            The Addition of Explicit Congestion Notification (ECN) to IP

Status of this Memo

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Abstract

   This memo specifies the incorporation of ECN (Explicit Congestion
   Notification) to TCP and IP, including ECN's use of two bits in the
   IP header.

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1.  Introduction

     We begin by describing TCP's use of packet drops as an indication of
     congestion.  Next we explain that with the addition of active queue
     management (e.g., RED) to the Internet infrastructure, where routers
     detect congestion before the queue overflows, routers are no longer
     limited to packet drops as an indication of congestion.  Routers can
     instead set the Congestion Experienced (CE) codepoint in the IP
     header of packets from ECN-capable transports.  We describe when the
     CE codepoint is to be set in routers, and describe modifications
     needed to TCP to make it ECN-capable.  Modifications to other
     transport protocols (e.g., unreliable unicast or multicast, reliable
     multicast, other reliable unicast transport protocols) could be
     considered as those protocols are developed and advance through the
     standards process.  We also describe in this document the issues
     involving the use of ECN within IP tunnels, and within IPsec tunnels
     in particular.

     One of the guiding principles for this document is that, to the
     extent possible, the mechanisms specified here be incrementally
     deployable.  One challenge to the principle of incremental deployment
     has been the prior existence of some IP tunnels that were not
     compatible with the use of ECN.  As ECN becomes deployed, non-
     compatible IP tunnels will have to be upgraded to conform to this
     document.

     This document obsoletes RFC 2481, "A Proposal to add Explicit
     Congestion Notification (ECN) to IP", which defined ECN as an
     Experimental Protocol for the Internet Community.  This document also
     updates RFC 2474, "Definition of the Differentiated Services Field
     (DS Field) in the IPv4 and IPv6 Headers", in defining the ECN field
     in the IP header, RFC 2401, "Security Architecture for the Internet
     Protocol" to change the handling of IPv4 TOS Byte and IPv6 Traffic
     Class Octet in tunnel mode header construction to be compatible with
     the use of ECN, and RFC 793, "Transmission Control Protocol", in
     defining two new flags in the TCP header.

     TCP's congestion control and avoidance algorithms are based on the
     notion that the network is a black-box [Jacobson88, Jacobson90].  The
     network's state of congestion or otherwise is determined by end-
     systems probing for the network state, by gradually increasing the
     load on the network (by increasing the window of packets that are
     outstanding in the network) until the network becomes congested and a
     packet is lost.  Treating the network as a "black-box" and treating

loss as an indication of congestion in the network is appropriate for
pure best-effort data carried by TCP, with little or no sensitivity
to delay or loss of individual packets.  In addition, TCP's
congestion management algorithms have techniques built-in (such as
Fast Retransmit and Fast Recovery) to minimize the impact of losses,
from a throughput perspective.  However, these mechanisms are not
intended to help applications that are in fact sensitive to the delay
or loss of one or more individual packets.  Interactive traffic such
as telnet, web-browsing, and transfer of audio and video data can be
sensitive to packet losses (especially when using an unreliable data
delivery transport such as UDP) or to the increased latency of the
packet caused by the need to retransmit the packet after a loss (with
the reliable data delivery semantics provided by TCP).

Since TCP determines the appropriate congestion window to use by
gradually increasing the window size until it experiences a dropped
packet, this causes the queues at the bottleneck router to build up.
With most packet drop policies at the router that are not sensitive
to the load placed by each individual flow (e.g., tail-drop on queue
overflow), this means that some of the packets of latency-sensitive
flows may be dropped. In addition, such drop policies lead to
synchronization of loss across multiple flows.

Active queue management mechanisms detect congestion before the queue
overflows, and provide an indication of this congestion to the end
nodes.  Thus, active queue management can reduce unnecessary queuing
delay for all traffic sharing that queue.  The advantages of active
queue management are discussed in RFC 2309 [RFC2309].  Active queue
management avoids some of the bad properties of dropping on queue
overflow, including the undesirable synchronization of loss across
multiple flows.  More importantly, active queue management means that
transport protocols with mechanisms for congestion control (e.g.,
TCP) do not have to rely on buffer overflow as the only indication of
congestion.

Active queue management mechanisms may use one of several methods for
indicating congestion to end-nodes. One is to use packet drops, as is
currently done. However, active queue management allows the router to
separate policies of queuing or dropping packets from the policies
for indicating congestion. Thus, active queue management allows
routers to use the Congestion Experienced (CE) codepoint in a packet
header as an indication of congestion, instead of relying solely on
packet drops. This has the potential of reducing the impact of loss
on latency-sensitive flows.

There exist some middleboxes (firewalls, load balancers, or intrusion
detection systems) in the Internet that either drop a TCP SYN packet
configured to negotiate ECN, or respond with a RST.  This document
specifies procedures that TCP implementations may use to provide
robust connectivity even in the presence of such equipment.

## 2.  Conventions and Acronyms

The keywords MUST, MUST NOT, REQUIRED, SHALL, SHALL NOT, SHOULD,
SHOULD NOT, RECOMMENDED, MAY, and OPTIONAL, when they appear in this
document, are to be interpreted as described in [RFC2119].

## 3.  Assumptions and General Principles

In this section, we describe some of the important design principles
and assumptions that guided the design choices in this proposal.

   * Because ECN is likely to be adopted gradually, accommodating
     migration is essential. Some routers may still only drop packets
     to indicate congestion, and some end-systems may not be ECN-
     capable. The most viable strategy is one that accommodates
     incremental deployment without having to resort to "islands" of
     ECN-capable and non-ECN-capable environments.

   * New mechanisms for congestion control and avoidance need to co-
     exist and cooperate with existing mechanisms for congestion
     control.  In particular, new mechanisms have to co-exist with
     TCP's current methods of adapting to congestion and with
     routers' current practice of dropping packets in periods of
     congestion.

   * Congestion may persist over different time-scales. The time
     scales that we are concerned with are congestion events that may
     last longer than a round-trip time.

   * The number of packets in an individual flow (e.g., TCP
     connection or an exchange using UDP) may range from a small
     number of packets to quite a large number. We are interested in
     managing the congestion caused by flows that send enough packets
     so that they are still active when network feedback reaches
     them.

   * Asymmetric routing is likely to be a normal occurrence in the
     Internet. The path (sequence of links and routers) followed by
     data packets may be different from the path followed by the
     acknowledgment packets in the reverse direction.

     * Many routers process the "regular" headers in IP packets more
       efficiently than they process the header information in IP
       options.  This suggests keeping congestion experienced
       information in the regular headers of an IP packet.

     * It must be recognized that not all end-systems will cooperate in
       mechanisms for congestion control. However, new mechanisms
       shouldn't make it easier for TCP applications to disable TCP
       congestion control.  The benefit of lying about participating in
       new mechanisms such as ECN-capability should be small.

4.  Active Queue Management (AQM)

   Random Early Detection (RED) is one mechanism for Active Queue
   Management (AQM) that has been proposed to detect incipient
   congestion [FJ93], and is currently being deployed in the Internet
   [RFC2309].  AQM is meant to be a general mechanism using one of
   several alternatives for congestion indication, but in the absence of
   ECN, AQM is restricted to using packet drops as a mechanism for
   congestion indication.  AQM drops packets based on the average queue
   length exceeding a threshold, rather than only when the queue
   overflows.  However, because AQM may drop packets before the queue
   actually overflows, AQM is not always forced by memory limitations to
   discard the packet.

   AQM can set a Congestion Experienced (CE) codepoint in the packet
   header instead of dropping the packet, when such a field is provided
   in the IP header and understood by the transport protocol.  The use
   of the CE codepoint with ECN allows the receiver(s) to receive the
   packet, avoiding the potential for excessive delays due to
   retransmissions after packet losses.  We use the term 'CE packet' to
   denote a packet that has the CE codepoint set.

5.  Explicit Congestion Notification in IP

   This document specifies that the Internet provide a congestion
   indication for incipient congestion (as in RED and earlier work
   [RJ90]) where the notification can sometimes be through marking
   packets rather than dropping them.  This uses an ECN field in the IP
   header with two bits, making four ECN codepoints, '00' to '11'.  The
   ECN-Capable Transport (ECT) codepoints '10' and '01' are set by the
   data sender to indicate that the end-points of the transport protocol
   are ECN-capable; we call them ECT(0) and ECT(1) respectively.  The
   phrase "the ECT codepoint" in this documents refers to either of the
   two ECT codepoints.  Routers treat the ECT(0) and ECT(1) codepoints
   as equivalent.  Senders are free to use either the ECT(0) or the
   ECT(1) codepoint to indicate ECT, on a packet-by-packet basis.

The use of both the two codepoints for ECT, ECT(0) and ECT(1), is
motivated primarily by the desire to allow mechanisms for the data
sender to verify that network elements are not erasing the CE
codepoint, and that data receivers are properly reporting to the
sender the receipt of packets with the CE codepoint set, as required
by the transport protocol.  Guidelines for the senders and receivers
to differentiate between the ECT(0) and ECT(1) codepoints will be
addressed in separate documents, for each transport protocol.  In
particular, this document does not address mechanisms for TCP end-
nodes to differentiate between the ECT(0) and ECT(1) codepoints.
Protocols and senders that only require a single ECT codepoint SHOULD
use ECT(0).

The not-ECT codepoint '00' indicates a packet that is not using ECN.
The CE codepoint '11' is set by a router to indicate congestion to
the end nodes.  Routers that have a packet arriving at a full queue
drop the packet, just as they do in the absence of ECN.

```
    +-----+-----+
    | ECN FIELD |
    +-----+-----+
      ECT   CE          [Obsolete] RFC 2481 names for the ECN bits.
       0    0           Not-ECT
       0    1           ECT(1)
       1    0           ECT(0)
       1    1           CE
```

        Figure 1: The ECN Field in IP.

The use of two ECT codepoints essentially gives a one-bit ECN nonce
in packet headers, and routers necessarily "erase" the nonce when
they set the CE codepoint [SCWA99].  For example, routers that erased
the CE codepoint would face additional difficulty in reconstructing
the original nonce, and thus repeated erasure of the CE codepoint
would be more likely to be detected by the end-nodes.  The ECN nonce
also can address the problem of misbehaving transport receivers lying
to the transport sender about whether or not the CE codepoint was set
in a packet.  The motivations for the use of two ECT codepoints is
discussed in more detail in Section 20, along with some discussion of
alternate possibilities for the fourth ECT codepoint (that is, the
codepoint '01').  Backwards compatibility with earlier ECN
implementations that do not understand the ECT(1) codepoint is
discussed in Section 11.

In RFC 2481 [RFC2481], the ECN field was divided into the ECN-Capable
Transport (ECT) bit and the CE bit.  The ECN field with only the
ECN-Capable Transport (ECT) bit set in RFC 2481 corresponds to the
ECT(0) codepoint in this document, and the ECN field with both the

ECT and CE bit in RFC 2481 corresponds to the CE codepoint in this
document.  The '01' codepoint was left undefined in RFC 2481, and
this is the reason for recommending the use of ECT(0) when only a
single ECT codepoint is needed.

```
      0     1     2     3     4     5     6     7
   +-----+-----+-----+-----+-----+-----+-----+-----+
   |           DS FIELD, DSCP          | ECN FIELD |
   +-----+-----+-----+-----+-----+-----+-----+-----+

     DSCP: differentiated services codepoint
     ECN:  Explicit Congestion Notification
```
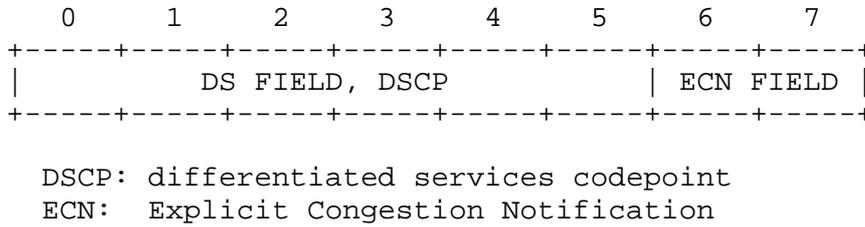
     Figure 2: The Differentiated Services and ECN Fields in IP.

Bits 6 and 7 in the IPv4 TOS octet are designated as the ECN field.
The IPv4 TOS octet corresponds to the Traffic Class octet in IPv6,
and the ECN field is defined identically in both cases.  The
definitions for the IPv4 TOS octet [RFC791] and the IPv6 Traffic
Class octet have been superseded by the six-bit DS (Differentiated
Services) Field [RFC2474, RFC2780].  Bits 6 and 7 are listed in
[RFC2474] as Currently Unused, and are specified in RFC 2780 as
approved for experimental use for ECN.  Section 22 gives a brief
history of the TOS octet.

Because of the unstable history of the TOS octet, the use of the ECN
field as specified in this document cannot be guaranteed to be
backwards compatible with those past uses of these two bits that
pre-date ECN.  The potential dangers of this lack of backwards
compatibility are discussed in Section 22.

Upon the receipt by an ECN-Capable transport of a single CE packet,
the congestion control algorithms followed at the end-systems MUST be
essentially the same as the congestion control response to a *single*
dropped packet.  For example, for ECN-Capable TCP the source TCP is
required to halve its congestion window for any window of data
containing either a packet drop or an ECN indication.

One reason for requiring that the congestion-control response to the
CE packet be essentially the same as the response to a dropped packet
is to accommodate the incremental deployment of ECN in both end-
systems and in routers.  Some routers may drop ECN-Capable packets
(e.g., using the same AQM policies for congestion detection) while
other routers set the CE codepoint, for equivalent levels of
congestion.  Similarly, a router might drop a non-ECN-Capable packet
but set the CE codepoint in an ECN-Capable packet, for equivalent

levels of congestion.  If there were different congestion control
responses to a CE codepoint than to a packet drop, this could result
in unfair treatment for different flows.

An additional goal is that the end-systems should react to congestion
at most once per window of data (i.e., at most once per round-trip
time), to avoid reacting multiple times to multiple indications of
congestion within a round-trip time.

For a router, the CE codepoint of an ECN-Capable packet SHOULD only
be set if the router would otherwise have dropped the packet as an
indication of congestion to the end nodes. When the router's buffer
is not yet full and the router is prepared to drop a packet to inform
end nodes of incipient congestion, the router should first check to
see if the ECT codepoint is set in that packet's IP header.  If so,
then instead of dropping the packet, the router MAY instead set the
CE codepoint in the IP header.

An environment where all end nodes were ECN-Capable could allow new
criteria to be developed for setting the CE codepoint, and new
congestion control mechanisms for end-node reaction to CE packets.
However, this is a research issue, and as such is not addressed in
this document.

When a CE packet (i.e., a packet that has the CE codepoint set) is
received by a router, the CE codepoint is left unchanged, and the
packet is transmitted as usual. When severe congestion has occurred
and the router's queue is full, then the router has no choice but to
drop some packet when a new packet arrives.  We anticipate that such
packet losses will become relatively infrequent when a majority of
end-systems become ECN-Capable and participate in TCP or other
compatible congestion control mechanisms. In an ECN-Capable
environment that is adequately-provisioned, packet losses should
occur primarily during transients or in the presence of non-
cooperating sources.

The above discussion of when CE may be set instead of dropping a
packet applies by default to all Differentiated Services Per-Hop
Behaviors (PHBs) [RFC 2475].  Specifications for PHBs MAY provide
more specifics on how a compliant implementation is to choose between
setting CE and dropping a packet, but this is NOT REQUIRED.  A router
MUST NOT set CE instead of dropping a packet when the drop that would
occur is caused by reasons other than congestion or the desire to
indicate incipient congestion to end nodes (e.g., a diffserv edge
node may be configured to unconditionally drop certain classes of
traffic to prevent them from entering its diffserv domain).

We expect that routers will set the CE codepoint in response to
incipient congestion as indicated by the average queue size, using
the RED algorithms suggested in [FJ93, RFC2309].  To the best of our
knowledge, this is the only proposal currently under discussion in
the IETF for routers to drop packets proactively, before the buffer
overflows.  However, this document does not attempt to specify a
particular mechanism for active queue management, leaving that
endeavor, if needed, to other areas of the IETF.  While ECN is
inextricably tied up with the need to have a reasonable active queue
management mechanism at the router, the reverse does not hold; active
queue management mechanisms have been developed and deployed
independent of ECN, using packet drops as indications of congestion
in the absence of ECN in the IP architecture.

5.1.  ECN as an Indication of Persistent Congestion

   We emphasize that a *single* packet with the CE codepoint set in an
   IP packet causes the transport layer to respond, in terms of
   congestion control, as it would to a packet drop.  The instantaneous
   queue size is likely to see considerable variations even when the
   router does not experience persistent congestion.  As such, it is
   important that transient congestion at a router, reflected by the
   instantaneous queue size reaching a threshold much smaller than the
   capacity of the queue, not trigger a reaction at the transport layer.
   Therefore, the CE codepoint should not be set by a router based on
   the instantaneous queue size.

   For example, since the ATM and Frame Relay mechanisms for congestion
   indication have typically been defined without an associated notion
   of average queue size as the basis for determining that an
   intermediate node is congested, we believe that they provide a very
   noisy signal. The TCP-sender reaction specified in this document for
   ECN is NOT the appropriate reaction for such a noisy signal of
   congestion notification.  However, if the routers that interface to
   the ATM network have a way of maintaining the average queue at the
   interface, and use it to come to a reliable determination that the
   ATM subnet is congested, they may use the ECN notification that is
   defined here.

   We continue to encourage experiments in techniques at layer 2 (e.g.,
   in ATM switches or Frame Relay switches) to take advantage of ECN.
   For example, using a scheme such as RED (where packet marking is
   based on the average queue length exceeding a threshold), layer 2
   devices could provide a reasonably reliable indication of congestion.
   When all the layer 2 devices in a path set that layer's own
   Congestion Experienced codepoint (e.g., the EFCI bit for ATM, the
   FECN bit in Frame Relay) in this reliable manner, then the interface
   router to the layer 2 network could copy the state of that layer 2

Congestion Experienced codepoint into the CE codepoint in the IP
header.  We recognize that this is not the current practice, nor is
it in current standards. However, encouraging experimentation in this
manner may provide the information needed to enable evolution of
existing layer 2 mechanisms to provide a more reliable means of
congestion indication, when they use a single bit for indicating
congestion.

## 5.2.  Dropped or Corrupted Packets

For the proposed use for ECN in this document (that is, for a
transport protocol such as TCP for which a dropped data packet is an
indication of congestion), end nodes detect dropped data packets, and
the congestion response of the end nodes to a dropped data packet is
at least as strong as the congestion response to a received CE
packet.  To ensure the reliable delivery of the congestion indication
of the CE codepoint, an ECT codepoint MUST NOT be set in a packet
unless the loss of that packet in the network would be detected by
the end nodes and interpreted as an indication of congestion.

Transport protocols such as TCP do not necessarily detect all packet
drops, such as the drop of a "pure" ACK packet; for example, TCP does
not reduce the arrival rate of subsequent ACK packets in response to
an earlier dropped ACK packet.  Any proposal for extending ECN-
Capability to such packets would have to address issues such as the
case of an ACK packet that was marked with the CE codepoint but was
later dropped in the network. We believe that this aspect is still
the subject of research, so this document specifies that at this
time, "pure" ACK packets MUST NOT indicate ECN-Capability.

Similarly, if a CE packet is dropped later in the network due to
corruption (bit errors), the end nodes should still invoke congestion
control, just as TCP would today in response to a dropped data
packet. This issue of corrupted CE packets would have to be
considered in any proposal for the network to distinguish between
packets dropped due to corruption, and packets dropped due to
congestion or buffer overflow.  In particular, the ubiquitous
deployment of ECN would not, in and of itself, be a sufficient
development to allow end-nodes to interpret packet drops as
indications of corruption rather than congestion.

## 5.3.  Fragmentation

ECN-capable packets MAY have the DF (Don't Fragment) bit set.
Reassembly of a fragmented packet MUST NOT lose indications of
congestion.  In other words, if any fragment of an IP packet to be
reassembled has the CE codepoint set, then one of two actions MUST be
taken:

        * Set the CE codepoint on the reassembled packet.  However, this
          MUST NOT occur if any of the other fragments contributing to
          this reassembly carries the Not-ECT codepoint.

        * The packet is dropped, instead of being reassembled, for any
          other reason.

   If both actions are applicable, either MAY be chosen.  Reassembly of
   a fragmented packet MUST NOT change the ECN codepoint when all of the
   fragments carry the same codepoint.

   We would note that because RFC 2481 did not specify reassembly
   behavior, older ECN implementations conformant with that Experimental
   RFC do not necessarily perform reassembly correctly, in terms of
   preserving the CE codepoint in a fragment.  The sender could avoid
   the consequences of this behavior by setting the DF bit in ECN-
   Capable packets.

   Situations may arise in which the above reassembly specification is
   insufficiently precise.  For example, if there is a malicious or
   broken entity in the path at or after the fragmentation point, packet
   fragments could carry a mixture of ECT(0), ECT(1), and/or Not-ECT
   codepoints.  The reassembly specification above does not place
   requirements on reassembly of fragments in this case.  In situations
   where more precise reassembly behavior would be required, protocol
   specifications SHOULD instead specify that DF MUST be set in all
   ECN-capable packets sent by the protocol.

6.  Support from the Transport Protocol

   ECN requires support from the transport protocol, in addition to the
   functionality given by the ECN field in the IP packet header. The
   transport protocol might require negotiation between the endpoints
   during setup to determine that all of the endpoints are ECN-capable,
   so that the sender can set the ECT codepoint in transmitted packets.
   Second, the transport protocol must be capable of reacting
   appropriately to the receipt of CE packets.  This reaction could be
   in the form of the data receiver informing the data sender of the
   received CE packet (e.g., TCP), of the data receiver unsubscribing to
   a layered multicast group (e.g., RLM [MJV96]), or of some other
   action that ultimately reduces the arrival rate of that flow on that
   congested link.  CE packets indicate persistent rather than transient
   congestion (see Section 5.1), and hence reactions to the receipt of
   CE packets should be those appropriate for persistent congestion.

   This document only addresses the addition of ECN Capability to TCP,
   leaving issues of ECN in other transport protocols to further
   research.  For TCP, ECN requires three new pieces of functionality:

negotiation between the endpoints during connection setup to
determine if they are both ECN-capable; an ECN-Echo (ECE) flag in the
TCP header so that the data receiver can inform the data sender when
a CE packet has been received; and a Congestion Window Reduced (CWR)
flag in the TCP header so that the data sender can inform the data
receiver that the congestion window has been reduced. The support
required from other transport protocols is likely to be different,
particularly for unreliable or reliable multicast transport
protocols, and will have to be determined as other transport
protocols are brought to the IETF for standardization.

In a mild abuse of terminology, in this document we refer to 'TCP
packets' instead of 'TCP segments'.

6.1.  TCP

The following sections describe in detail the proposed use of ECN in
TCP.  This proposal is described in essentially the same form in
[Floyd94]. We assume that the source TCP uses the standard congestion
control algorithms of Slow-start, Fast Retransmit and Fast Recovery
[RFC2581].

This proposal specifies two new flags in the Reserved field of the
TCP header.  The TCP mechanism for negotiating ECN-Capability uses
the ECN-Echo (ECE) flag in the TCP header.  Bit 9 in the Reserved
field of the TCP header is designated as the ECN-Echo flag.  The
location of the 6-bit Reserved field in the TCP header is shown in
Figure 4 of RFC 793 [RFC793] (and is reproduced below for
completeness).  This specification of the ECN Field leaves the
Reserved field as a 4-bit field using bits 4-7.

To enable the TCP receiver to determine when to stop setting the
ECN-Echo flag, we introduce a second new flag in the TCP header, the
CWR flag.  The CWR flag is assigned to Bit 8 in the Reserved field of
the TCP header.

```
    0   1   2   3   4   5   6   7   8   9   10  11  12  13  14  15
  +---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+
  |               |                       | U | A | P | R | S | F |
  | Header Length |        Reserved       | R | C | S | S | Y | I |
  |               |                       | G | K | H | T | N | N |
  +---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+
```
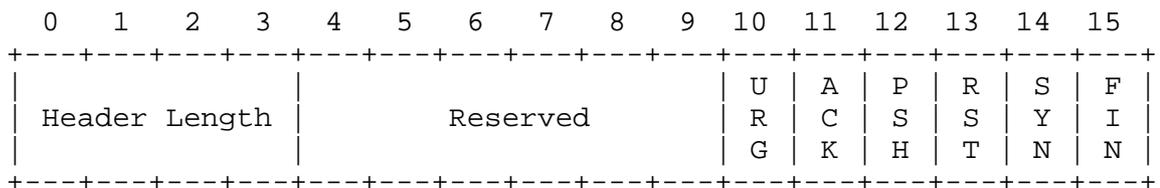
     Figure 3: The old definition of bytes 13 and 14 of the TCP
               header.

```
      0   1   2   3   4   5   6   7   8   9   10  11  12  13  14  15
    +---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+
    |                       |           |   | C | E | U | A | P | R | S | F |
    |   Header Length       |  Reserved |   | W | C | R | C | S | S | Y | I |
    |                       |           |   | R | E | G | K | H | T | N | N |
    +---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+
```
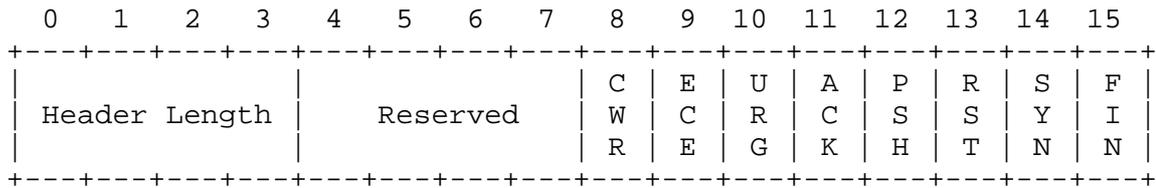
         Figure 4: The new definition of bytes 13 and 14 of the TCP
                  Header.

   Thus, ECN uses the ECT and CE flags in the IP header (as shown in
   Figure 1) for signaling between routers and connection endpoints, and
   uses the ECN-Echo and CWR flags in the TCP header (as shown in Figure
   4) for TCP-endpoint to TCP-endpoint signaling.  For a TCP connection,
   a typical sequence of events in an ECN-based reaction to congestion
   is as follows:

      * An ECT codepoint is set in packets transmitted by the sender to
        indicate that ECN is supported by the transport entities for
        these packets.

      * An ECN-capable router detects impending congestion and detects
        that an ECT codepoint is set in the packet it is about to drop.
        Instead of dropping the packet, the router chooses to set the CE
        codepoint in the IP header and forwards the packet.

      * The receiver receives the packet with the CE codepoint set, and
        sets the ECN-Echo flag in its next TCP ACK sent to the sender.

      * The sender receives the TCP ACK with ECN-Echo set, and reacts to
        the congestion as if a packet had been dropped.

      * The sender sets the CWR flag in the TCP header of the next
        packet sent to the receiver to acknowledge its receipt of and
        reaction to the ECN-Echo flag.

   The negotiation for using ECN by the TCP transport entities and the
   use of the ECN-Echo and CWR flags is described in more detail in the
   sections below.

6.1.1  TCP Initialization

   In the TCP connection setup phase, the source and destination TCPs
   exchange information about their willingness to use ECN.  Subsequent
   to the completion of this negotiation, the TCP sender sets an ECT
   codepoint in the IP header of data packets to indicate to the network
   that the transport is capable and willing to participate in ECN for
   this packet. This indicates to the routers that they may mark this

packet with the CE codepoint, if they would like to use that as a
method of congestion notification. If the TCP connection does not
wish to use ECN notification for a particular packet, the sending TCP
sets the ECN codepoint to not-ECT, and the TCP receiver ignores the
CE codepoint in the received packet.

For this discussion, we designate the initiating host as Host A and
the responding host as Host B.  We call a SYN packet with the ECE and
CWR flags set an "ECN-setup SYN packet", and we call a SYN packet
with at least one of the ECE and CWR flags not set a "non-ECN-setup
SYN packet".  Similarly, we call a SYN-ACK packet with only the ECE
flag set but the CWR flag not set an "ECN-setup SYN-ACK packet", and
we call a SYN-ACK packet with any other configuration of the ECE and
CWR flags a "non-ECN-setup SYN-ACK packet".

Before a TCP connection can use ECN, Host A sends an ECN-setup SYN
packet, and Host B sends an ECN-setup SYN-ACK packet.  For a SYN
packet, the setting of both ECE and CWR in the ECN-setup SYN packet
is defined as an indication that the sending TCP is ECN-Capable,
rather than as an indication of congestion or of response to
congestion. More precisely, an ECN-setup SYN packet indicates that
the TCP implementation transmitting the SYN packet will participate
in ECN as both a sender and receiver.  Specifically, as a receiver,
it will respond to incoming data packets that have the CE codepoint
set in the IP header by setting ECE in outgoing TCP Acknowledgement
(ACK) packets.  As a sender, it will respond to incoming packets that
have ECE set by reducing the congestion window and setting CWR when
appropriate.  An ECN-setup SYN packet does not commit the TCP sender
to setting the ECT codepoint in any or all of the packets it may
transmit.  However, the commitment to respond appropriately to
incoming packets with the CE codepoint set remains even if the TCP
sender in a later transmission, within this TCP connection, sends a
SYN packet without ECE and CWR set.

When Host B sends an ECN-setup SYN-ACK packet, it sets the ECE flag
but not the CWR flag.  An ECN-setup SYN-ACK packet is defined as an
indication that the TCP transmitting the SYN-ACK packet is ECN-
Capable.  As with the SYN packet, an ECN-setup SYN-ACK packet does
not commit the TCP host to setting the ECT codepoint in transmitted
packets.

The following rules apply to the sending of ECN-setup packets within
a TCP connection, where a TCP connection is defined by the standard
rules for TCP connection establishment and termination.

   * If a host has received an ECN-setup SYN packet, then it MAY send
     an ECN-setup SYN-ACK packet.  Otherwise, it MUST NOT send an
     ECN-setup SYN-ACK packet.

     * A host MUST NOT set ECT on data packets unless it has sent at
       least one ECN-setup SYN or ECN-setup SYN-ACK packet, and has
       received at least one ECN-setup SYN or ECN-setup SYN-ACK packet,
       and has sent no non-ECN-setup SYN or non-ECN-setup SYN-ACK
       packet.  If a host has received at least one non-ECN-setup SYN
       or non-ECN-setup SYN-ACK packet, then it SHOULD NOT set ECT on
       data packets.

     * If a host ever sets the ECT codepoint on a data packet, then
       that host MUST correctly set/clear the CWR TCP bit on all
       subsequent packets in the connection.

     * If a host has sent at least one ECN-setup SYN or ECN-setup SYN-
       ACK packet, and has received no non-ECN-setup SYN or non-ECN-
       setup SYN-ACK packet, then if that host receives TCP data
       packets with ECT and CE codepoints set in the IP header, then
       that host MUST process these packets as specified for an ECN-
       capable connection.

     * A host that is not willing to use ECN on a TCP connection SHOULD
       clear both the ECE and CWR flags in all non-ECN-setup SYN and/or
       SYN-ACK packets that it sends to indicate this unwillingness.
       Receivers MUST correctly handle all forms of the non-ECN-setup
       SYN and SYN-ACK packets.

     * A host MUST NOT set ECT on SYN or SYN-ACK packets.

   A TCP client enters TIME-WAIT state after receiving a FIN-ACK, and
   transitions to CLOSED state after a timeout.  Many TCP
   implementations create a new TCP connection if they receive an in-
   window SYN packet during TIME-WAIT state.  When a TCP host enters
   TIME-WAIT or CLOSED state, it should ignore any previous state about
   the negotiation of ECN for that connection.

6.1.1.1.  Middlebox Issues

   ECN introduces the use of the ECN-Echo and CWR flags in the TCP
   header (as shown in Figure 3) for initialization.  There exist some
   faulty firewalls, load balancers, and intrusion detection systems in
   the Internet that either drop an ECN-setup SYN packet or respond with
   a RST, in the belief that such a packet (with these bits set) is a
   signature for a port-scanning tool that could be used in a denial-
   of-service attack.  Some of the offending equipment has been
   identified, and a web page [FIXES] contains a list of non-compliant
   products and the fixes posted by the vendors, where these are
   available.  The TBIT web page [TBIT] lists some of the web servers
   affected by this faulty equipment.  We mention this in this document
   as a warning to the community of this problem.

To provide robust connectivity even in the presence of such faulty
equipment, a host that receives a RST in response to the transmission
of an ECN-setup SYN packet MAY resend a SYN with CWR and ECE cleared.
This could result in a TCP connection being established without using
ECN.

A host that receives no reply to an ECN-setup SYN within the normal
SYN retransmission timeout interval MAY resend the SYN and any
subsequent SYN retransmissions with CWR and ECE cleared.  To overcome
normal packet loss that results in the original SYN being lost, the
originating host may retransmit one or more ECN-setup SYN packets
before giving up and retransmitting the SYN with the CWR and ECE bits
cleared.

We note that in this case, the following example scenario is
possible:

(1) Host A: Sends an ECN-setup SYN.
(2) Host B: Sends an ECN-setup SYN/ACK, packet is dropped or delayed.
(3) Host A: Sends a non-ECN-setup SYN.
(4) Host B: Sends a non-ECN-setup SYN/ACK.

We note that in this case, following the procedures above, neither
Host A nor Host B may set the ECT bit on data packets.  Further, an
important consequence of the rules for ECN setup and usage in Section
6.1.1 is that a host is forbidden from using the reception of ECT
data packets as an implicit signal that the other host is ECN-
capable.

6.1.1.2.  Robust TCP Initialization with an Echoed Reserved Field

There is the question of why we chose to have the TCP sending the SYN
set two ECN-related flags in the Reserved field of the TCP header for
the SYN packet, while the responding TCP sending the SYN-ACK sets
only one ECN-related flag in the SYN-ACK packet.  This asymmetry is
necessary for the robust negotiation of ECN-capability with some
deployed TCP implementations.  There exists at least one faulty TCP
implementation in which TCP receivers set the Reserved field of the
TCP header in ACK packets (and hence the SYN-ACK) simply to reflect
the Reserved field of the TCP header in the received data packet.
Because the TCP SYN packet sets the ECN-Echo and CWR flags to
indicate ECN-capability, while the SYN-ACK packet sets only the ECN-
Echo flag, the sending TCP correctly interprets a receiver's
reflection of its own flags in the Reserved field as an indication
that the receiver is not ECN-capable.  The sending TCP is not mislead
by a faulty TCP implementation sending a SYN-ACK packet that simply
reflects the Reserved field of the incoming SYN packet.

6.1.2.  The TCP Sender

   For a TCP connection using ECN, new data packets are transmitted with
   an ECT codepoint set in the IP header.  When only one ECT codepoint
   is needed by a sender for all packets sent on a TCP connection,
   ECT(0) SHOULD be used.  If the sender receives an ECN-Echo (ECE) ACK
   packet (that is, an ACK packet with the ECN-Echo flag set in the TCP
   header), then the sender knows that congestion was encountered in the
   network on the path from the sender to the receiver.  The indication
   of congestion should be treated just as a congestion loss in non-
   ECN-Capable TCP. That is, the TCP source halves the congestion window
   "cwnd" and reduces the slow start threshold "ssthresh".  The sending
   TCP SHOULD NOT increase the congestion window in response to the
   receipt of an ECN-Echo ACK packet.

   TCP should not react to congestion indications more than once every
   window of data (or more loosely, more than once every round-trip
   time). That is, the TCP sender's congestion window should be reduced
   only once in response to a series of dropped and/or CE packets from a
   single window of data.  In addition, the TCP source should not
   decrease the slow-start threshold, ssthresh, if it has been decreased
   within the last round trip time.  However, if any retransmitted
   packets are dropped, then this is interpreted by the source TCP as a
   new instance of congestion.

   After the source TCP reduces its congestion window in response to a
   CE packet, incoming acknowledgments that continue to arrive can
   "clock out" outgoing packets as allowed by the reduced congestion
   window.  If the congestion window consists of only one MSS (maximum
   segment size), and the sending TCP receives an ECN-Echo ACK packet,
   then the sending TCP should in principle still reduce its congestion
   window in half. However, the value of the congestion window is
   bounded below by a value of one MSS.  If the sending TCP were to
   continue to send, using a congestion window of 1 MSS, this results in
   the transmission of one packet per round-trip time.  It is necessary
   to still reduce the sending rate of the TCP sender even further, on
   receipt of an ECN-Echo packet when the congestion window is one.  We
   use the retransmit timer as a means of reducing the rate further in
   this circumstance.  Therefore, the sending TCP MUST reset the
   retransmit timer on receiving the ECN-Echo packet when the congestion
   window is one.  The sending TCP will then be able to send a new
   packet only when the retransmit timer expires.

   When an ECN-Capable TCP sender reduces its congestion window for any
   reason (because of a retransmit timeout, a Fast Retransmit, or in
   response to an ECN Notification), the TCP sender sets the CWR flag in
   the TCP header of the first new data packet sent after the window
   reduction.  If that data packet is dropped in the network, then the

sending TCP will have to reduce the congestion window again and
retransmit the dropped packet.

We ensure that the "Congestion Window Reduced" information is
reliably delivered to the TCP receiver.  This comes about from the
fact that if the new data packet carrying the CWR flag is dropped,
then the TCP sender will have to again reduce its congestion window,
and send another new data packet with the CWR flag set.  Thus, the
CWR bit in the TCP header SHOULD NOT be set on retransmitted packets.

When the TCP data sender is ready to set the CWR bit after reducing
the congestion window, it SHOULD set the CWR bit only on the first
new data packet that it transmits.

[Floyd94] discusses TCP's response to ECN in more detail.  [Floyd98]
discusses the validation test in the ns simulator, which illustrates
a wide range of ECN scenarios. These scenarios include the following:
an ECN followed by another ECN, a Fast Retransmit, or a Retransmit
Timeout; a Retransmit Timeout or a Fast Retransmit followed by an
ECN; and a congestion window of one packet followed by an ECN.

TCP follows existing algorithms for sending data packets in response
to incoming ACKs, multiple duplicate acknowledgments, or retransmit
timeouts [RFC2581].  TCP also follows the normal procedures for
increasing the congestion window when it receives ACK packets without
the ECN-Echo bit set [RFC2581].

6.1.3.  The TCP Receiver

When TCP receives a CE data packet at the destination end-system, the
TCP data receiver sets the ECN-Echo flag in the TCP header of the
subsequent ACK packet.  If there is any ACK withholding implemented,
as in current "delayed-ACK" TCP implementations where the TCP
receiver can send an ACK for two arriving data packets, then the
ECN-Echo flag in the ACK packet will be set to '1' if the CE
codepoint is set in any of the data packets being acknowledged.  That
is, if any of the received data packets are CE packets, then the
returning ACK has the ECN-Echo flag set.

To provide robustness against the possibility of a dropped ACK packet
carrying an ECN-Echo flag, the TCP receiver sets the ECN-Echo flag in
a series of ACK packets sent subsequently.  The TCP receiver uses the
CWR flag received from the TCP sender to determine when to stop
setting the ECN-Echo flag.

After a TCP receiver sends an ACK packet with the ECN-Echo bit set,
that TCP receiver continues to set the ECN-Echo flag in all the ACK
packets it sends (whether they acknowledge CE data packets or non-CE

data packets) until it receives a CWR packet (a packet with the CWR
flag set).  After the receipt of the CWR packet, acknowledgments for
subsequent non-CE data packets do not have the ECN-Echo flag set. If
another CE packet is received by the data receiver, the receiver
would once again send ACK packets with the ECN-Echo flag set.  While
the receipt of a CWR packet does not guarantee that the data sender
received the ECN-Echo message, this does suggest that the data sender
reduced its congestion window at some point *after* it sent the data
packet for which the CE codepoint was set.

We have already specified that a TCP sender is not required to reduce
its congestion window more than once per window of data.  Some care
is required if the TCP sender is to avoid unnecessary reductions of
the congestion window when a window of data includes both dropped
packets and (marked) CE packets.  This is illustrated in [Floyd98].

## 6.1.4.  Congestion on the ACK-path

For the current generation of TCP congestion control algorithms, pure
acknowledgement packets (e.g., packets that do not contain any
accompanying data) MUST be sent with the not-ECT codepoint.  Current
TCP receivers have no mechanisms for reducing traffic on the ACK-path
in response to congestion notification.  Mechanisms for responding to
congestion on the ACK-path are areas for current and future research.
(One simple possibility would be for the sender to reduce its
congestion window when it receives a pure ACK packet with the CE
codepoint set). For current TCP implementations, a single dropped ACK
generally has only a very small effect on the TCP's sending rate.

## 6.1.5.  Retransmitted TCP packets

This document specifies ECN-capable TCP implementations MUST NOT set
either ECT codepoint (ECT(0) or ECT(1)) in the IP header for
retransmitted data packets, and that the TCP data receiver SHOULD
ignore the ECN field on arriving data packets that are outside of the
receiver's current window.  This is for greater security against
denial-of-service attacks, as well as for robustness of the ECN
congestion indication with packets that are dropped later in the
network.

First, we note that if the TCP sender were to set an ECT codepoint on
a retransmitted packet, then if an unnecessarily-retransmitted packet
was later dropped in the network, the end nodes would never receive
the indication of congestion from the router setting the CE
codepoint.  Thus, setting an ECT codepoint on retransmitted data
packets is not consistent with the robust delivery of the congestion
indication even for packets that are later dropped in the network.

In addition, an attacker capable of spoofing the IP source address of
the TCP sender could send data packets with arbitrary sequence
numbers, with the CE codepoint set in the IP header.  On receiving
this spoofed data packet, the TCP data receiver would determine that
the data does not lie in the current receive window, and return a
duplicate acknowledgement.  We define an out-of-window packet at the
TCP data receiver as a data packet that lies outside the receiver's
current window.  On receiving an out-of-window packet, the TCP data
receiver has to decide whether or not to treat the CE codepoint in
the packet header as a valid indication of congestion, and therefore
whether to return ECN-Echo indications to the TCP data sender.  If
the TCP data receiver ignored the CE codepoint in an out-of-window
packet, then the TCP data sender would not receive this possibly-
legitimate indication of congestion from the network, resulting in a
violation of end-to-end congestion control.  On the other hand, if
the TCP data receiver honors the CE indication in the out-of-window
packet, and reports the indication of congestion to the TCP data
sender, then the malicious node that created the spoofed, out-of-
window packet has successfully "attacked" the TCP connection by
forcing the data sender to unnecessarily reduce (halve) its
congestion window.  To prevent such a denial-of-service attack, we
specify that a legitimate TCP data sender MUST NOT set an ECT
codepoint on retransmitted data packets, and that the TCP data
receiver SHOULD ignore the CE codepoint on out-of-window packets.

One drawback of not setting ECT(0) or ECT(1) on retransmitted packets
is that it denies ECN protection for retransmitted packets.  However,
for an ECN-capable TCP connection in a fully-ECN-capable environment
with mild congestion, packets should rarely be dropped due to
congestion in the first place, and so instances of retransmitted
packets should rarely arise.  If packets are being retransmitted,
then there are already packet losses (from corruption or from
congestion) that ECN has been unable to prevent.

We note that if the router sets the CE codepoint for an ECN-capable
data packet within a TCP connection, then the TCP connection is
guaranteed to receive that indication of congestion, or to receive
some other indication of congestion within the same window of data,
even if this packet is dropped or reordered in the network.  We
consider two cases, when the packet is later retransmitted, and when
the packet is not later retransmitted.

In the first case, if the packet is either dropped or delayed, and at
some point retransmitted by the data sender, then the retransmission
is a result of a Fast Retransmit or a Retransmit Timeout for either
that packet or for some prior packet in the same window of data.  In
this case, because the data sender already has retransmitted this
packet, we know that the data sender has already responded to an

indication of congestion for some packet within the same window of
data as the original packet.  Thus, even if the first transmission of
the packet is dropped in the network, or is delayed, if it had the CE
codepoint set, and is later ignored by the data receiver as an out-
of-window packet, this is not a problem, because the sender has
already responded to an indication of congestion for that window of
data.

In the second case, if the packet is never retransmitted by the data
sender, then this data packet is the only copy of this data received
by the data receiver, and therefore arrives at the data receiver as
an in-window packet, regardless of how much the packet might be
delayed or reordered.  In this case, if the CE codepoint is set on
the packet within the network, this will be treated by the data
receiver as a valid indication of congestion.

6.1.6.  TCP Window Probes.

When the TCP data receiver advertises a zero window, the TCP data
sender sends window probes to determine if the receiver's window has
increased.  Window probe packets do not contain any user data except
for the sequence number, which is a byte.  If a window probe packet
is dropped in the network, this loss is not detected by the receiver.
Therefore, the TCP data sender MUST NOT set either an ECT codepoint
or the CWR bit on window probe packets.

However, because window probes use exact sequence numbers, they
cannot be easily spoofed in denial-of-service attacks.  Therefore, if
a window probe arrives with the CE codepoint set, then the receiver
SHOULD respond to the ECN indications.

7.  Non-compliance by the End Nodes

This section discusses concerns about the vulnerability of ECN to
non-compliant end-nodes (i.e., end nodes that set the ECT codepoint
in transmitted packets but do not respond to received CE packets).
We argue that the addition of ECN to the IP architecture will not
significantly increase the current vulnerability of the architecture
to unresponsive flows.

Even for non-ECN environments, there are serious concerns about the
damage that can be done by non-compliant or unresponsive flows (that
is, flows that do not respond to congestion control indications by
reducing their arrival rate at the congested link).  For example, an
end-node could "turn off congestion control" by not reducing its
congestion window in response to packet drops. This is a concern for
the current Internet.  It has been argued that routers will have to
deploy mechanisms to detect and differentially treat packets from

non-compliant flows [RFC2309,FF99].  It has also been suggested that
techniques such as end-to-end per-flow scheduling and isolation of
one flow from another, differentiated services, or end-to-end
reservations could remove some of the more damaging effects of
unresponsive flows.

It might seem that dropping packets in itself is an adequate
deterrent for non-compliance, and that the use of ECN removes this
deterrent.  We would argue in response that (1) ECN-capable routers
preserve packet-dropping behavior in times of high congestion; and
(2) even in times of high congestion, dropping packets in itself is
not an adequate deterrent for non-compliance.

First, ECN-Capable routers will only mark packets (as opposed to
dropping them) when the packet marking rate is reasonably low. During
periods where the average queue size exceeds an upper threshold, and
therefore the potential packet marking rate would be high, our
recommendation is that routers drop packets rather then set the CE
codepoint in packet headers.

During the periods of low or moderate packet marking rates when ECN
would be deployed, there would be little deterrent effect on
unresponsive flows of dropping rather than marking those packets. For
example, delay-insensitive flows using reliable delivery might have
an incentive to increase rather than to decrease their sending rate
in the presence of dropped packets.  Similarly, delay-sensitive flows
using unreliable delivery might increase their use of FEC in response
to an increased packet drop rate, increasing rather than decreasing
their sending rate.  For the same reasons, we do not believe that
packet dropping itself is an effective deterrent for non-compliance
even in an environment of high packet drop rates, when all flows are
sharing the same packet drop rate.

Several methods have been proposed to identify and restrict non-
compliant or unresponsive flows. The addition of ECN to the network
environment would not in any way increase the difficulty of designing
and deploying such mechanisms. If anything, the addition of ECN to
the architecture would make the job of identifying unresponsive flows
slightly easier.  For example, in an ECN-Capable environment routers
are not limited to information about packets that are dropped or have
the CE codepoint set at that router itself; in such an environment,
routers could also take note of arriving CE packets that indicate
congestion encountered by that packet earlier in the path.

8.  Non-compliance in the Network

   This section considers the issues when a router is operating,
   possibly maliciously, to modify either of the bits in the ECN field.
   We note that in IPv4, the IP header is protected from bit errors by a
   header checksum;  this is not the case in IPv6.  Thus for IPv6 the
   ECN field can be accidentally modified by bit errors on links or in
   routers without being detected by an IP header checksum.

   By tampering with the bits in the ECN field, an adversary (or a
   broken router) could do one or more of the following: falsely report
   congestion, disable ECN-Capability for an individual packet, erase
   the ECN congestion indication, or falsely indicate ECN-Capability.
   Section 18 systematically examines the various cases by which the ECN
   field could be modified.  The important criterion considered in
   determining the consequences of such modifications is whether it is
   likely to lead to poorer behavior in any dimension (throughput,
   delay, fairness or functionality) than if a router were to drop a
   packet.

   The first two possible changes, falsely reporting congestion or
   disabling ECN-Capability for an individual packet, are no worse than
   if the router were to simply drop the packet.  From a congestion
   control point of view, setting the CE codepoint in the absence of
   congestion by a non-compliant router would be no worse than a router
   dropping a packet unnecessarily. By "erasing" an ECT codepoint of a
   packet that is later dropped in the network, a router's actions could
   result in an unnecessary packet drop for that packet later in the
   network.

   However, as discussed in Section 18, a router that erases the ECN
   congestion indication or falsely indicates ECN-Capability could
   potentially do more damage to the flow that if it has simply dropped
   the packet.  A rogue or broken router that "erased" the CE codepoint
   in arriving CE packets would prevent that indication of congestion
   from reaching downstream receivers.  This could result in the failure
   of congestion control for that flow and a resulting increase in
   congestion in the network, ultimately resulting in subsequent packets
   dropped for this flow as the average queue size increased at the
   congested gateway.

   Section 19 considers the potential repercussions of subverting end-
   to-end congestion control by either falsely indicating ECN-
   Capability, or by erasing the congestion indication in ECN (the CE-
   codepoint).  We observe in Section 19 that the consequence of
   subverting ECN-based congestion control may lead to potential
   unfairness, but this is likely to be no worse than the subversion of
   either ECN-based or packet-based congestion control by the end nodes.

8.1.  Complications Introduced by Split Paths

   If a router or other network element has access to all of the packets
   of a flow, then that router could do no more damage to a flow by
   altering the ECN field than it could by simply dropping all of the
   packets from that flow.  However, in some cases, a malicious or
   broken router might have access to only a subset of the packets from
   a flow.  The question is as follows:  can this router, by altering
   the ECN field in this subset of the packets, do more damage to that
   flow than if it has simply dropped that set of the packets?

   This is also discussed in detail in Section 18, which concludes as
   follows:  It is true that the adversary that has access only to a
   subset of packets in an aggregate might, by subverting ECN-based
   congestion control, be able to deny the benefits of ECN to the other
   packets in the aggregate.  While this is undesirable, this is not a
   sufficient concern to result in disabling ECN.

9.   Encapsulated Packets

9.1.  IP packets encapsulated in IP

   The encapsulation of IP packet headers in tunnels is used in many
   places, including IPsec and IP in IP [RFC2003].  This section
   considers issues related to interactions between ECN and IP tunnels,
   and specifies two alternative solutions.  This discussion is
   complemented by RFC 2983's discussion of interactions between
   Differentiated Services and IP tunnels of various forms [RFC 2983],
   as Differentiated Services uses the remaining six bits of the IP
   header octet that is used by ECN (see Figure 2 in Section 5).


   Some IP tunnel modes are based on adding a new "outer" IP header that
   encapsulates the original, or "inner" IP header and its associated
   packet.  In many cases, the new "outer" IP header may be added and
   removed at intermediate points along a connection, enabling the
   network to establish a tunnel without requiring endpoint
   participation.  We denote tunnels that specify that the outer header
   be discarded at tunnel egress as "simple tunnels".

   ECN uses the ECN field in the IP header for signaling between routers
   and connection endpoints.  ECN interacts with IP tunnels based on the
   treatment of the ECN field in the IP header.  In simple IP tunnels
   the octet containing the ECN field is copied or mapped from the inner
   IP header to the outer IP header at IP tunnel ingress, and the outer
   header's copy of this field is discarded at IP tunnel egress.  If the
   outer header were to be simply discarded without taking care to deal
   with the ECN field, and an ECN-capable router were to set the CE

(Congestion Experienced) codepoint within a packet in a simple IP
tunnel, this indication would be discarded at tunnel egress, losing
the indication of congestion.

Thus, the use of ECN over simple IP tunnels would result in routers
attempting to use the outer IP header to signal congestion to
endpoints, but those congestion warnings never arriving because the
outer header is discarded at the tunnel egress point.  This problem
was encountered with ECN and IPsec in tunnel mode, and RFC 2481
recommended that ECN not be used with the older simple IPsec tunnels
in order to avoid this behavior and its consequences.  When ECN
becomes widely deployed, then simple tunnels likely to carry ECN-
capable traffic will have to be changed.  If ECN-capable traffic is
carried by a simple tunnel through a congested, ECN-capable router,
this could result in subsequent packets being dropped for this flow
as the average queue size increases at the congested router, as
discussed in Section 8 above.

From a security point of view, the use of ECN in the outer header of
an IP tunnel might raise security concerns because an adversary could
tamper with the ECN information that propagates beyond the tunnel
endpoint.  Based on an analysis in Sections 18 and 19 of these
concerns and the resultant risks, our overall approach is to make
support for ECN an option for IP tunnels, so that an IP tunnel can be
specified or configured either to use ECN or not to use ECN in the
outer header of the tunnel.  Thus, in environments or tunneling
protocols where the risks of using ECN are judged to outweigh its
benefits, the tunnel can simply not use ECN in the outer header.
Then the only indication of congestion experienced at routers within
the tunnel would be through packet loss.

The result is that there are two viable options for the behavior of
ECN-capable connections over an IP tunnel, including IPsec tunnels:

    * A limited-functionality option in which ECN is preserved in the
      inner header, but disabled in the outer header.  The only
      mechanism available for signaling congestion occurring within
      the tunnel in this case is dropped packets.

    * A full-functionality option that supports ECN in both the inner
      and outer headers, and propagates congestion warnings from nodes
      within the tunnel to endpoints.

Support for these options requires varying amounts of changes to IP
header processing at tunnel ingress and egress.  A small subset of
these changes sufficient to support only the limited-functionality
option would be sufficient to eliminate any incompatibility between
ECN and IP tunnels.

   One goal of this document is to give guidance about the tradeoffs
   between the limited-functionality and full-functionality options.  A
   full discussion of the potential effects of an adversary's
   modifications of the ECN field is given in Sections 18 and 19.

9.1.1.  The Limited-functionality and Full-functionality Options

   The limited-functionality option for ECN encapsulation in IP tunnels
   is for the not-ECT codepoint to be set in the outside (encapsulating)
   header regardless of the value of the ECN field in the inside
   (encapsulated) header.  With this option, the ECN field in the inner
   header is not altered upon de-capsulation.  The disadvantage of this
   approach is that the flow does not have ECN support for that part of
   the path that is using IP tunneling, even if the encapsulated packet
   (from the original TCP sender) is ECN-Capable.  That is, if the
   encapsulated packet arrives at a congested router that is ECN-
   capable, and the router can decide to drop or mark the packet as an
   indication of congestion to the end nodes, the router will not be
   permitted to set the CE codepoint in the packet header, but instead
   will have to drop the packet.

   The full-functionality option for ECN encapsulation is to copy the
   ECN codepoint of the inside header to the outside header on
   encapsulation if the inside header is not-ECT or ECT, and to set the
   ECN codepoint of the outside header to ECT(0) if the ECN codepoint of
   the inside header is CE.  On decapsulation, if the CE codepoint is
   set on the outside header, then the CE codepoint is also set in the
   inner header.  Otherwise, the ECN codepoint on the inner header is
   left unchanged.  That is, for full ECN support the encapsulation and
   decapsulation processing involves the following:  At tunnel ingress,
   the full-functionality option sets the ECN codepoint in the outer
   header.  If the ECN codepoint in the inner header is not-ECT or ECT,
   then it is copied to the ECN codepoint in the outer header.  If the
   ECN codepoint in the inner header is CE, then the ECN codepoint in
   the outer header is set to ECT(0).  Upon decapsulation at the tunnel
   egress, the full-functionality option sets the CE codepoint in the
   inner header if the CE codepoint is set in the outer header.
   Otherwise, no change is made to this field of the inner header.

   With the full-functionality option, a flow can take advantage of ECN
   in those parts of the path that might use IP tunneling.  The
   disadvantage of the full-functionality option from a security
   perspective is that the IP tunnel cannot protect the flow from
   certain modifications to the ECN bits in the IP header within the
   tunnel.  The potential dangers from modifications to the ECN bits in
   the IP header are described in detail in Sections 18 and 19.

(1) An IP tunnel MUST modify the handling of the DS field octet at
IP tunnel endpoints by implementing either the limited-
functionality or the full-functionality option.

(2) Optionally, an IP tunnel MAY enable the endpoints of an IP
tunnel to negotiate the choice between the limited-functionality
and the full-functionality option for ECN in the tunnel.

The minimum required to make ECN usable with IP tunnels is the
limited-functionality option, which prevents ECN from being enabled
in the outer header of the tunnel.  Full support for ECN requires the
use of the full-functionality option.  If there are no optional
mechanisms for the tunnel endpoints to negotiate a choice between the
limited-functionality or full-functionality option, there can be a
pre-existing agreement between the tunnel endpoints about whether to
support the limited-functionality or the full-functionality ECN
option.

All IP tunnels MUST implement the limited-functionality option, and
SHOULD support the full-functionality option.

In addition, it is RECOMMENDED that packets with the CE codepoint in
the outer header be dropped if they arrive at the tunnel egress point
for a tunnel that uses the limited-functionality option, or for a
tunnel that uses the full-functionality option but for which the
not-ECT codepoint is set in the inner header.  This is motivated by
backwards compatibility and to ensure that no unauthorized
modifications of the ECN field take place, and is discussed further
in the next Section (9.1.2).

9.1.2.  Changes to the ECN Field within an IP Tunnel.

The presence of a copy of the ECN field in the inner header of an IP
tunnel mode packet provides an opportunity for detection of
unauthorized modifications to the ECN field in the outer header.
Comparison of the ECT fields in the inner and outer headers falls
into two categories for implementations that conform to this
document:

    * If the IP tunnel uses the full-functionality option, then the
      not-ECT codepoint should be set in the outer header if and only
      if it is also set in the inner header.

    * If the tunnel uses the limited-functionality option, then the
      not-ECT codepoint should be set in the outer header.

Receipt of a packet not satisfying the appropriate condition could be
a cause of concern.

Consider the case of an IP tunnel where the tunnel ingress point has
not been updated to this document's requirements, while the tunnel
egress point has been updated to support ECN.  In this case, the IP
tunnel is not explicitly configured to support the full-functionality
ECN option. However, the tunnel ingress point is behaving identically
to a tunnel ingress point that supports the full-functionality
option.  If packets from an ECN-capable connection use this tunnel,
the ECT codepoint will be set in the outer header at the tunnel
ingress point.  Congestion within the tunnel may then result in ECN-
capable routers setting CE in the outer header.  Because the tunnel
has not been explicitly configured to support the full-functionality
option, the tunnel egress point expects the not-ECT codepoint to be
set in the outer header.  When an ECN-capable tunnel egress point
receives a packet with the ECT or CE codepoint in the outer header,
in a tunnel that has not been configured to support the full-
functionality option, that packet should be processed, according to
whether the CE codepoint was set, as follows.  It is RECOMMENDED that
on a tunnel that has not been configured to support the full-
functionality option, packets should be dropped at the egress point
if the CE codepoint is set in the outer header but not in the inner
header, and should be forwarded otherwise.

An IP tunnel cannot provide protection against erasure of congestion
indications based on changing the ECN codepoint from CE to ECT.  The
erasure of congestion indications may impact the network and other
flows in ways that would not be possible in the absence of ECN.  It
is important to note that erasure of congestion indications can only
be performed to congestion indications placed by nodes within the
tunnel; the copy of the ECN field in the inner header preserves
congestion notifications from nodes upstream of the tunnel ingress
(unless the inner header is also erased).  If erasure of congestion
notifications is judged to be a security risk that exceeds the
congestion management benefits of ECN, then tunnels could be
specified or configured to use the limited-functionality option.

9.2.  IPsec Tunnels

   IPsec supports secure communication over potentially insecure network
   components such as intermediate routers.  IPsec protocols support two
   operating modes, transport mode and tunnel mode, that span a wide
   range of security requirements and operating environments.  Transport
   mode security protocol header(s) are inserted between the IP (IPv4 or
   IPv6) header and higher layer protocol headers (e.g., TCP), and hence
   transport mode can only be used for end-to-end security on a
   connection.  IPsec tunnel mode is based on adding a new "outer" IP
   header that encapsulates the original, or "inner" IP header and its
   associated packet.  Tunnel mode security headers are inserted between
   these two IP headers.  In contrast to transport mode, the new "outer"

IP header and tunnel mode security headers can be added and removed
at intermediate points along a connection, enabling security gateways
to secure vulnerable portions of a connection without requiring
endpoint participation in the security protocols.  An important
aspect of tunnel mode security is that in the original specification,
the outer header is discarded at tunnel egress, ensuring that
security threats based on modifying the IP header do not propagate
beyond that tunnel endpoint.  Further discussion of IPsec can be
found in [RFC2401].

The IPsec protocol as originally defined in [ESP, AH] required that
the inner header's ECN field not be changed by IPsec decapsulation
processing at a tunnel egress node; this would have ruled out the
possibility of full-functionality mode for ECN.  At the same time,
this would ensure that an adversary's modifications to the ECN field
cannot be used to launch theft- or denial-of-service attacks across
an IPsec tunnel endpoint, as any such modifications will be discarded
at the tunnel endpoint.

In principle, permitting the use of ECN functionality in the outer
header of an IPsec tunnel raises security concerns because an
adversary could tamper with the information that propagates beyond
the tunnel endpoint.  Based on an analysis (included in Sections 18
and 19) of these concerns and the associated risks, our overall
approach has been to provide configuration support for IPsec changes
to remove the conflict with ECN.

In particular, in tunnel mode the IPsec tunnel MUST support the
limited-functionality option outlined in Section 9.1.1, and SHOULD
support the full-functionality option outlined in Section 9.1.1.

This makes permission to use ECN functionality in the outer header of
an IPsec tunnel a configurable part of the corresponding IPsec
Security Association (SA), so that it can be disabled in situations
where the risks are judged to outweigh the benefits.  The result is
that an IPsec security administrator is presented with two
alternatives for the behavior of ECN-capable connections within an
IPsec tunnel, the limited-functionality alternative and full-
functionality alternative described earlier.

In addition, this document specifies how the endpoints of an IPsec
tunnel could negotiate enabling ECN functionality in the outer
headers of that tunnel based on security policy.  The ability to
negotiate ECN usage between tunnel endpoints would enable a security
administrator to disable ECN in situations where she believes the
risks (e.g., of lost congestion notifications) outweigh the benefits
of ECN.

The IPsec protocol, as defined in [ESP, AH], does not include the IP
header's ECN field in any of its cryptographic calculations (in the
case of tunnel mode, the outer IP header's ECN field is not
included).  Hence modification of the ECN field by a network node has
no effect on IPsec's end-to-end security, because it cannot cause any
IPsec integrity check to fail.  As a consequence, IPsec does not
provide any defense against an adversary's modification of the ECN
field (i.e., a man-in-the-middle attack), as the adversary's
modification will also have no effect on IPsec's end-to-end security.
In some environments, the ability to modify the ECN field without
affecting IPsec integrity checks may constitute a covert channel; if
it is necessary to eliminate such a channel or reduce its bandwidth,
then the IPsec tunnel should be run in limited-functionality mode.

9.2.1.  Negotiation between Tunnel Endpoints

   This section describes the detailed changes to enable usage of ECN
   over IPsec tunnels, including the negotiation of ECN support between
   tunnel endpoints.  This is supported by three changes to IPsec:

      * An optional Security Association Database (SAD) field indicating
        whether tunnel encapsulation and decapsulation processing allows
        or forbids ECN usage in the outer IP header.

      * An optional Security Association Attribute that enables
        negotiation of this SAD field between the two endpoints of an SA
        that supports tunnel mode.

      * Changes to tunnel mode encapsulation and decapsulation
        processing to allow or forbid ECN usage in the outer IP header
        based on the value of the SAD field.  When ECN usage is allowed
        in the outer IP header, the ECT codepoint is set in the outer
        header for ECN-capable connections and congestion notifications
        (indicated by the CE codepoint) from such connections are
        propagated to the inner header at tunnel egress.

   If negotiation of ECN usage is implemented, then the SAD field SHOULD
   also be implemented.  On the other hand, negotiation of ECN usage is
   OPTIONAL in all cases, even for implementations that support the SAD
   field.  The encapsulation and decapsulation processing changes are
   REQUIRED, but MAY be implemented without the other two changes by
   assuming that ECN usage is always forbidden.  The full-functionality
   alternative for ECN usage over IPsec tunnels consists of the SAD
   field and the full version of encapsulation and decapsulation
   processing changes, with or without the OPTIONAL negotiation support.
   The limited-functionality alternative consists of a subset of the
   encapsulation and decapsulation changes that always forbids ECN
   usage.

These changes are covered further in the following three subsections.

9.2.1.1.  ECN Tunnel Security Association Database Field

Full ECN functionality adds a new field to the SAD (see [RFC2401]):

ECN Tunnel: allowed or forbidden.

Indicates whether ECN-capable connections using this SA in tunnel
mode are permitted to receive ECN congestion notifications for
congestion occurring within the tunnel.  The allowed value enables
ECN congestion notifications.  The forbidden value disables such
notifications, causing all congestion to be indicated via dropped
packets.

[OPTIONAL.  The value of this field SHOULD be assumed to be
"forbidden" in implementations that do not support it.]

If this attribute is implemented, then the SA specification in a
Security Policy Database (SPD) entry MUST support a corresponding
attribute, and this SPD attribute MUST be covered by the SPD
administrative interface (currently described in Section 4.4.1 of
[RFC2401]).

9.2.1.2.  ECN Tunnel Security Association Attribute

A new IPsec Security Association Attribute is defined to enable the
support for ECN congestion notifications based on the outer IP header
to be negotiated for IPsec tunnels (see [RFC2407]).  This attribute
is OPTIONAL, although implementations that support it SHOULD also
support the SAD field defined in Section 9.2.1.1.

Attribute Type

```
        class                 value          type
     -------------------------------------------------
     ECN Tunnel                10            Basic
```

The IPsec SA Attribute value 10 has been allocated by IANA to
indicate that the ECN Tunnel SA Attribute is being negotiated; the
type of this attribute is Basic (see Section 4.5 of [RFC2407]).  The
Class Values are used to conduct the negotiation.  See [RFC2407,
RFC2408, RFC2409] for further information including encoding formats
and requirements for negotiating this SA attribute.

Class Values

ECN Tunnel

Specifies whether ECN functionality is allowed to be used with Tunnel
Encapsulation Mode.  This affects tunnel encapsulation and
decapsulation processing - see Section 9.2.1.3.

RESERVED            0
Allowed             1
Forbidden           2

Values 3-61439 are reserved to IANA.  Values 61440-65535 are for
private use.

If unspecified, the default shall be assumed to be Forbidden.

ECN Tunnel is a new SA attribute, and hence initiators that use it
can expect to encounter responders that do not understand it, and
therefore reject proposals containing it.  For backwards
compatibility with such implementations initiators SHOULD always also
include a proposal without the ECN Tunnel attribute to enable such a
responder to select a transform or proposal that does not contain the
ECN Tunnel attribute.  RFC 2407 currently requires responders to
reject all proposals if any proposal contains an unknown attribute;
this requirement is expected to be changed to require a responder not
to select proposals or transforms containing unknown attributes.

9.2.1.3.  Changes to IPsec Tunnel Header Processing

   For full ECN support, the encapsulation and decapsulation processing
   for the IPv4 TOS field and the IPv6 Traffic Class field are changed
   from that specified in [RFC2401] to the following:

```
                     <-- How Outer Hdr Relates to Inner Hdr -->
                     Outer Hdr at               Inner Hdr at
   IPv4              Encapsulator               Decapsulator
     Header fields:  --------------------       ------------
       DS Field      copied from inner hdr (5)  no change
       ECN Field     constructed (7)            constructed (8)

   IPv6
     Header fields:
       DS Field      copied from inner hdr (6)  no change
       ECN Field     constructed (7)            constructed (8)
```

(5)(6) If the packet will immediately enter a domain for which the
DSCP value in the outer header is not appropriate, that value MUST
be mapped to an appropriate value for the domain [RFC 2474].  Also
see [RFC 2475] for further information.

(7) If the value of the ECN Tunnel field in the SAD entry for this
SA is "allowed" and the ECN field in the inner header is set to
any value other than CE, copy this ECN field to the outer header.
If the ECN field in the inner header is set to CE, then set the
ECN field in the outer header to ECT(0).

(8) If the value of the ECN tunnel field in the SAD entry for this
SA is "allowed" and the ECN field in the inner header is set to
ECT(0) or ECT(1) and the ECN field in the outer header is set to
CE, then copy the ECN field from the outer header to the inner
header.  Otherwise, make no change to the ECN field in the inner
header.

(5) and (6) are identical to match usage in [RFC2401], although
they are different in [RFC2401].

The above description applies to implementations that support the ECN
Tunnel field in the SAD; such implementations MUST implement this
processing instead of the processing of the IPv4 TOS octet and IPv6
Traffic Class octet defined in [RFC2401].  This constitutes the
full-functionality alternative for ECN usage with IPsec tunnels.

An implementation that does not support the ECN Tunnel field in the
SAD MUST implement this processing by assuming that the value of the
ECN Tunnel field of the SAD is "forbidden" for every SA.  In this
case, the processing of the ECN field reduces to:

(7) Set the ECN field to not-ECT in the outer header.
(8) Make no change to the ECN field in the inner header.

This constitutes the limited functionality alternative for ECN usage
with IPsec tunnels.

For backwards compatibility, packets with the CE codepoint set in the
outer header SHOULD be dropped if they arrive on an SA that is using
the limited-functionality option, or that is using the full-
functionality option with the not-ECN codepoint set in the inner
header.

9.2.2.  Changes to the ECN Field within an IPsec Tunnel.

   If the ECN Field is changed inappropriately within an IPsec tunnel,
   and this change is detected at the tunnel egress, then the receipt of
   a packet not satisfying the appropriate condition for its SA is an
   auditable event.  An implementation MAY create audit records with
   per-SA counts of incorrect packets over some time period rather than
   creating an audit record for each erroneous packet.  Any such audit
   record SHOULD contain the headers from at least one erroneous packet,
   but need not contain the headers from every packet represented by the
   entry.

9.2.3.  Comments for IPsec Support

   Substantial comments were received on two areas of this document
   during review by the IPsec working group.  This section describes
   these comments and explains why the proposed changes were not
   incorporated.

   The first comment indicated that per-node configuration is easier to
   implement than per-SA configuration.  After serious thought and
   despite some initial encouragement of per-node configuration, it no
   longer seems to be a good idea. The concern is that as ECN-awareness
   is progressively deployed in IPsec, many ECN-aware IPsec
   implementations will find themselves communicating with a mixture of
   ECN-aware and ECN-unaware IPsec tunnel endpoints.  In such an
   environment with per-node configuration, the only reasonable thing to
   do is forbid ECN usage for all IPsec tunnels, which is not the
   desired outcome.

   In the second area, several reviewers noted that SA negotiation is
   complex, and adding to it is non-trivial.  One reviewer suggested
   using ICMP after tunnel setup as a possible alternative.  The
   addition to SA negotiation in this document is OPTIONAL and will
   remain so; implementers are free to ignore it.  The authors believe
   that the assurance it provides can be useful in a number of
   situations.  In practice, if this is not implemented, it can be
   deleted at a subsequent stage in the standards process.  Extending
   ICMP to negotiate ECN after tunnel setup is more complex than
   extending SA attribute negotiation.  Some tunnels do not permit
   traffic to be addressed to the tunnel egress endpoint, hence the ICMP
   packet would have to be addressed to somewhere else, scanned for by
   the egress endpoint, and discarded there or at its actual
   destination.  In addition, ICMP delivery is unreliable, and hence
   there is a possibility of an ICMP packet being dropped, entailing the
   invention of yet another ack/retransmit mechanism.  It seems better
   simply to specify an OPTIONAL extension to the existing SA
   negotiation mechanism.

9.3.  IP packets encapsulated in non-IP Packet Headers.

   A different set of issues are raised, relative to ECN, when IP
   packets are encapsulated in tunnels with non-IP packet headers.  This
   occurs with MPLS [MPLS], GRE [GRE], L2TP [L2TP], and PPTP [PPTP].
   For these protocols, there is no conflict with ECN; it is just that
   ECN cannot be used within the tunnel unless an ECN codepoint can be
   specified for the header of the encapsulating protocol.  Earlier work
   considered a preliminary proposal for incorporating ECN into MPLS,
   and proposals for incorporating ECN into GRE, L2TP, or PPTP will be
   considered as the need arises.

10.  Issues Raised by Monitoring and Policing Devices

   One possibility is that monitoring and policing devices (or more
   informally, "penalty boxes") will be installed in the network to
   monitor whether best-effort flows are appropriately responding to
   congestion, and to preferentially drop packets from flows determined
   not to be using adequate end-to-end congestion control procedures.

   We recommend that any "penalty box" that detects a flow or an
   aggregate of flows that is not responding to end-to-end congestion
   control first change from marking to dropping packets from that flow,
   before taking any additional action to restrict the bandwidth
   available to that flow.  Thus, initially, the router may drop packets
   in which the router would otherwise would have set the CE codepoint.
   This could include dropping those arriving packets for that flow that
   are ECN-Capable and that already have the CE codepoint set.  In this
   way, any congestion indications seen by that router for that flow
   will be guaranteed to also be seen by the end nodes, even in the
   presence of malicious or broken routers elsewhere in the path.  If we
   assume that the first action taken at any "penalty box" for an ECN-
   capable flow will be to drop packets instead of marking them, then
   there is no way that an adversary that subverts ECN-based end-to-end
   congestion control can cause a flow to be characterized as being
   non-cooperative and placed into a more severe action within the
   "penalty box".

   The monitoring and policing devices that are actually deployed could
   fall short of the 'ideal' monitoring device described above, in that
   the monitoring is applied not to a single flow, but to an aggregate
   of flows (e.g., those sharing a single IPsec tunnel).  In this case,
   the switch from marking to dropping would apply to all of the flows
   in that aggregate, denying the benefits of ECN to the other flows in
   the aggregate also.  At the highest level of aggregation, another
   form of the disabling of ECN happens even in the absence of

   monitoring and policing devices, when ECN-Capable RED queues switch
   from marking to dropping packets as an indication of congestion when
   the average queue size has exceeded some threshold.

11.  Evaluations of ECN

11.1.  Related Work Evaluating ECN

   This section discusses some of the related work evaluating the use of
   ECN.  The ECN Web Page [ECN] has pointers to other papers, as well as
   to implementations of ECN.

   [Floyd94] considers the advantages and drawbacks of adding ECN to the
   TCP/IP architecture.  As shown in the simulation-based comparisons,
   one advantage of ECN is to avoid unnecessary packet drops for short
   or delay-sensitive TCP connections.  A second advantage of ECN is in
   avoiding some unnecessary retransmit timeouts in TCP.  This paper
   discusses in detail the integration of ECN into TCP's congestion
   control mechanisms.  The possible disadvantages of ECN discussed in
   the paper are that a non-compliant TCP connection could falsely
   advertise itself as ECN-capable, and that a TCP ACK packet carrying
   an ECN-Echo message could itself be dropped in the network.  The
   first of these two issues is discussed in the appendix of this
   document, and the second is addressed by the addition of the CWR flag
   in the TCP header.

   Experimental evaluations of ECN include [RFC2884,K98].  The
   conclusions of [K98] and [RFC2884] are that ECN TCP gets moderately
   better throughput than non-ECN TCP; that ECN TCP flows are fair
   towards non-ECN TCP flows; and that ECN TCP is robust with two-way
   traffic (with congestion in both directions) and with multiple
   congested gateways.  Experiments with many short web transfers show
   that, while most of the short connections have similar transfer times
   with or without ECN, a small percentage of the short connections have
   very long transfer times for the non-ECN experiments as compared to
   the ECN experiments.

11.2.  A Discussion of the ECN nonce.

   The use of two ECT codepoints, ECT(0) and ECT(1), can provide a one-
   bit ECN nonce in packet headers [SCWA99].  The primary motivation for
   this is the desire to allow mechanisms for the data sender to verify
   that network elements are not erasing the CE codepoint, and that data
   receivers are properly reporting to the sender the receipt of packets
   with the CE codepoint set, as required by the transport protocol.
   This section discusses issues of backwards compatibility with IP ECN
   implementations in routers conformant with RFC 2481, in which only
   one ECT codepoint was defined.  We do not believe that the

incremental deployment of ECN implementations that understand the
ECT(1) codepoint will cause significant operational problems.  This
is particularly likely to be the case when the deployment of the
ECT(1) codepoint begins with routers, before the ECT(1) codepoint
starts to be used by end-nodes.

11.2.1.  The Incremental Deployment of ECT(1) in Routers.

ECN has been an Experimental standard since January 1999, and there
are already implementations of ECN in routers that do not understand
the ECT(1) codepoint.  When the use of the ECT(1) codepoint is
standardized for TCP or for other transport protocols, this could
mean that a data sender is using the ECT(1) codepoint, but that this
codepoint is not understood by a congested router on the path.

If allowed by the transport protocol, a data sender would be free not
to make use of ECT(1) at all, and to send all ECN-capable packets
with the codepoint ECT(0).  However, if an ECN-capable sender is
using ECT(1), and the congested router on the path did not understand
the ECT(1) codepoint, then the router would end up marking some of
the ECT(0) packets, and dropping some of the ECT(1) packets, as
indications of congestion.  Since TCP is required to react to both
marked and dropped packets, this behavior of dropping packets that
could have been marked poses no significant threat to the network,
and is consistent with the overall approach to ECN that allows
routers to determine when and whether to mark packets as they see fit
(see Section 5).

12.  Summary of changes required in IP and TCP

This document specified two bits in the IP header to be used for ECN.
The not-ECT codepoint indicates that the transport protocol will
ignore the CE codepoint.  This is the default value for the ECN
codepoint.  The ECT codepoints indicate that the transport protocol
is willing and able to participate in ECN.

The router sets the CE codepoint to indicate congestion to the end
nodes.  The CE codepoint in a packet header MUST NOT be reset by a
router.

TCP requires three changes for ECN, a setup phase and two new flags
in the TCP header. The ECN-Echo flag is used by the data receiver to
inform the data sender of a received CE packet.  The Congestion
Window Reduced (CWR) flag is used by the data sender to inform the
data receiver that the congestion window has been reduced.

When ECN (Explicit Congestion Notification) is used, it is required that congestion indications generated within an IP tunnel not be lost at the tunnel egress.  We specified a minor modification to the IP protocol's handling of the ECN field during encapsulation and de-capsulation to allow flows that will undergo IP tunneling to use ECN.

Two options for ECN in tunnels were specified:

1) A limited-functionality option that does not use ECN inside the IP tunnel, by setting the ECN field in the outer header to not-ECT, and not altering the inner header at the time of decapsulation.

2) The full-functionality option, which sets the ECN field in the outer header to either not-ECT or to one of the ECT codepoints, depending on the ECN field in the inner header.  At decapsulation, if the CE codepoint is set in the outer header, and the inner header is set to one of the ECT codepoints, then the CE codepoint is copied to the inner header.

For IPsec tunnels, this document also defines an optional IPsec Security Association (SA) attribute that enables negotiation of ECN usage within IPsec tunnels and an optional field in the Security Association Database to indicate whether ECN is permitted in tunnel mode on a SA.  The required changes to IPsec tunnels for ECN usage modify RFC 2401 [RFC2401], which defines the IPsec architecture and specifies some aspects of its implementation.  The new IPsec SA attribute is in addition to those already defined in Section 4.5 of [RFC2407].

This document obsoletes RFC 2481, "A Proposal to add Explicit Congestion Notification (ECN) to IP", which defined ECN as an Experimental Protocol for the Internet Community.  The rest of this section describes the relationship between this document and its predecessor.

RFC 2481 included a brief discussion of the use of ECN with encapsulated packets, and noted that for the IPsec specifications at the time (January 1999), flows could not safely use ECN if they were to traverse IPsec tunnels.  RFC 2481 also described the changes that could be made to IPsec tunnel specifications to made them compatible with ECN.

This document also incorporates work that was done after RFC 2481. First was to describe the changes to IPsec tunnels in detail, and extensively discuss the security implications of ECN (now included as Sections 18 and 19 of this document).  Second was to extend the discussion of IPsec tunnels to include all IP tunnels.  Because older IP tunnels are not compatible with a flow's use of ECN, the

deployment of ECN in the Internet will create strong pressure for
older IP tunnels to be updated to an ECN-compatible version, using
either the limited-functionality or the full-functionality option.

This document does not address the issue of including ECN in non-IP
tunnels such as MPLS, GRE, L2TP, or PPTP.  An earlier preliminary
document about adding ECN support to MPLS was not advanced.

A third new piece of work after RFC2481 was to describe the ECN
procedure with retransmitted data packets, that an ECT codepoint
should not be set on retransmitted data packets.  The motivation for
this additional specification is to eliminate a possible avenue for
denial-of-service attacks on an existing TCP connection.  Some prior
deployments of ECN-capable TCP might not conform to the (new)
requirement not to set an ECT codepoint on retransmitted packets; we
do not believe this will cause significant problems in practice.

This document also expands slightly on the specification of the use
of SYN packets for the negotiation of ECN.  While some prior
deployments of ECN-capable TCP might not conform to the requirements
specified in this document, we do not believe that this will lead to
any performance or compatibility problems for TCP connections with a
combination of TCP implementations at the endpoints.

This document also includes the specification of the ECT(1)
codepoint, which may be used by TCP as part of the implementation of
an ECN nonce.

13.  Conclusions

Given the current effort to implement AQM, we believe this is the
right time to deploy congestion avoidance mechanisms that do not
depend on packet drops alone.  With the increased deployment of
applications and transports sensitive to the delay and loss of a
single packet (e.g., realtime traffic, short web transfers),
depending on packet loss as a normal congestion notification
mechanism appears to be insufficient (or at the very least, non-
optimal).

We examined the consequence of modifications of the ECN field within
the network, analyzing all the opportunities for an adversary to
change the ECN field.  In many cases, the change to the ECN field is
no worse than dropping a packet. However, we noted that some changes
have the more serious consequence of subverting end-to-end congestion
control.  However, we point out that even then the potential damage
is limited, and is similar to the threat posed by end-systems
intentionally failing to cooperate with end-to-end congestion
control.

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16.  Security Considerations

   Security considerations have been discussed in Sections 7, 8, 18, and
   19.

17.  IPv4 Header Checksum Recalculation

   IPv4 header checksum recalculation is an issue with some high-end
   router architectures using an output-buffered switch, since most if
   not all of the header manipulation is performed on the input side of
   the switch, while the ECN decision would need to be made local to the
   output buffer. This is not an issue for IPv6, since there is no IPv6
   header checksum. The IPv4 TOS octet is the last byte of a 16-bit
   half-word.

   RFC 1141 [RFC1141] discusses the incremental updating of the IPv4
   checksum after the TTL field is decremented.  The incremental
   updating of the IPv4 checksum after the CE codepoint was set would
   work as follows: Let HC be the original header checksum for an ECT(0)
   packet, and let HC' be the new header checksum after the CE bit has
   been set.  That is, the ECN field has changed from '10' to '11'.
   Then for header checksums calculated with one's complement
   subtraction, HC' would be recalculated as follows:

        HC' = { HC - 1      HC > 1
              { 0x0000      HC = 1

   For header checksums calculated on two's complement machines, HC'
   would be recalculated as follows after the CE bit was set:

        HC' = { HC - 1      HC > 0
              { 0xFFFE      HC = 0

   A similar incremental updating of the IPv4 checksum can be carried
   out when the ECN field is changed from ECT(1) to CE, that is, from '
   01' to '11'.

18.  Possible Changes to the ECN Field in the Network

   This section discusses in detail possible changes to the ECN field in
   the network, such as falsely reporting congestion, disabling ECN-
   Capability for an individual packet, erasing the ECN congestion
   indication, or falsely indicating ECN-Capability.

18.1.  Possible Changes to the IP Header

18.1.1.  Erasing the Congestion Indication

   First, we consider the changes that a router could make that would
   result in effectively erasing the congestion indication after it had
   been set by a router upstream.  The convention followed is:  ECN
   codepoint of received packet -> ECN codepoint of packet transmitted.

   Replacing the CE codepoint with the ECT(0) or ECT(1) codepoint
   effectively erases the congestion indication.  However, with the use
   of two ECT codepoints, a router erasing the CE codepoint has no way
   to know whether the original ECT codepoint was ECT(0) or ECT(1).
   Thus, it is possible for the transport protocol to deploy mechanisms
   to detect such erasures of the CE codepoint.

   The consequence of the erasure of the CE codepoint for the upstream
   router is that there is a potential for congestion to build for a
   time, because the congestion indication does not reach the source.
   However, the packet would be received and acknowledged.

   The potential effect of erasing the congestion indication is complex,
   and is discussed in depth in Section 19 below.  Note that the effect
   of erasing the congestion indication is different from dropping a
   packet in the network.  When a data packet is dropped, the drop is
   detected by the TCP sender, and interpreted as an indication of
   congestion.  Similarly, if a sufficient number of consecutive
   acknowledgement packets are dropped, causing the cumulative
   acknowledgement field not to be advanced at the sender, the sender is
   limited by the congestion window from sending additional packets, and
   ultimately the retransmit timer expires.

   In contrast, a systematic erasure of the CE bit by a downstream
   router can have the effect of causing a queue buildup at an upstream
   router, including the possible loss of packets due to buffer
   overflow.  There is a potential of unfairness in that another flow
   that goes through the congested router could react to the CE bit set
   while the flow that has the CE bit erased could see better
   performance.  The limitations on this potential unfairness are
   discussed in more detail in Section 19 below.

   The last of the three changes is to replace the CE codepoint with the
   not-ECT codepoint, thus erasing the congestion indication and
   disabling ECN-Capability at the same time.

   The 'erasure' of the congestion indication is only effective if the
   packet does not end up being marked or dropped again by a downstream
   router.  If the CE codepoint is replaced by an ECT codepoint, the

packet remains ECN-Capable, and could be either marked or dropped by
a downstream router as an indication of congestion.  If the CE
codepoint is replaced by the not-ECT codepoint, the packet is no
longer ECN-capable, and can therefore be dropped but not marked by a
downstream router as an indication of congestion.

18.1.2.  Falsely Reporting Congestion

   This change is to set the CE codepoint when an ECT codepoint was
   already set, even though there was no congestion.  This change does
   not affect the treatment of that packet along the rest of the path.
   In particular, a router does not examine the CE codepoint in deciding
   whether to drop or mark an arriving packet.

   However, this could result in the application unnecessarily invoking
   end-to-end congestion control, and reducing its arrival rate.  By
   itself, this is no worse (for the application or for the network)
   than if the tampering router had actually dropped the packet.

18.1.3.  Disabling ECN-Capability

   This change is to turn off the ECT codepoint of a packet.  This means
   that if the packet later encounters congestion (e.g., by arriving to
   a RED queue with a moderate average queue size), it will be dropped
   instead of being marked.  By itself, this is no worse (for the
   application) than if the tampering router had actually dropped the
   packet.  The saving grace in this particular case is that there is no
   congested router upstream expecting a reaction from setting the CE
   bit.

18.1.4.  Falsely Indicating ECN-Capability

   This change would incorrectly label a packet as ECN-Capable. The
   packet may have been sent either by an ECN-Capable transport or a
   transport that is not ECN-Capable.

   If the packet later encounters moderate congestion at an ECN-Capable
   router, the router could set the CE codepoint instead of dropping the
   packet.  If the transport protocol in fact is not ECN-Capable, then
   the transport will never receive this indication of congestion, and
   will not reduce its sending rate in response.  The potential
   consequences of falsely indicating ECN-capability are discussed
   further in Section 19 below.

   If the packet never later encounters congestion at an ECN-Capable
   router, then the first of these two changes would have no effect,
   other than possibly interfering with the use of the ECN nonce by the
   transport protocol.  The last change, however, would have the effect

of giving false reports of congestion to a monitoring device along
the path.  If the transport protocol is ECN-Capable, then this change
could also have an effect at the transport level, by combining
falsely indicating ECN-Capability with falsely reporting congestion.
For an ECN-capable transport, this would cause the transport to
unnecessarily react to congestion.  In this particular case, the
router that is incorrectly changing the ECN field could have dropped
the packet. Thus for this case of an ECN-capable transport, the
consequence of this change to the ECN field is no worse than dropping
the packet.

18.2.  Information carried in the Transport Header

For TCP, an ECN-capable TCP receiver informs its TCP peer that it is
ECN-capable at the TCP level, conveying this information in the TCP
header at the time the connection is setup.  This document does not
consider potential dangers introduced by changes in the transport
header within the network.  We note that when IPsec is used, the
transport header is protected both in tunnel and transport modes
[ESP, AH].

Another issue concerns TCP packets with a spoofed IP source address
carrying invalid ECN information in the transport header.  For
completeness, we examine here some possible ways that a node spoofing
the IP source address of another node could use the two ECN flags in
the TCP header to launch a denial-of-service attack. However, these
attacks would require an ability for the attacker to use valid TCP
sequence numbers, and any attacker with this ability and with the
ability to spoof IP source addresses could damage the TCP connection
without using the ECN flags.  Therefore, ECN does not add any new
vulnerabilities in this respect.

An acknowledgement packet with a spoofed IP source address of the TCP
data receiver could include the ECE bit set.  If accepted by the TCP
data sender as a valid packet, this spoofed acknowledgement packet
could result in the TCP data sender unnecessarily halving its
congestion window.  However, to be accepted by the data sender, such
a spoofed acknowledgement packet would have to have the correct 32-
bit sequence number as well as a valid acknowledgement number.  An
attacker that could successfully send such a spoofed acknowledgement
packet could also send a spoofed RST packet, or do other equally
damaging operations to the TCP connection.

Packets with a spoofed IP source address of the TCP data sender could
include the CWR bit set.  Again, to be accepted, such a packet would
have to have a valid sequence number.  In addition, such a spoofed
packet would have a limited performance impact.  Spoofing a data
packet with the CWR bit set could result in the TCP data receiver

sending fewer ECE packets than it would otherwise, if the data
receiver was sending ECE packets when it received the spoofed CWR
packet.

18.3.  Split Paths

In some cases, a malicious or broken router might have access to only
a subset of the packets from a flow.  The question is as follows:
can this router, by altering the ECN field in this subset of the
packets, do more damage to that flow than if it had simply dropped
that set of packets?

We will classify the packets in the flow as A packets and B packets,
and assume that the adversary only has access to A packets.  Assume
that the adversary is subverting end-to-end congestion control along
the path traveled by A packets only, by either falsely indicating
ECN-Capability upstream of the point where congestion occurs, or
erasing the congestion indication downstream.  Consider also that
there exists a monitoring device that sees both the A and B packets,
and will "punish" both the A and B packets if the total flow is
determined not to be properly responding to indications of
congestion.  Another key characteristic that we believe is likely to
be true is that the monitoring device, before 'punishing' the A&B
flow, will first drop packets instead of setting the CE codepoint,
and will drop arriving packets of that flow that already have the CE
codepoint set.  If the end nodes are in fact using end-to-end
congestion control, they will see all of the indications of
congestion seen by the monitoring device, and will begin to respond
to these indications of congestion. Thus, the monitoring device is
successful in providing the indications to the flow at an early
stage.

It is true that the adversary that has access only to the A packets
might, by subverting ECN-based congestion control, be able to deny
the benefits of ECN to the other packets in the A&B aggregate.  While
this is unfortunate, this is not a reason to disable ECN.

A variant of falsely reporting congestion occurs when there are two
adversaries along a path, where the first adversary falsely reports
congestion, and the second adversary 'erases' those reports. (Unlike
packet drops, ECN congestion reports can be 'reversed' later in the
network by a malicious or broken router.  However, the use of the ECN
nonce could help the transport to detect this behavior.)  While this
would be transparent to the end node, it is possible that a
monitoring device between the first and second adversaries would see
the false indications of congestion.  Keep in mind our recommendation
in this document, that before 'punishing' a flow for not responding
appropriately to congestion, the router will first switch to dropping

rather than marking as an indication of congestion, for that flow.
When this includes dropping arriving packets from that flow that have
the CE codepoint set, this ensures that these indications of
congestion are being seen by the end nodes.  Thus, there is no
additional harm that we are able to postulate as a result of multiple
conflicting adversaries.

19.  Implications of Subverting End-to-End Congestion Control

   This section focuses on the potential repercussions of subverting
   end-to-end congestion control by either falsely indicating ECN-
   Capability, or by erasing the congestion indication in ECN (the CE
   codepoint).  Subverting end-to-end congestion control by either of
   these two methods can have consequences both for the application and
   for the network.  We discuss these separately below.

   The first method to subvert end-to-end congestion control, that of
   falsely indicating ECN-Capability, effectively subverts end-to-end
   congestion control only if the packet later encounters congestion
   that results in the setting of the CE codepoint.  In this case, the
   transport protocol (which may not be ECN-capable) does not receive
   the indication of congestion from these downstream congested routers.

   The second method to subvert end-to-end congestion control, 'erasing'
   the CE codepoint in a packet, effectively subverts end-to-end
   congestion control only when the CE codepoint in the packet was set
   earlier by a congested router.  In this case, the transport protocol
   does not receive the indication of congestion from the upstream
   congested routers.

   Either of these two methods of subverting end-to-end congestion
   control can potentially introduce more damage to the network (and
   possibly to the flow itself) than if the adversary had simply dropped
   packets from that flow.  However, as we discuss later in this section
   and in Section 7, this potential damage is limited.

19.1.  Implications for the Network and for Competing Flows

   The CE codepoint of the ECN field is only used by routers as an
   indication of congestion during periods of *moderate* congestion.
   ECN-capable routers should drop rather than mark packets during heavy
   congestion even if the router's queue is not yet full.  For example,
   for routers using active queue management based on RED, the router
   should drop rather than mark packets that arrive while the average
   queue sizes exceed the RED queue's maximum threshold.

One consequence for the network of subverting end-to-end congestion
control is that flows that do not receive the congestion indications
from the network might increase their sending rate until they drive
the network into heavier congestion.  Then, the congested router
could begin to drop rather than mark arriving packets.  For flows
that are not isolated by some form of per-flow scheduling or other
per-flow mechanisms, but are instead aggregated with other flows in a
single queue in an undifferentiated fashion, this packet-dropping at
the congested router would apply to all flows that share that queue.
Thus, the consequences would be to increase the level of congestion
in the network.

In some cases, the increase in the level of congestion will lead to a
substantial buffer buildup at the congested queue that will be
sufficient to drive the congested queue from the packet-marking to
the packet-dropping regime.  This transition could occur either
because of buffer overflow, or because of the active queue management
policy described above that drops packets when the average queue is
above RED's maximum threshold.  At this point, all flows, including
the subverted flow, will begin to see packet drops instead of packet
marks, and a malicious or broken router will no longer be able to '
erase' these indications of congestion in the network.  If the end
nodes are deploying appropriate end-to-end congestion control, then
the subverted flow will reduce its arrival rate in response to
congestion.  When the level of congestion is sufficiently reduced,
the congested queue can return from the packet-dropping regime to the
packet-marking regime.  The steady-state pattern could be one of the
congested queue oscillating between these two regimes.

In other cases, the consequences of subverting end-to-end congestion
control will not be severe enough to drive the congested link into
sufficiently-heavy congestion that packets are dropped instead of
being marked.  In this case, the implications for competing flows in
the network will be a slightly-increased rate of packet marking or
dropping, and a corresponding decrease in the bandwidth available to
those flows.  This can be a stable state if the arrival rate of the
subverted flow is sufficiently small, relative to the link bandwidth,
that the average queue size at the congested router remains under
control.  In particular, the subverted flow could have a limited
bandwidth demand on the link at this router, while still getting more
than its "fair" share of the link.  This limited demand could be due
to a limited demand from the data source; a limitation from the TCP
advertised window; a lower-bandwidth access pipe; or other factors.
Thus the subversion of ECN-based congestion control can still lead to
unfairness, which we believe is appropriate to note here.

The threat to the network posed by the subversion of ECN-based
congestion control in the network is essentially the same as the
threat posed by an end-system that intentionally fails to cooperate
with end-to-end congestion control.  The deployment of mechanisms in
routers to address this threat is an open research question, and is
discussed further in Section 10.

Let us take the example described in Section 18.1.1, where the CE
codepoint that was set in a packet is erased: {'11' -> '10' or '11'
-> '01'}.  The consequence for the congested upstream router that set
the CE codepoint is that this congestion indication does not reach
the end nodes for that flow. The source (even one which is completely
cooperative and not malicious) is thus allowed to continue to
increase its sending rate (if it is a TCP flow, by increasing its
congestion window).  The flow potentially achieves better throughput
than the other flows that also share the congested router, especially
if there are no policing mechanisms or per-flow queuing mechanisms at
that router.  Consider the behavior of the other flows, especially if
they are cooperative: that is, the flows that do not experience
subverted end-to-end congestion control.  They are likely to reduce
their load (e.g., by reducing their window size) on the congested
router, thus benefiting our subverted flow. This results in
unfairness.  As we discussed above, this unfairness could either be
transient (because the congested queue is driven into the packet-
marking regime), oscillatory (because the congested queue oscillates
between the packet marking and the packet dropping regime), or more
moderate but a persistent stable state (because the congested queue
is never driven to the packet dropping regime).

The results would be similar if the subverted flow was intentionally
avoiding end-to-end congestion control.  One difference is that a
flow that is intentionally avoiding end-to-end congestion control at
the end nodes can avoid end-to-end congestion control even when the
congested queue is in packet-dropping mode, by refusing to reduce its
sending rate in response to packet drops in the network.  Thus the
problems for the network from the subversion of ECN-based congestion
control are less severe than the problems caused by the intentional
avoidance of end-to-end congestion control in the end nodes.  It is
also the case that it is considerably more difficult to control the
behavior of the end nodes than it is to control the behavior of the
infrastructure itself.  This is not to say that the problems for the
network posed by the network's subversion of ECN-based congestion
control are small; just that they are dwarfed by the problems for the
network posed by the subversion of either ECN-based or other
currently known packet-based congestion control mechanisms by the end
nodes.

19.2.  Implications for the Subverted Flow

   When a source indicates that it is ECN-capable, there is an
   expectation that the routers in the network that are capable of
   participating in ECN will use the CE codepoint for indication of
   congestion. There is the potential benefit of using ECN in reducing
   the amount of packet loss (in addition to the reduced queuing delays
   because of active queue management policies).  When the packet flows
   through an IPsec tunnel where the nodes that the tunneled packets
   traverse are untrusted in some way, the expectation is that IPsec
   will protect the flow from subversion that results in undesirable
   consequences.

   In many cases, a subverted flow will benefit from the subversion of
   end-to-end congestion control for that flow in the network, by
   receiving more bandwidth than it would have otherwise, relative to
   competing non-subverted flows.  If the congested queue reaches the
   packet-dropping stage, then the subversion of end-to-end congestion
   control might or might not be of overall benefit to the subverted
   flow, depending on that flow's relative tradeoffs between throughput,
   loss, and delay.

   One form of subverting end-to-end congestion control is to falsely
   indicate ECN-capability by setting the ECT codepoint.  This has the
   consequence of downstream congested routers setting the CE codepoint
   in vain.  However, as described in Section 9.1.2, if an ECT codepoint
   is changed in an IP tunnel, this can be detected at the egress point
   of the tunnel, as long as the inner header was not changed within the
   tunnel.

   The second form of subverting end-to-end congestion control is to
   erase the congestion indication by erasing the CE codepoint.  In this
   case, it is the upstream congested routers that set the CE codepoint
   in vain.

   If an ECT codepoint is erased within an IP tunnel, then this can be
   detected at the egress point of the tunnel, as long as the inner
   header was not changed within the tunnel.  If the CE codepoint is set
   upstream of the IP tunnel, then any erasure of the outer header's CE
   codepoint within the tunnel will have no effect because the inner
   header preserves the set value of the CE codepoint.  However, if the
   CE codepoint is set within the tunnel, and erased either within or
   downstream of the tunnel, this is not necessarily detected at the
   egress point of the tunnel.

   With this subversion of end-to-end congestion control, an end-system
   transport does not respond to the congestion indication.  Along with
   the increased unfairness for the non-subverted flows described in the

previous section, the congested router's queue could continue to
build, resulting in packet loss at the congested router - which is a
means for indicating congestion to the transport in any case.  In the
interim, the flow might experience higher queuing delays, possibly
along with an increased bandwidth relative to other non-subverted
flows.  But transports do not inherently make assumptions of
consistently experiencing carefully managed queuing in the path.  We
believe that these forms of subverting end-to-end congestion control
are no worse for the subverted flow than if the adversary had simply
dropped the packets of that flow itself.

19.3.  Non-ECN-Based Methods of Subverting End-to-end Congestion Control

We have shown that, in many cases, a malicious or broken router that
is able to change the bits in the ECN field can do no more damage
than if it had simply dropped the packet in question.  However, this
is not true in all cases, in particular in the cases where the broken
router subverted end-to-end congestion control by either falsely
indicating ECN-Capability or by erasing the ECN congestion indication
(in the CE codepoint).  While there are many ways that a router can
harm a flow by dropping packets, a router cannot subvert end-to-end
congestion control by dropping packets.  As an example, a router
cannot subvert TCP congestion control by dropping data packets,
acknowledgement packets, or control packets.

Even though packet-dropping cannot be used to subvert end-to-end
congestion control, there *are* non-ECN-based methods for subverting
end-to-end congestion control that a broken or malicious router could
use.  For example, a broken router could duplicate data packets, thus
effectively negating the effects of end-to-end congestion control
along some portion of the path.  (For a router that duplicated
packets within an IPsec tunnel, the security administrator can cause
the duplicate packets to be discarded by configuring anti-replay
protection for the tunnel.)  This duplication of packets within the
network would have similar implications for the network and for the
subverted flow as those described in Sections 18.1.1 and 18.1.4
above.

20.  The Motivation for the ECT Codepoints.

20.1.  The Motivation for an ECT Codepoint.

The need for an ECT codepoint is motivated by the fact that ECN will
be deployed incrementally in an Internet where some transport
protocols and routers understand ECN and some do not. With an ECT
codepoint, the router can drop packets from flows that are not ECN-
capable, but can *instead* set the CE codepoint in packets that *are*

ECN-capable. Because an ECT codepoint allows an end node to have the
CE codepoint set in a packet *instead* of having the packet dropped,
an end node might have some incentive to deploy ECN.

If there was no ECT codepoint, then the router would have to set the
CE codepoint for packets from both ECN-capable and non-ECN-capable
flows.  In this case, there would be no incentive for end-nodes to
deploy ECN, and no viable path of incremental deployment from a non-
ECN world to an ECN-capable world.  Consider the first stages of such
an incremental deployment, where a subset of the flows are ECN-
capable.  At the onset of congestion, when the packet
dropping/marking rate would be low, routers would only set CE
codepoints, rather than dropping packets.  However, only those flows
that are ECN-capable would understand and respond to CE packets. The
result is that the ECN-capable flows would back off, and the non-
ECN-capable flows would be unaware of the ECN signals and would
continue to open their congestion windows.

In this case, there are two possible outcomes: (1) the ECN-capable
flows back off, the non-ECN-capable flows get all of the bandwidth,
and congestion remains mild, or (2) the ECN-capable flows back off,
the non-ECN-capable flows don't, and congestion increases until the
router transitions from setting the CE codepoint to dropping packets.
While this second outcome evens out the fairness, the ECN-capable
flows would still receive little benefit from being ECN-capable,
because the increased congestion would drive the router to packet-
dropping behavior.

A flow that advertised itself as ECN-Capable but does not respond to
CE codepoints is functionally equivalent to a flow that turns off
congestion control, as discussed earlier in this document.

Thus, in a world when a subset of the flows are ECN-capable, but
where ECN-capable flows have no mechanism for indicating that fact to
the routers, there would be less effective and less fair congestion
control in the Internet, resulting in a strong incentive for end
nodes not to deploy ECN.

20.2.  The Motivation for two ECT Codepoints.

The primary motivation for the two ECT codepoints is to provide a
one-bit ECN nonce.  The ECN nonce allows the development of
mechanisms for the sender to probabilistically verify that network
elements are not erasing the CE codepoint, and that data receivers
are properly reporting to the sender the receipt of packets with the
CE codepoint set.

Another possibility for senders to detect misbehaving network
elements or receivers would be for the data sender to occasionally
send a data packet with the CE codepoint set, to see if the receiver
reports receiving the CE codepoint.  Of course, if these packets
encountered congestion in the network, the router might make no
change in the packets, because the CE codepoint would already be set.
Thus, for packets sent with the CE codepoint set, the TCP end-nodes
could not determine if some router intended to set the CE codepoint
in these packets.  For this reason, sending packets with the CE
codepoint would have to be done sparingly, and would be a less
effective check against misbehaving network elements and receivers
than would be the ECN nonce.

The assignment of the fourth ECN codepoint to ECT(1) precludes the
use of this codepoint for some other purposes.  For clarity, we
briefly list other possible purposes here.

One possibility might have been for the data sender to use the fourth
ECN codepoint to indicate an alternate semantics for ECN.  However,
this seems to us more appropriate to be signaled using a
differentiated services codepoint in the DS field.

A second possible use for the fourth ECN codepoint would have been to
give the router two separate codepoints for the indication of
congestion, CE(0) and CE(1), for mild and severe congestion
respectively.  While this could be useful in some cases, this
certainly does not seem a compelling requirement at this point.  If
there was judged to be a compelling need for this, the complications
of incremental deployment would most likely necessitate more that
just one codepoint for this function.

A third use that has been informally proposed for the ECN codepoint
is for use in some forms of multicast congestion control, based on
randomized procedures for duplicating marked packets at routers.
Some proposed multicast packet duplication procedures are based on a
new ECN codepoint that (1) conveys the fact that congestion occurred
upstream of the duplication point that marked the packet with this
codepoint and (2) can detect congestion downstream of that
duplication point.  ECT(1) can serve this purpose because it is both
distinct from ECT(0) and is replaced by CE when ECN marking occurs in
response to congestion or incipient congestion.  Explanation of how
this enhanced version of ECN would be used by multicast congestion
control is beyond the scope of this document, as are ECN-aware
multicast packet duplication procedures and the processing of the ECN
field at multicast receivers in all cases (i.e., irrespective of the
multicast packet duplication procedure(s) used).

The specification of IP tunnel modifications for ECN in this document
assumes that the only change made to the outer IP header's ECN field
between tunnel endpoints is to set the CE codepoint to indicate
congestion.  This is not consistent with some of the proposed uses of
ECT(1) by the multicast duplication procedures in the previous
paragraph, and such procedures SHOULD NOT be deployed unless this
inconsistency between multicast duplication procedures and IP tunnels
with full ECN functionality is resolved.  Limited ECN functionality
may be used instead, although in practice many tunnel protocols
(including IPsec) will not work correctly if multicast traffic
duplication occurs within the tunnel

21.  Why use Two Bits in the IP Header?

Given the need for an ECT indication in the IP header, there still
remains the question of whether the ECT (ECN-Capable Transport) and
CE (Congestion Experienced) codepoints should have been overloaded on
a single bit.  This overloaded-one-bit alternative, explored in
[Floyd94], would have involved a single bit with two values.  One
value, "ECT and not CE", would represent an ECN-Capable Transport,
and the other value, "CE or not ECT", would represent either
Congestion Experienced or a non-ECN-Capable transport.

One difference between the one-bit and two-bit implementations
concerns packets that traverse multiple congested routers.  Consider
a CE packet that arrives at a second congested router, and is
selected by the active queue management at that router for either
marking or dropping.  In the one-bit implementation, the second
congested router has no choice but to drop the CE packet, because it
cannot distinguish between a CE packet and a non-ECT packet.  In the
two-bit implementation, the second congested router has the choice of
either dropping the CE packet, or of leaving it alone with the CE
codepoint set.

Another difference between the one-bit and two-bit implementations
comes from the fact that with the one-bit implementation, receivers
in a single flow cannot distinguish between CE and non-ECT packets.
Thus, in the one-bit implementation an ECN-capable data sender would
have to unambiguously indicate to the receiver or receivers whether
each packet had been sent as ECN-Capable or as non-ECN-Capable.  One
possibility would be for the sender to indicate in the transport
header whether the packet was sent as ECN-Capable.  A second
possibility that would involve a functional limitation for the one-
bit implementation would be for the sender to unambiguously indicate
that it was going to send *all* of its packets as ECN-Capable or as
non-ECN-Capable.  For a multicast transport protocol, this
unambiguous indication would have to be apparent to receivers joining
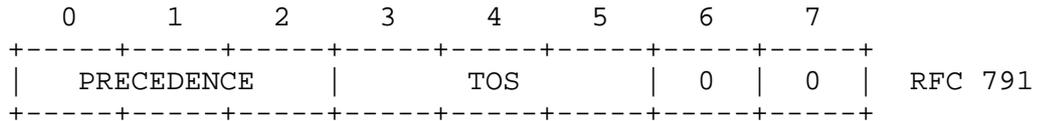an on-going multicast session.

Another concern that was described earlier (and recommended in this
document) is that transports (particularly TCP) should not mark pure
ACK packets or retransmitted packets as being ECN-Capable.  A pure
ACK packet from a non-ECN-capable transport could be dropped, without
necessarily having an impact on the transport from a congestion
control perspective (because subsequent ACKs are cumulative).  An
ECN-capable transport reacting to the CE codepoint in a pure ACK
packet by reducing the window would be at a disadvantage in
comparison to a non-ECN-capable transport. For this reason (and for
reasons described earlier in relation to retransmitted packets), it
is desirable to have the ECT codepoint set on a per-packet basis.

Another advantage of the two-bit approach is that it is somewhat more
robust.  The most critical issue, discussed in Section 8, is that the
default indication should be that of a non-ECN-Capable transport.  In
a two-bit implementation, this requirement for the default value
simply means that the not-ECT codepoint should be the default.  In
the one-bit implementation, this means that the single overloaded bit
should by default be in the "CE or not ECT" position.  This is less
clear and straightforward, and possibly more open to incorrect
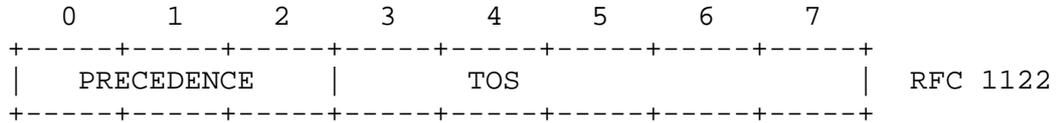implementations either in the end nodes or in the routers.

In summary, while the one-bit implementation could be a possible
implementation, it has the following significant limitations relative
to the two-bit implementation.  First, the one-bit implementation has
more limited functionality for the treatment of CE packets at a
second congested router.  Second, the one-bit implementation requires
either that extra information be carried in the transport header of
packets from ECN-Capable flows (to convey the functionality of the
second bit elsewhere, namely in the transport header), or that
senders in ECN-Capable flows accept the limitation that receivers
must be able to determine a priori which packets are ECN-Capable and
which are not ECN-Capable. Third, the one-bit implementation is
possibly more open to errors from faulty implementations that choose
the wrong default value for the ECN bit.  We believe that the use of
the extra bit in the IP header for the ECT-bit is extremely valuable
to overcome these limitations.

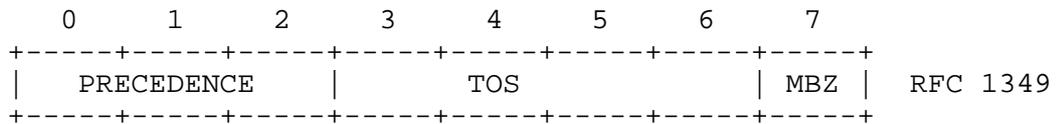22.  Historical Definitions for the IPv4 TOS Octet

   RFC 791 [RFC791] defined the ToS (Type of Service) octet in the IP
   header.  In RFC 791, bits 6 and 7 of the ToS octet are listed as
   "Reserved for Future Use", and are shown set to zero.  The first two
   fields of the ToS octet were defined as the Precedence and Type of
   Service (TOS) fields.

```
        0     1     2     3     4     5     6     7
     +-----+-----+-----+-----+-----+-----+-----+-----+
     |   PRECEDENCE    |       TOS       |  0  |  0  |  RFC 791
     +-----+-----+-----+-----+-----+-----+-----+-----+
```

   RFC 1122 included bits 6 and 7 in the TOS field, though it did not
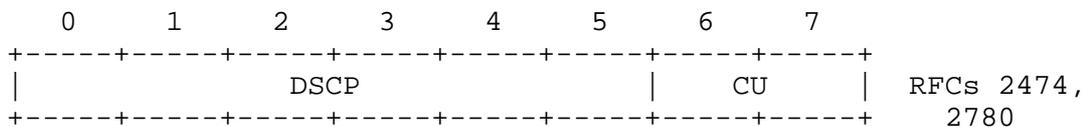   discuss any specific use for those two bits:

```
        0     1     2     3     4     5     6     7
     +-----+-----+-----+-----+-----+-----+-----+-----+
     |   PRECEDENCE    |              TOS            |  RFC 1122
     +-----+-----+-----+-----+-----+-----+-----+-----+
```

   The IPv4 TOS octet was redefined in RFC 1349 [RFC1349] as follows:

```
        0     1     2     3     4     5     6     7
     +-----+-----+-----+-----+-----+-----+-----+-----+
     |   PRECEDENCE    |        TOS         | MBZ |  RFC 1349
     +-----+-----+-----+-----+-----+-----+-----+-----+
```

   Bit 6 in the TOS field was defined in RFC 1349 for "Minimize Monetary
   Cost".  In addition to the Precedence and Type of Service (TOS)
   fields, the last field, MBZ (for "must be zero") was defined as
   currently unused.  RFC 1349 stated that "The originator of a datagram
   sets [the MBZ] field to zero (unless participating in an Internet
   protocol experiment which makes use of that bit)."

   RFC 1455 [RFC 1455] defined an experimental standard that used all
   four bits in the TOS field to request a guaranteed level of link
   security.

   RFC 1349 and RFC 1455 have been obsoleted by "Definition of the
   Differentiated Services Field (DS Field) in the IPv4 and IPv6
   Headers" [RFC2474] in which bits 6 and 7 of the DS field are listed
   as Currently Unused (CU).  RFC 2780 [RFC2780] specified ECN as an
   experimental use of the two-bit CU field.  RFC 2780 updated the
   definition of the DS Field to only encompass the first six bits of
   this octet rather than all eight bits; these first six bits are
   defined as the Differentiated Services CodePoint (DSCP):

```
        0     1     2     3     4     5     6     7
      +-----+-----+-----+-----+-----+-----+-----+-----+
      |               DSCP               |     CU    |  RFCs 2474,
      +-----+-----+-----+-----+-----+-----+-----+-----+    2780
```

   Because of this unstable history, the definition of the ECN field in
   this document cannot be guaranteed to be backwards compatible with
   all past uses of these two bits.

Prior to RFC 2474, routers were not permitted to modify bits in
either the DSCP or ECN field of packets forwarded through them, and
hence routers that comply only with RFCs prior to 2474 should have no
effect on ECN.  For end nodes, bit 7 (the second ECN bit) must be
transmitted as zero for any implementation compliant only with RFCs
prior to 2474.  Such nodes may transmit bit 6 (the first ECN bit) as
one for the "Minimize Monetary Cost" provision of RFC 1349 or the
experiment authorized by RFC 1455; neither this aspect of RFC 1349
nor the experiment in RFC 1455 were widely implemented or used.  The
damage that could be done by a broken, non-conformant router would
include "erasing" the CE codepoint for an ECN-capable packet that
arrived at the router with the CE codepoint set, or setting the CE
codepoint even in the absence of congestion.  This has been discussed
in the section on "Non-compliance in the Network".

The damage that could be done in an ECN-capable environment by a
non-ECN-capable end-node transmitting packets with the ECT codepoint
set has been discussed in the section on "Non-compliance by the End
Nodes".

23.  IANA Considerations

   This section contains the namespaces that have either been created in
   this specification, or the values assigned in existing namespaces
   managed by IANA.

23.1.  IPv4 TOS Byte and IPv6 Traffic Class Octet

   The codepoints for the ECN Field of the IP header are specified by
   the Standards Action of this RFC, as is required by RFC 2780.

   When this document is published as an RFC, IANA should create a new
   registry, "IPv4 TOS Byte and IPv6 Traffic Class Octet", with the
   namespace as follows:

   IPv4 TOS Byte and IPv6 Traffic Class Octet

   Description:  The registrations are identical for IPv4 and IPv6.

   Bits 0-5:  see Differentiated Services Field Codepoints Registry
          (http://www.iana.org/assignments/dscp-registry)

Bits 6-7, ECN Field:

```
Binary   Keyword                                    References
------   -------                                    ----------
  00      Not-ECT (Not ECN-Capable Transport)       [RFC 3168]
  01      ECT(1) (ECN-Capable Transport(1))         [RFC 3168]
  10      ECT(0) (ECN-Capable Transport(0))         [RFC 3168]
  11      CE (Congestion Experienced)               [RFC 3168]
```
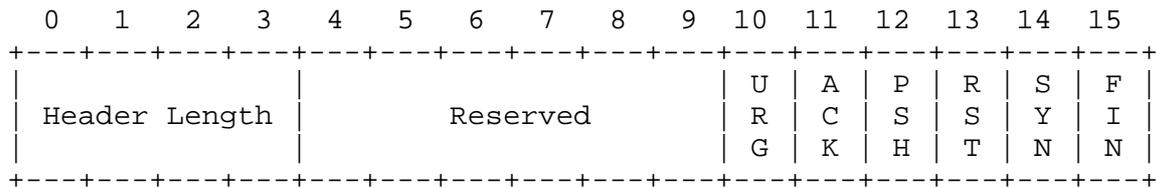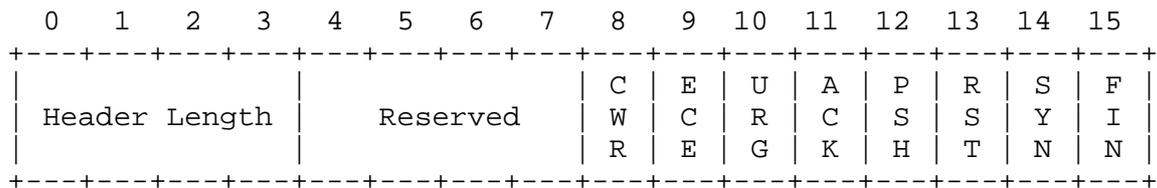
23.2.  TCP Header Flags

   The codepoints for the CWR and ECE flags in the TCP header are
   specified by the Standards Action of this RFC, as is required by RFC
   2780.

   When this document is published as an RFC, IANA should create a new
   registry, "TCP Header Flags", with the namespace as follows:

   TCP Header Flags

   The Transmission Control Protocol (TCP) included a 6-bit Reserved
   field defined in RFC 793, reserved for future use, in bytes 13 and 14
   of the TCP header, as illustrated below.  The other six Control bits
   are defined separately by RFC 793.

```
    0   1   2   3   4   5   6   7   8   9  10  11  12  13  14  15
  +---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+
  |               |                   | U | A | P | R | S | F |
  | Header Length |      Reserved     | R | C | S | S | Y | I |
  |               |                   | G | K | H | T | N | N |
  +---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+
```

   RFC 3168 defines two of the six bits from the Reserved field to be
   used for ECN, as follows:

```
    0   1   2   3   4   5   6   7   8   9  10  11  12  13  14  15
  +---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+
  |               |               | C | E | U | A | P | R | S | F |
  | Header Length |    Reserved   | W | C | R | C | S | S | Y | I |
  |               |               | R | E | G | K | H | T | N | N |
  +---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+
```

     TCP Header Flags

     Bit      Name                                   Reference
     ---      ----                                   ---------
      8         CWR (Congestion Window Reduced)      [RFC 3168]
      9         ECE (ECN-Echo)                       [RFC 3168]

23.3. IPSEC Security Association Attributes

   IANA allocated the IPSEC Security Association Attribute value 10 for
   the ECN Tunnel use described in Section 9.2.1.2 above at the request
   of David Black in November 1999.  The IANA has changed the Reference
   for this allocation from David Black's request to this RFC.

24.  Authors' Addresses

   K. K. Ramakrishnan
   TeraOptic Networks, Inc.

   Phone: +1 (408) 666-8650
   EMail: kk@teraoptic.com


   Sally Floyd
   ACIRI

   Phone: +1 (510) 666-2989
   EMail: floyd@aciri.org
   URL: http://www.aciri.org/floyd/


   David L. Black
   EMC Corporation
   42 South St.
   Hopkinton, MA  01748

   Phone:  +1 (508) 435-1000 x75140
   EMail: black_david@emc.com

25.  Full Copyright Statement

Acknowledgement