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SONET/SDH Circuit Emulation Service Over MPLS (CEM) Encapsulation
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Status of this Memo

1. Abstract

This document describes a method for encapsulating SONET/SDH Path signals for transport across an MPLS network.

2. Conventions used in this document

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in RFC 2119 [2].

3. Introduction

This document describes a method for encapsulating time division multiplexed (TDM) digital signals for transmission over a packet-oriented MPLS network. The transmission system for circuit-oriented TDM signals is the Synchronous Optical Network (SONET) [3], [6] / Synchronous Digital Hierarchy (SDH) [4]. To support TDM traffic, which includes voice, data, and private leased line service, the MPLS network must emulate the circuit characteristics of SONET/SDH payloads. MPLS labels and a new circuit emulation header are used to encapsulate TDM signals and provide the Circuit Emulation Service over MPLS (CEM).

This document also describes an optional extension to CEM called Dynamic Bandwidth Allocation (DBA). This is a method for dynamically reducing the bandwidth utilized by emulated SONET/SDH circuits in the packet network. This bandwidth reduction is accomplished by not sending the SONET/SDH payload through the packet network under certain conditions such as AIS-P or STS SPE Unequipped.

This document is closely related to references [5], which describes the control protocol methods used to signal the usage of CEM, and [7], which describes a related method of encapsulating Layer 2 frames over MPLS and which shares the same signaling.

4. Scope

This document describes how to provide CEM for the following digital signals:

1. SONET STS-1 synchronous payload envelope (SPE)/SDH VC-3

2. STS-Nc SPE (N = 3, 12, or 48)/SDH VC-4, VC-4-4c, VC-4-16c

For the remainder of this document, these constructs will be referred to as SONET/SDH channels.

Other SONET/SDH signals, such as virtual tributary (VT) structured sub-rate mapping, are not explicitly discussed in this document; however, it can be extended in the future to support VT and lower speed non-SONET/SDH services. OC-192c SPE/VC-4-64c are also not included at this point, since most MPLS networks use OC-192c or slower trunks, and thus would not have sufficient capacity. As trunk capacities increase in the future, the scope of this document can be accordingly extended.

5. CEM Encapsulation Format

In order to transport SONET/SDH SPEs through a packet-oriented network, the SPE is broken into fragments. A 32-bit CEM Header is pre-pended to each fragment. The Basic CEM packet appears in Figure 1.

```
+-----------------------------------+
|             CEM Header            |
+-----------------------------------+
|                                   |
|                                   |
|         SONET/SDH SPE Fragment    |
|                                   |
|                                   |
+-----------------------------------+
```

Figure 1. Basic CEM Packet

The 32-bit CEM header has the following format:

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|D|Resvd|   Sequence Num    | Structure Pointer |N|P|   ECC-6   |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 2. CEM Header Format

The above fields are defined as follows:

D bit: Signals DBA Mode. MUST be set to zero for Normal Operation. MUST be set to one if CEM is currently in DBA mode. DBA is an optional mode during which trivial SPEs are not transmitted into the packet network. See Table 1 and sections 7 and 8 for further details.

Reserved: These bits are reserved for future use, and MUST be set to zero.

Sequence Number: This is a packet sequence number, which MUST continuously cycle from 0 to 1023. It SHOULD begin at zero when a CEM LSP is created.

Structure Pointer: The Structure Pointer MUST contain the offset of the J1 byte within the CEM payload. The value is from 0 to 1,022, where 0 means the first byte after the CEM header. The Structure

Pointer MUST be set to 0x3FF (1,023) if a packet does not carry the J1 byte. See [3], [4] and [6] for more information on the J1 byte and the SONET/SDH payload pointer.

The N and P bits: Indicate negative and positive pointer adjustment events. They are also used to relay SONET/SDH maintenance signals such as AIS-P. See Table 1 and sections 7 and 8 for more details.

D	N	P	Interpretation
0	0	0	Normal Mode û No Ptr Adjustment
0	0	1	Normal Mode û Positive Ptr Adjustment
0	1	0	Normal Mode û Negative Ptr Adjustment
0	1	1	Normal Mode û AIS-P
1	0	0	DBA Mode û STS SPE Unequipped
1	0	1	DBA Mode û STS SPE Unequipped Pos Ptr Adj
1	1	0	DBA Mode û STS SPE Unequipped Neg Ptr Adj
1	1	1	DBA Mode û AIS-P

Table 1. Interpretation of D, N, and P bits

ECC-6: An Error Correction Code to protect the CEM header. This offers the ability to correct single bit errors and detect up to two bit errors. The ECC algorithm is described in Appendix B.

Note: CEM packets are fixed in length for all of the packets of a particular emulated TDM stream. This length is signaled using the CEM Payload Bytes parameter defined in [5], or is statically provisioned for each TDM stream. Therefore, the length of each CEM packet does not need to be carried in the CEM header.

5.1 Transport Encapsulation

In principle, CEM packets can be transported over any packet-oriented network. The following sections describe specifically how CEM packets MUST be encapsulated for transport over MPLS or IP networks.

5.1.1 MPLS Transport

To transport a CEM packet over an MPLS network, an MPLS label-stack MUST be pushed on top of the CEM packet.

The last two labels prior to the CEM header are referred to as the Tunnel and VC labels.

The VC label is required, and is the last label prior to the CEM Header. The VC label MUST be used to identify the CEM connection within the MPLS tunnel.

The optional tunnel label is immediately above the VC label on the label stack. If present, the tunnel label MUST be used to identify the MPLS LSP used to tunnel the TDM packets through the MPLS network (the tunnel LSP).

This is similar to the label stack usage defined in [5] and [7].

```
+------------------------------------+
| Additional MPLS Labels (Optional) |
+------------------------------------+
|       Tunnel Label (Optional)      |
+------------------------------------+
|             VC Label               |
+------------------------------------+
|            CEM Header              |
+------------------------------------+
|                                    |
|                                    |
|       SONET/SDH SPE Fragment       |
|                                    |
|                                    |
+------------------------------------+
```

Figure 3. Typical MPLS Transport Encapsulation

5.1.1 IP Transport

It is highly desirable to define a single encapsulation format that will work for both IP and MPLS. Furthermore, it is desirable that the encapsulation mechanism be as efficient as possible.

One way to achieve these goals is to map CEM directly onto IP by mapping the previously described MPLS packets onto IP.

A mechanism for carrying MPLS over IP is described in [8].

Using this encapsulation scheme would result in the packet format illustrated in figure 4.

```
+------------------------------------+
|                                    |
|        IPv6/v4 Header [8]          |
|                                    |
+------------------------------------+
|      Tunnel Label (Optional)       |
+------------------------------------+
|             VC Label               |
+------------------------------------+
|            CEM Header              |
+------------------------------------+
|                                    |
|                                    |
|       SONET/SDH SPE Fragment       |
|                                    |
|                                    |
+------------------------------------+
```

Figure 4. MPLS Transport Encapsulation

6. CEM Operation

The following sections describe CEM operation.

6.1 Introduction and Terminology

CEM MUST support a normal mode of operation and MAY support an optional extension called Dynamic Bandwidth Allocation (DBA). During normal operation, SONET/SDH payloads are fragmented, pre-pended with the CEM Header and the MPLS label-stack, and then transmitted into the packet network. During DBA mode, only the CEM header and MPLS label stack are transmitted. This is done to conserve bandwidth when meaningful user data is not present in the SPE, such as during AIS-P or STS SPE Unequipped.

6.1.1 CEM Packetizer and De-Packetizer

As with all adaptation functions, CEM has two distinct components: adapting TDM SONET/SDH into a CEM packet stream, and converting the CEM packet stream back into a TDM SONET/SDH. The first function will be referred to as CEM Packetizer and the second as CEM De-Packetizer. This terminology is illustrated in figure 5.

```
          +------------+             +---------------+
          |            |             |               |
SONET --> |    CEM     | --> MPLS --> |      CEM      | --> SONET
 SDH      | Packetizer |             | De-Packetizer |      SDH
          |            |             |               |
          +------------+             +---------------+
```

Figure 5. CEM Terminology

Note: the CEM receive function requires a buffering mechanism to account for delay variation in the CEM packet stream. This buffering mechanism will be generically referred to as the CEM jitter buffer.

6.1.2 CEM DBA

CEM DBA is an optional mode of operation that only transmits the CEM Header and MPLS Label Stack into the packet network under certain circumstances such as AIS-P or STS Unequipped.

If DBA is supported by a CEM implementation, the user SHOULD be able to configure if DBA will be triggered by AIS-P, STS Unequipped, both, or neither on a per channel basis.

If DBA is supported, the determination of AIS-P and STS Unequipped MUST be based on the state of SONET/SDH Section, Line, and Path Overhead bytes. DBA based on pattern detection within the SPE (i.e. all zeros, 7Es, or ATM idle cells) is for further study.

During AIS-P, there is no valid payload pointer, so pointer adjustments cannot occur. During STS Unequipped, the SONET/SDH payload pointer is valid, and therefore pointer adjustments MUST be supported even during DBA. See Table 1 for details.

6.2 Description of Normal CEM Operation

During normal operation, the CEM packetizer will receive a fixed rate byte stream from a SONET/SDH interface. When a packets worth of data has been received from a SONET/SDH channel, the CEM Header and MPLS label stack are pre-pended to the SPE fragment and the resulting CEM packet is transmitted into the MPLS network. Because all CEM packets associated with a specific SONET/SDH channel will have the same length, the transmission of CEM packets for that channel SHOULD occur at regular intervals.

At the far end of the packet network, the CEM de-packetizer will receive packets into a jitter buffer and then play out the received byte stream at a fixed rate onto the corresponding SONET/SDH channel. The jitter buffer SHOULD be adjustable in length to account for varying network delay behavior. The receive packet rate from the packet network should be exactly balanced by the transmission rate onto the SONET/SDH channel, on average. The time over which this average is taken corresponds to the depth of the jitter buffer for a specific CEM channel.

6.3 Description of CEM Operation during DBA

There are several issues that should be addressed by a workable CEM DBA mechanism. First, when DBA is invoked, there should be a substantial savings in bandwidth utilization in the packet network. The second issue is that the transition in and out of DBA should be tightly coordinated between the local CEM packetizer and CEM de-packetizer at the far side of the packet network. A third is that the transition in and out of DBA should be accomplished with minimal disruption to the adapted data stream.

Another goal is that the reduction of CEM traffic due to DBA should not be mistaken for a fault in the packet network or vice-versa. Finally, the implementation of DBA should require minimal modifications beyond what is necessary for the nominal CEM case. The mechanism described below is a reasonable balance of these goals.

During DBA, packets MUST be emitted at exactly the same rate as they would be during normal operation. This SHOULD be accomplished by transmitting each DBA packet after a complete packet of data has been received from the SONET/SDH channel. The only change from normal operation is that the CEM packets during DBA MUST only carry the CEM header and the MPLS label stack. The D-bit MUST be set to one, to indicate that DBA is active.

The CEM de-packetizer MUST assume that each packet received with the D-bit set represents a normal-sized packet containing an AIS-P or SPE Unequipped payload as noted by N and P. See Table 1.

This allows the CEM packetization and de-packetization logic during DBA to be virtually identical to the nominal case. It insures that the correct SONET/SDH indication is reliably transmitted between CEM adaptation points. It minimizes the risk of under or over running the jitter buffer during the transition in and out of DBA. And, it guarantees that faults in the packet network are recognized as distinctly different from line conditioning on the SONET/SDH interfaces.

7. SONET/SDH Maintenance Signals

There are several issues that must be considered in the mapping of maintenance signals between SONET/SDH and MPLS. A description of how these signals and conditions are mapped between the two domains is described below.

For clarity, the mappings are split into two groups: SONET/SDH to MPLS, and MPLS to SONET/SDH.

7.1 SONET/SDH to MPLS

The following sections describe how SONET/SDH Maintenance Signals and Alarm conditions are mapped into MPLS.

7.1.1 AIS-P Indication

In a SONET/SDH network, circuit outages are signaled using maintenance alarms such as Path AIS (AIS-P). In particular, AIS-P indicates that the SONET/SDH Path is not currently transmitting valid end-user data, and the SPE contains all ones.

It should be noted that nearly every type of service-effecting section or line defect will result in an AIS-P condition.
The SONET/SDH hierarchy is illustrated below.

```
               +----------+
               |   PATH   |
               +----------+
                    ^
                    |
                  AIS-P
                    |
                    |
               +----------+
               |   LINE   |
               + ---------+
                  ^     ^
                  |     |
                AIS-L   +------ LOP
                  |
                  |
               +----------+
               | SECTION  |
               +----------+
                  ^    ^
                  |    |
                  |    |
                 LOS  LOF
```

Figure 6. SONET/SDH Fault Hierarchy.

Should the Section Layer detect a Loss of Section (LOS) or Loss of Frame (LOF) condition, it sends AIS-L up to the Line Layer. If the Line Layer detects AIS-L or Loss of Path (LOP), it sends AIS-P to the Path Layer.

In normal mode during AIS-P, CEM packets are generated as usual. The N and P bits MUST be set to 11 binary to signal AIS-P explicitly through the packet network. The D-bit MUST be set to zero to indicate that the SPE is being carried through the packet network. Normal CEM packets with the SPE fragment, CEM Header, and MPLS label stack MUST be transmitted into the packet network.

However, to conserve network bandwidth during AIS-P, DBA MAY be employed. If DBA has been enabled for AIS-P and AIS-P is currently occurring, the N and P bits MUST be set to 11 binary to signal AIS, and the D-bit MUST be set to one to indicate that the SPE is not being carried through the packet network. Only the CEM header and the MPLS label stack MUST be transmitted into the packet network.

Also note that this differs from the outage mechanism in [5], which withdraws labels as a result of an endpoint outage. TDM circuit emulation requires the ability to distinguish between the de-provisioning of a circuit, which would cause the labels to be withdrawn, and temporary outages, which are signaled using AIS-P.

7.1.2 STS SPE Unequipped Indication

The STS SPE Unequipped Indication is a slightly different case than AIS-P. When byte C2 of the Path Overhead (STS path signal label) is 00h and Byte B3 (STS Path BIP-8) is valid, it indicates that the SPE is unequipped. Note: this is typically signaled by setting the entire SPE to zeros.

For normal operation during SPE Unequipped, the N and P bits MUST be interpreted as usual. The SPE MUST be transmitted into the packet network along with the CEM Header and MPLS label stack, and the D-Bit MUST be set to zero.

If DBA has been enabled for STS SPE Unequipped and the Unequipped is occurring on the SONET/SDH channel, the D-bit MUST be set to one to indicate DBA is active. Only the CEM Header and MPLS Label Stack must be transmitted into the packet network. The N and P bits MUST be used to signal pointer adjustments as normal. See Table 1 and section 8 for details.

7.1.3 RDI-P Indication

The CEM function MUST send RDI-P towards the packet network under a variety of network errors such as loss of packet synchronization. This MUST be accomplished by modifying the SONET/SDH Path Overhead within the CEM packets. Specifically the G1 byte must be updated to signal RDI-P and the B3 (Path BIP-8) must be re-computed. See [3], [4], and [6] for details.

7.2 MPLS to SONET/SDH

The following sections discuss how the various conditions on the packet network are converted into SONET/SDH indications.

7.2.1 AIS-P Indication

There are several conditions in the packet network that will cause the CEM de-packetization function to send an AIS-P indication onto a SONET/SDH channel.

The first of these is the receipt of CEM packets with the N and P bits set to one, and the D-bit set to zero. This is an explicit indication of AIS-P being received at the far-end of the packet network, with DBA disabled for AIS-P. The CEM de-packetizer MUST play out the received SPE fragment (which will incidentally be carrying all ones), and MUST configure the SONET/SDH Overhead to signal AIS-P as defined in [3], [4], and [6].

The second case is the receipt of CEM packets with the N and P bits set to one, and the D-bit set to one. This is an explicit indication of AIS-P being received at the far-end of the packet network, with DBA enabled for AIS-P. The CEM de-packetizer MUST play out one packetÆs worth of all ones for each packet received, and MUST configure the SONET/SDH Overhead to signal AIS-P as defined in [3], [4], and [6].

Additional conditions that SHOULD trigger the transmission of AIS-P onto a SONET/SDH channel include loss of packet synchronization and jitter buffer under-run. The definition of these conditions are under investigation and will be clarified in a subsequent revision of this draft.

7.2.2 STS SPE Unequipped Indication

There are two conditions in the packet network that will cause the CEM function to transmit STS SPE Unequipped indications onto the SONET/SDH channel.

The first, which is transparent to CEM, is the receipt of regular CEM packets that happen to be carrying an SPE that contains the appropriate Path overhead to signal STS SPE unequipped. This case does not require any special processing on the part of the CEM de-packetizer.

The second case is the receipt of CEM packets that have the D-bit set to one to indicate DBA active and the N and P bits set to 00 binary, 01 binary, or 10 binary to indicate SPE Unequipped with or without pointer adjustments. The CEM de-packetizer MUST use this information to transmit a packet of all zeros onto the SONET/SDH interface, and adjust the payload pointer as necessary.

7.2.3 RDI-P Indication

The CEM function MUST send an RDI-P towards a SONET/SDH channel under the conditions defined for SONET/SDH Line Terminating equipment in [3], [4], and [6].

8. Clocking Modes

It is necessary to be able to regenerate the input service clock at the output interface. Two clocking modes are supported: synchronous and asynchronous.

8.1 Synchronous

When synchronous SONET/SDH timing is available at both ends of the circuit, the N and P bits are used to signal negative or positive pointer justification events.

If there is a frequency offset between the frame rate of the transport overhead and that of the SONET/SDH SPE, then the alignment of the SPE shall periodically slip back or advance in time through positive or negative stuffing. The N and P bits are used to replay the stuff indicators and eliminate transport jitter.

The pointer adjustment event MUST be transmitted in three consecutive packets by the packetizer. The de-packetizer MUST play out the pointer adjustment event when any one packet with N/P bit set is received.

Furthermore, it is possible for pointer adjustments to occur in back to back SONET/SDH frames. In order to support this possibility, the packet size for a particular circuit MUST be no larger than (783*N)/3. Where N is the STS-Nc multiplier.

Since the minimum value of N is one, all CEM implementations MUST support a minimum payload length of 783/3 or 261 bytes. Smaller payload lengths MAY be supported as an option.

The CEM de-packetizer MUST utilize the CEM sequence numbers to insure that SONET/SDH pointer adjustment events are not played any more frequently than once per every three CEM packets transmitted by the remote CEM packetizer.

If both bits are set, then an AIS-P event has occurred (this is further discussed in section 7).

When DBA is invoked (i.e. the D-bit = 1), N and P have additional meanings. See Table 1 and section 7.

8.2 Asynchronous

If synchronous timing is not available, the N and P bits are not used for frequency justification and adaptive methods are used to recover the timing. The N and P bits are only used for the occurrence of a path AIS event. An example adaptive method can be found in section 3.4.2 of [9].

9. CEM LSP Signaling

For maximum network scaling, CEM LSP signaling may be performed using the LDP Extended Discovery mechanism as augmented by the VC FEC Element defined in [5]. MPLS traffic tunnels may be dedicated to CEM, or shared with other MPLS-based services. The value 8008 is used for the VC Type in the VC FEC Element in order to signify that the LSP being signaled is to carry CEM. Note that the generic control word defined in [6] is not used, as its functionality is included in the CEM encapsulation header.

Alternatively, static label assignment may be used, or a dedicated traffic engineered LSP may be used for each CEM circuit.

CEM packets are fixed in length for all of the packets of a particular emulated TDM stream. This length is signaled using the CEM Payload Bytes parameter defined in [5], or is statically provisioned for each TDM stream.

The use of DBA is signaled by the use of the CEM Options parameter defined in [5], or is statically provisioned for each TDM stream.

10. Open Issues

Future revisions of this document may discuss the following items.

Underlying MPLS QoS requirements are not covered by this revision of the draft. Future revisions may discuss underlying QoS requirements.

Support for VT and lower speed non-SONET/SDH services are not covered in this revision of the draft. Future revisions may address VT and non-SONET/SDH TDM services.

The current draft only considers DBA based on SONET/SDH Overhead. It would be very desirable to extending DBA to include pattern-based suppression such as long runs of HDLC flags (i.e. 0x7E). One issue that complicates pattern-based DBA is that the path overhead appears every Nx87 bytes within the SPE. One solution may be to have a special mode of DBA, where the Path Overhead is explicitly transported within the packet along with the specific pattern (e.g. 7E).

This revision of the draft does not provide a definition for æloss of packet synchronizationÆ or æjitter buffer under-runÆ. Details for declaring these conditions at the de-packetizer will be addressed in future revisions.

11. Security Considerations

As with [5], this document does not affect the underlying security issues of MPLS.

12. Intellectual Property Disclaimer

This document is being submitted for use in IETF standards discussions. Vivace Networks, Inc. has filed one or more patent applications relating to the CEM technology outlined in this document. Vivace Networks, Inc. will grant free unlimited licenses for use of this technology.

13. References

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Appendix A. SONET/SDH Rates and Formats

For simplicity, the discussion in this section uses SONET terminology, but it applies equally to SDH as well. SDH-equivalent terminology is shown in the tables.

The basic SONET modular signal is the synchronous transport signal-level 1 (STS-1). A number of STS-1s may be multiplexed into higher-level signals denoted as STS-N, with N synchronous payload envelopes (SPEs). The optical counterpart of the STS-N is the Optical Carrier-level N, or OC-N. Table 2 lists standard SONET line rates discussed in this document.

OC Level	OC-1	OC-3	OC-12	OC-48	OC-192
SDH Term	-	STM-1	STM-4	STM-16	STM-64
Line Rate(Mb/s)	51.840	155.520	622.080	2,488.320	9,953.280

Table 2. Standard SONET Line Rates

Each SONET frame is 125 ´s and consists of nine rows. An STS-N frame has nine rows and N*90 columns. Of the N*90 columns, the first N*3 columns are transport overhead and the other N*87 columns are SPEs. A number of STS-1s may also be linked together to form a super-rate signal with only one SPE. The optical super-rate signal is denoted as OC-Nc, which has a higher payload capacity than OC-N.

The first 9-byte column of each SPE is the path overhead (POH) and the remaining columns form the payload capacity with fixed stuff (STS-Nc only). The fixed stuff, which is purely overhead, is N/3-1 columns for STS-Nc. Thus, STS-1 and STS-3c do not have any fixed stuff, STS-12c has three columns of fixed stuff, and so on.

The POH of an STS-1 or STS-Nc is always nine bytes in nine rows. The payload capacity of an STS-1 is 86 columns (774 bytes) per frame. The payload capacity of an STS-Nc is (N*87)-(N/3) columns per frame. Thus, the payload capacity of an STS-3c is (3*87 - 1)*9 = 2,340 bytes per frame. As another example, the payload capacity of an STS-192c is 149,760 bytes, which is exactly 64 times larger than the STS-3c.

There are 8,000 SONET frames per second. Therefore, the SPE size, (POH plus payload capacity) of an STS-1 is 783*8*8,000 = 50.112 Mb/s. The SPE size of a concatenated STS-3c is 2,349 bytes per frame or 150.336 Mb/s. The payload capacity of an STS-192c is 149,760 bytes per frame, which is equivalent to 9,584.640 Mb/s. Table 2 lists the SPE and payload rates supported.

SONET STS Level	STS-1	STS-3c	STS-12c	STS-48c	STS-192c
SDH VC Level	-	VC-4	VC-4-4c	VC-4-16c	VC-4-64c
Payload Size(Bytes)	774	2,340	9,360	37,440	149,760
Payload Rate(Mb/s)	49.536	149.760	599.040	2,396.160	9,584.640
SPE Size(Bytes)	783	2,349	9,396	37,584	150,336
SPE Rate(Mb/s)	50.112	150.336	601.344	2,405.376	9,621.504

Table 2. Payload Size and Rate

To support circuit emulation, the entire SPE of a SONET STS or SDH VC level is encapsulated into packets, using the encapsulation defined in section 5, for carriage across MPLS networks.

Appendix B. ECC-6 Definition

ECC-6 is an Error Correction Code to protect the CEM header. This provides single bit correction and the ability to detect up to two bit errors.

Error Correction Code:

```
|---------------Header bits 0-25 -------------------| ECC-6 code|
0                   1                   2                   3
0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|1 1 1 1 1 0 0 0 1 0 0 0 1 1 1 1 1 0 1 0 0 0 1 0 1 1|1 0 0 0 0 0|
|1 1 1 1 0 1 0 0 0 1 0 0 1 0 0 0 0 1 0 1 1 1 1 1 1 1|0 1 0 0 0 0|
|1 0 0 0 1 1 1 1 0 0 1 0 1 1 1 0 0 0 1 1 1 1 0 0 1 1|0 0 1 0 0 0|
|0 1 0 0 1 1 1 1 0 0 0 1 1 0 0 1 1 1 1 1 0 0 1 1 0 1|0 0 0 1 0 0|
|0 0 1 0 0 0 1 0 1 1 1 1 1 1 0 0 1 1 1 1 1 0 1 0 1 0|0 0 0 0 1 0|
|0 0 0 1 0 0 0 1 1 1 1 1 0 0 1 1 0 0 1 1 0 1 1 1 1 1|0 0 0 0 0 1|
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 7. ECC-6 Check Matrix X

The ECC-6 code protects the 32 bit CEM header as follows:

The encoder generates the 6 bit ECC using the matrix shown in Figure 7. In brief, the encoder builds another 26 column by 6 row matrix and calculates even parity over the rows. The matrix columns represent CEM header bits 0 through 25.

Denote each column of the ECC-6 check matrix by X[], and each column of the intermediate encoder matrix as Y[]. CEM[] denotes the CEM header and ECC[] is the error correction code that is inserted into CEM header bits 26 through 31.

```
for i = 0 to 25 {
     if CEM[i] = 0 {
             Y[i] = 0;
     } else {
             Y[i] = X[i];
     }
}
```

In other words, for each CEM header bit (i) set to 1, set the resulting matrix column Y[i] according to Figure 7.

The final ECC-6 code is calculated as even parity of each row in Y (i.e. ECC[k]=CEM[25+k]=even parity of row k).

The receiver also uses matrix X to calculate an intermediate matrix YÆ based on all 32 bits of the CEM header. Therefore YÆ is 32 columns wide and includes the ECC-6 code.

```
for i = 0 to 31 {
     if CEM[i] = 0 {
             YÆ[i] = 0;
     } else {
             YÆ[i] = X[i];
     }
}
```

The receiver then appends the incoming ECC-6 code to Y as column 32 (ECC[0] should align with row 0) and calculates even parity for each row. The result is a single 6 bit column Z. If all 6 bits are 0, there are no bit errors (or at least no detectable errors). Otherwise, it uses Z to perform a reverse lookup on X[] from Figure 7. If Z matches column X[i], then there is a single bit error. The receiver should invert bit CEM[i] to correct the header. If Z fails to match any column of X, then the CEM header contains more than one bit error and the CEM packet MUST be discarded.

Note that the ECC-6 code provides single bit correction and 2-bit detection of errors within the received ECC-6 code itself

Full Copyright Statement

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