numbers can be determined only because of the assumption of a constant data packet size of 1500 bytes. When the data packet sizes are variable, more or fewer sequence numbers MAY be consumed transmitting the same amount (TXW_BYTES) of data.

So, for a given transport session identified by a TSI, a source maintains:

TXW_MAX_RTE	a maximum transmit rate in kBytes per second, the cumulative transmit rate of some combination of SPMs, ODATA, and RDATA depending on the transmit window advancement strategy
TXW_TRAIL	the sequence number defining the trailing edge of the transmit window, the sequence number of the oldest data packet available for repair
TXW_LEAD	the sequence number defining the leading edge of the transmit window, the sequence number of the most recently transmitted ODATA packet
TXW_INC	the sequence number defining the leading edge of the increment window, the sequence number of the most recently transmitted data packet amongst those that will expire upon the next increment of the transmit window

PGM does not constrain the strategies that a source may use for advancing the transmit window. A source MAY implement any scheme or number of schemes. This is possible because a PGM receiver must obey the window provided by the source in its packets. Three strategies are suggested within this document.

In the first, called "Advance with Time", the transmit window maintains the last TXW_SECS of data in real-time, regardless of whether any data was sent in that real time period or not. The actual number of bytes maintained at any instant in time will vary between 0 and TXW_BYTES, depending on traffic during the last TXW_SECS. In this case, TXW_MAX_RTE is the cumulative transmit rate of SPMs and ODATA.

In the second, called "Advance with Data", the transmit window maintains the last TXW_BYTES bytes of data for repair. That is, it maintains the theoretical maximum amount of data that could be transmitted in the time period TXW_SECS, regardless of when they were transmitted. In this case, TXW_MAX_RTE is the cumulative transmit rate of SPMs, ODATA, and RDATA.

The third strategy leaves control of the window in the hands of the application. The API provided by a source implementation for this, could allow the application to control the window in terms of APDUs and to manually step the window. This gives a form of Application Level Framing (ALF). In this case, TXW_MAX_RTE is the cumulative transmit rate of SPMs, ODATA, and RDATA.

16.2. Advancing with Data

In the first strategy, TXW_MAX_RTE is calculated from SPMs and both ODATA and RDATA, and NAKs reset TXW_ADV_IVL_TMR. In this mode of operation the transmit window maintains the last TXW_BYTES bytes of data for repair. That is, it maintains the theoretical maximum amount of data that could be transmitted in the time period TXW_SECS. This means that the following timers are not treated as real-time timers, instead they are "data driven". That is, they expire when the amount of data that could be sent in the time period they define is sent. They are the SPM ambient time interval, TXW_ADV_SECS, TXW_SECS, TXW_ADV_IVL, TXW_ADV_IVL_TMR and the join interval. Note that the SPM heartbeat timers still run in real-time.

While TXW_ADV_IVL_TMR is running, a source uses the receipt of a NAK for ODATA within the increment window to reset timer TXW_ADV_IVL_TMR to TXW_ADV_IVL so that transmit window advancement is delayed until no NAKs for data in the increment window are seen for TXW_ADV_IVL seconds. If the transmit window should fill in the meantime, further transmissions would be suspended until the transmit window can be advanced.

A source MUST advance the transmit window across the increment window only upon expiry of TXW_ADV_IVL_TMR.

This mode of operation is intended for non-real-time, messaging applications based on the receipt of complete data at the expense of delay.

16.3. Advancing with Time

This strategy advances the transmit window in real-time. In this mode of operation, TXW_MAX_RTE is calculated from SPMs and ODATA only to maintain a constant data throughput rate by consuming extra bandwidth for repairs. TXW_ADV_IVL has the value 0 which advances the transmit window without regard for whether NAKs for data in the increment window are still being received.

In this mode of operation, all timers are treated as real-time timers.

This mode of operation is intended for real-time, streaming applications based on the receipt of timely data at the expense of completeness.

16.4. Advancing under explicit application control

Some applications may wish more explicit control of the transmit window than that provided by the advance with data / time strategies above. An implementation MAY provide this mode of operation and allow an application to explicitly control the window in terms of APDUs.

17. Appendix G - Applicability Statement

As stated in the introduction, PGM has been designed with a specific class of applications in mind in recognition of the fact that a general solution for reliable multicast has proven elusive. The applicability of PGM is narrowed further, and perhaps more significantly, by the prototypical nature of at least four of the transport elements the protocol incorporates. These are congestion control, router assist, local retransmission, and a programmatic API for reliable multicast protocols of this class. At the same time as standardization efforts address each of these elements individually, this publication is intended to foster experimentation with these elements in general, and to inform that standardization process with results from practise.

This section briefly describes some of the experimental aspects of PGM and makes non-normative references to some examples of current practise based upon them.

At least 3 different approaches to congestion control can be explored with PGM: a receiver-feedback based approach, a router-assist based approach, and layer-coding based approach. The first is supported by the negative acknowledgement mechanism in PGM augmented by an application-layer acknowledgement mechanism. The second is supported by the router exception processing mechanism in PGM. The third is supported by the FEC mechanisms in PGM. An example of a receiver-feedback based approach is provided in [16], and a proposal for a router-assist based approach was proposed in [17]. Open issues for the researchers include how do each of these approaches behave in the presence of multiple competing sessions of the same discipline or of different disciplines, TCP most notably; how do each of them behave over a particular range of topologies, and over a particular range of loads; and how do each of them scale as a function of the size of the receiver population.

Router assist has applications not just to implosion control and retransmit constraint as described in this specification, but also to congestion control as described above, and more generally to any feature which may be enhanced by access to per-network-element state and processing. The full range of these features is as yet

unexplored, but a general mechanism for providing router assist in a transport-protocol independent way (GRA) is a topic of active research [18]. That effort has been primarily informed by the router assist component of PGM, and implementation and deployment experience with PGM will continue to be fed back into the specification and eventual standardization of GRA. Open questions facing the researchers ([19], [20], [21]) include how router-based state scales relative to the feature benefit obtained, how system-wide factors (such as throughput and retransmit latency) vary relative to the scale and topology of deployed router assistance, and how incremental deployment considerations affect the tractability of router-assist based features. Router assist may have additional implications in the area of congestion control to the extent that it may be applied in multi-group layered coding schemes to increase the granularity and reduce the latency of receiver based congestion control.

GRA itself explicitly incorporates elements of active networking, and to the extent that the router assist component of PGM is reflected in GRA, experimentation with the narrowly defined network-element functionality of PGM will provide some of the first real world experience with this promising if controversial technology.

Local retransmission is not a new idea in general in reliable multicast, but the specific approach taken in PGM of locating re-transmitters on the distribution tree for the session, diverting repair requests from network elements to the re-transmitters, and then propagating repairs downward from the repair point on the distribution tree raises interesting questions concerning where to locate re-transmitters in a given topology, and how network elements locate those re-transmitters and evaluate their efficiency relative to other available sources of retransmissions, most notably the source itself. This particular aspect of PGM, while fully specified, has only been implemented on the network element side, and awaits a host-side implementation before questions like these can be addressed.

PGM presents the opportunity to develop a programming API for reliable multicast applications that reflects both those applications' service requirements as well as the services provided by PGM in support of those applications that may usefully be made visible above the transport interface. At least a couple of host-side implementations of PGM and a concomitant API have been developed for research purposes ([22], [23]), and are available as open source explicitly for the kind of experimentation described in this section.

Perhaps the broadest experiment that PGM can enable in a community of researchers using a reasonable scale experimental transport protocol is simply in the definition, implementation, and deployment of IP

multicast applications for which the reliability provided by PGM is a significant enabler. Experience with such applications will not just illuminate the value of reliable multicast, but will also provoke practical examination of and responses to the attendant policy issues (such as peering, billing, access control, firewalls, NATs, etc.), and, if successful, will ultimately encourage more wide spread deployment of IP multicast itself.

18. Abbreviations

ACK	Acknowledgment
AFI	Address Family Indicator
ALF	Application Level Framing
APDU	Application Protocol Data Unit
ARQ	Automatic Repeat reQuest
DLR	Designated Local Repairer
GSI	Globally Unique Source Identifier
FEC	Forward Error Correction
MD5	Message-Digest Algorithm
MTU	Maximum Transmission Unit
NAK	Negative Acknowledgment
NCF	NAK Confirmation
NLA	Network Layer Address
NNAK	Null Negative Acknowledgment
ODATA	Original Data
POLL	Poll Request
POLR	Poll Response
RDATA	Repair Data
RSN	Receive State Notification
SPM	Source Path Message
SPMR	SPM Request
TG	Transmission Group
TGSIZE	Transmission Group Size
TPDU	Transport Protocol Data Unit
TSDU	Transport Service Data Unit
TSI	Transport Session Identifier
TSN	Transmit State Notification

19. Acknowledgements

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