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SERIES G: TRANSMISSION SYSTEMS AND MEDIA, DIGITAL SYSTEMS AND NETWORKS

Digital sections and digital line system – Access networks

ATM-based multi-pair bonding

ITU-T Recommendation G.998.1

ITU-T

ITU-T G-SERIES RECOMMENDATIONS

TRANSMISSION SYSTEMS AND MEDIA, DIGITAL SYSTEMS AND NETWORKS

INTERNATIONAL TELEPHONE CONNECTIONS AND CIRCUITS	G.100–G.199
GENERAL CHARACTERISTICS COMMON TO ALL ANALOGUE CARRIER-TRANSMISSION SYSTEMS	G.200–G.299
INDIVIDUAL CHARACTERISTICS OF INTERNATIONAL CARRIER TELEPHONE SYSTEMS ON METALLIC LINES	G.300–G.399
GENERAL CHARACTERISTICS OF INTERNATIONAL CARRIER TELEPHONE SYSTEMS ON RADIO-RELAY OR SATELLITE LINKS AND INTERCONNECTION WITH METALLIC LINES	G.400–G.449
COORDINATION OF RADIOTELEPHONY AND LINE TELEPHONY	G.450–G.499
TRANSMISSION MEDIA CHARACTERISTICS	G.600–G.699
DIGITAL TERMINAL EQUIPMENTS	G.700–G.799
DIGITAL NETWORKS	G.800–G.899
DIGITAL SECTIONS AND DIGITAL LINE SYSTEM	G.900–G.999
General	G.900–G.909
Parameters for optical fibre cable systems	G.910–G.919
Digital sections at hierarchical bit rates based on a bit rate of 2048 kbit/s	G.920–G.929
Digital line transmission systems on cable at non-hierarchical bit rates	G.930–G.939
Digital line systems provided by FDM transmission bearers	G.940–G.949
Digital line systems	G.950–G.959
Digital section and digital transmission systems for customer access to ISDN	G.960–G.969
Optical fibre submarine cable systems	G.970–G.979
Optical line systems for local and access networks	G.980–G.989
Acess networks	**G.990–G.999**
QUALITY OF SERVICE AND PERFORMANCE – GENERIC AND USER-RELATED ASPECTS	G.1000–G.1999
TRANSMISSION MEDIA CHARACTERISTICS	G.6000–G.6999
DIGITAL TERMINAL EQUIPMENTS	G.7000–G.7999
DIGITAL NETWORKS	G.8000–G.8999

For further details, please refer to the list of ITU-T Recommendations.

ITU-T Recommendation G.998.1

ATM-based multi-pair bonding

Summary

This Recommendation describes a method for bonding of multiple digital subscriber lines (DSL) to transport ATM streams. The specifications of this Recommendation provide a complete description of startup, operational, and contingency modes of operation which allows for interoperability between vendors.

This Recommendation includes the following types of requirements, recommendations, and information for defined DSL systems, including:

– higher-layer transport-independent requirements;

– higher-layer transport-dependent, e.g., ATM, requirements.

Source

ITU-T Recommendation G.998.1 was approved on 13 January 2005 by ITU-T Study Group 15 (2005-2008) under the ITU-T Recommendation A.8 procedure.

FOREWORD

The International Telecommunication Union (ITU) is the United Nations specialized agency in the field of telecommunications. The ITU Telecommunication Standardization Sector (ITU-T) is a permanent organ of ITU. ITU-T is responsible for studying technical, operating and tariff questions and issuing Recommendations on them with a view to standardizing telecommunications on a worldwide basis.

The World Telecommunication Standardization Assembly (WTSA), which meets every four years, establishes the topics for study by the ITU-T study groups which, in turn, produce Recommendations on these topics.

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In some areas of information technology which fall within ITU-T's purview, the necessary standards are prepared on a collaborative basis with ISO and IEC.

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In this Recommendation, the expression "Administration" is used for conciseness to indicate both a telecommunication administration and a recognized operating agency.

Compliance with this Recommendation is voluntary. However, the Recommendation may contain certain mandatory provisions (to ensure e.g. interoperability or applicability) and compliance with the Recommendation is achieved when all of these mandatory provisions are met. The words "shall" or some other obligatory language such as "must" and the negative equivalents are used to express requirements. The use of such words does not suggest that compliance with the Recommendation is required of any party.

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As of the date of approval of this Recommendation, ITU had received notice of intellectual property, protected by patents, which may be required to implement this Recommendation. However, implementors are cautioned that this may not represent the latest information and are therefore strongly urged to consult the TSB patent database.

CONTENTS

ITU-T Recommendation G.998.1

ATM-based multi-pair bonding

1 Scope

The purpose of this Recommendation is to assist manufacturers, providers, and users of products on how to use multiple DSL lines to carry a single ATM payload stream. In order to satisfy this purpose, requirements and guidelines are provided. This Recommendation is written to satisfy the following bonding objectives:

1) bonding shall support dynamic removal and restoration of pairs without human intervention;
2) bonding shall support disparate data rates, up to a ratio of 4-to-1 (fastest to slowest), amongst its pairs;
3) the protocol shall allow bonding of 2-32 pairs;
4) the protocol shall permit bonding of randomly assigned ports on an access node;
5) the protocol shall be PHY independent;
6) the protocol shall incur a maximum overall one-way bonding delay of 2 ms.

In order for implementations compliant to this Recommendation to be interoperable between vendors, an initialization procedure, a payload tagging method, and OAM capability are provided.

The applications supported within this Recommendation relate to bonding of multiple DSL loops to deliver ATM payload beyond the rate/reach capability of a single DSL loop. Each ATM TPS-TC (assuming multiple bearer channels) shall operate in an independent bonded group. As described within this Recommendation, the customer premises equipment (CPE) represents the User-Network Interface (UNI) to the ATM network.

2 References

The following ITU-T Recommendations and other references contain provisions which, through reference in this text, constitute provisions of this Recommendation. At the time of publication, the editions indicated were valid. All Recommendations and other references are subject to revision; users of this Recommendation are therefore encouraged to investigate the possibility of applying the most recent edition of the Recommendations and other references listed below. A list of the currently valid ITU-T Recommendations is regularly published. The reference to a document within this Recommendation does not give it, as a stand-alone document, the status of a Recommendation

[1] ITU-T Recommendation G.992.3 (2005), *Asymmetric digital subscriber line transceivers2 (ADSL2)*.

[2] ITU-T Recommendation G.994.1 (2003), *Handshake procedures for digital subscriber line (DSL) transceivers*.

[3] ITU-T Recommendation G.997.1 (2003), *Physical layer management for digital subscriber line (DSL) transceivers*.

[4] ITU-T Recommendation I.363.5 (1996), *B-ISDN ATM Adaptation Layer specification: Type 5 AAL*.

3 Definitions

This Recommendation defines the following terms:

3.1 carrier: An organization that provides telecommunications services to customer installations.

3.2 central office: In this Recommendation, the telephone building that is the origin of the outside loop plant.

3.3 customer installation: All cabling and equipment on the customer side of the network interface.

3.4 customer premises equipment: Telecommunications equipment located at the customer installation on the customer side of the network interface. For the purposes of this Recommendation, it is defined as multiple receivers that aggregate traffic from multiple lines into one ATM stream.

3.5 downstream: The direction of transmission from the carrier central office to the customer installation.

3.6 Inverse Multiplexing over ATM (IMA): IMA is used in this Recommendation to refer to ATM Forum specifications, not the bonding method of this Recommendation.

3.7 loop: A communication path between the distributing frame in a carrier central office and the network interface at a customer location.

3.8 network: All equipment and facilities, including loop plant, located on the carrier side of the network interface.

3.9 network interface: The physical demarcation point between carrier network loop facilities and the CI.

3.10 pair: Two insulated conductors.

3.11 showtime: A mode of operation of DSL modems that corresponds to transmission of live user data. It follows as a last step after all initialization and retraining procedures.

3.12 upstream: The direction of transmission from the customer installation to the carrier Central Office.

4 Abbreviations and acronyms

This Recommendation uses the following abbreviations:

AAL 5	ATM Adaptation Layer 5
ADSL	Asymmetric Digital Subscriber Line
ANSI	American National Standards Institute
ASM	Autonomous Status Message
ATM	Asynchronous Transfer Mode
ATM-TC	ATM Transmission Convergence (sublayer)
CAC	Connection Admission Control
CI	Customer Installation (see definition)
CLP	Cell Loss Priority
CO	Central Office (see definition)
CPE	Customer Premises Equipment (see definition)

CRC	Cyclic Redundancy Check
DS	Downstream
DSL	Digital Subscriber Line
FE	Far End
GID	Group Identifier
GFC	Generic Flow Control
HEC	Header Error Control
ICP	IMA Control Protocol (cell)
IMA	Inverse Multiplexing over ATM (see definition)
ITU-T	International Telecommunication Union – Telecommunication Standardization Sector
ME	Management Entity
MIB	Management Information Base
ms	Millisecond
NE	Near End
NI	Network Interface (see definition)
NMS	Network Management System
OAM	Operations, Administration and Maintenance
PHY	Physical layer
PMD	Physical Media Dependent (sublayer)
PMS-TC	Physical Media-Specific Transmission Convergence (sublayer)
PTI	Payload Type Identifier
Rx	Receive
SAR	Segmentation And Reassembly
SID	Sequence Index
SNMP	Simple Network Management Protocol
TPS-TC	Transport Protocol Specific – Transmission Convergence (sublayer)
TU-C	Transceiver Unit – Central office end. Sometimes combined with another letter; e.g., ATU-C for a central office ADSL transceiver
TU-R	Transceiver Unit – Remote terminal end. Sometimes combined with another letter; e.g., ATU-R for a remote ADSL transceiver
Tx	Transmit
UNI	User-Network Interface
US	Upstream
UTOPIA	Universal Test and Operations PHY Interface for ATM
VC	Virtual Channel
VCI	VC Identifier
VP	Virtual Path

VPI VP Identifier

5 Overview

An illustration of the bonding system for transport of an ATM payload across several DSL lines with disparate data rates is provided in Figure 1 below. In traditional inverse multiplexing over ATM (IMA) as specified in the ATM Forum document, Inverse Multiplexing for ATM (IMA) Specification, Version 1.1 [B1], it is assumed that all bonded links operate at the same nominal rate. The original cells are not modified, and control (ICP) cells are inserted for OAM communication between the two ends. In this Recommendation, each cell is tagged with a Sequence ID (SID). The transmitter may place any cell on any link, and the receiver can reassemble the original sequence.

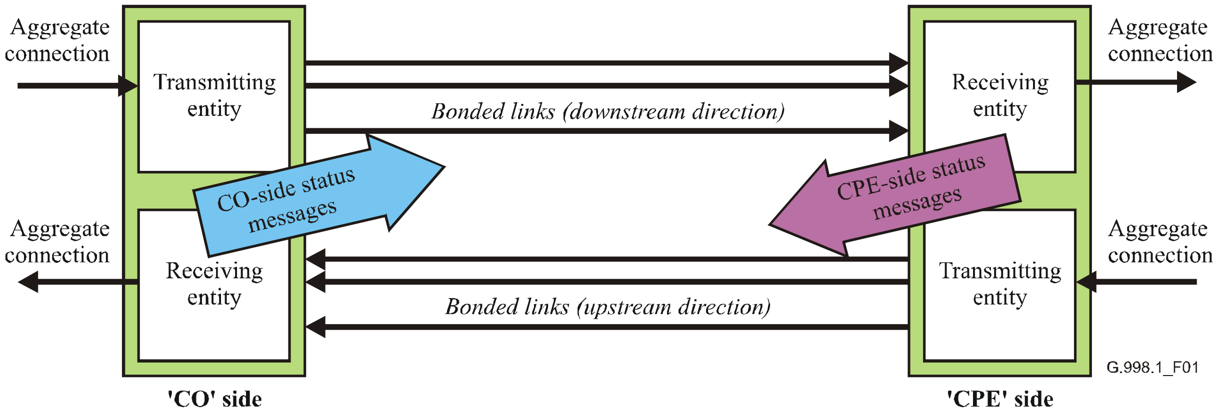

Figure 1/G.998.1 – Status message flow. Each transmission direction is treated independently

A bonding group is defined as a bidirectional ATM stream transported by multiple bidirectional bearers across multiple physical media in both upstream and downstream directions.[1] A single bonding group cannot span multiple CPE entities or CO-side access nodes. As a consequence, the control channel is also a bidirectional ATM stream, consisting of ATM messages called Autonomous Status Messages (ASMs). The content and sequence of these messages defines a control protocol between the two bonding entities in both directions. Some implementations may support multiple bearers on each physical link. Different bearers on the same line shall never be bonded together into the same group.

The control protocol communicates the status of each link in the bonding group. The way a bonding group is defined at startup, maintained during operation, and put out of service is discussed below.

The underlying bit rate of the individual links within a bonded group may be freely and independently changed by their respective PHY layers.[2] It is the responsibility of the transmitter not to overrun PHY transmit buffers, nor add delay created by excess buffering (by either carefully controlling the PHY bit rate itself, by allowing the PHY bit rate to "float" and then honoring back pressure, or by monitoring instantaneous bit rate and rate shaping its transmissions, matching multiplex ordering to rates, etc.).

[1] It should be noted that the upstream and downstream rates may be different.

[2] Resultant changes in bit rate are subject to constraints of buffer size, number of lines, and differential delay. The 4-to-1 ratio is not a hard limit, and may be violated provided these other constraints are satisfied.

6 Mode of operation

6.1 Sequencing payload traffic

The method for bonding ATM paths defined in this Recommendation is to tag each ATM cell with an 8-bit or 12-bit Sequence Index (SID)[3,4], which is done by replacing bits in the ATM header with SID bits between bonding entities and, depending on implementation, may recalculate the HEC. Although cells may be transmitted along paths with different delays, changing bit rates, and non-stationary delays, receivers can temporarily store incoming cells and use the SID to determine their original order.

Within the group, the SID increments consecutively from '0' through '255' (8-bit SID) or '0' through '4095' (12-bit SID), and wraps around to '0' again. After assembling the aggregate cell stream, these SID bits are replaced with zeros at the receiver. A transmitter shall never skip any of the sequence indices in this sequence.

The ATM cell header mappings are shown in Figure 2. CPE shall support all configurations. The CO may support either (or both) formats, but only one format shall be used in any given bonded group.

GFC	VPI (bits 7:0)	VCI (bits 15:0)	PTI	CLP	HEC (bits 7:0)

a) Standard ATM cell header

SID (bits 11:8)	VPI (bits 7:0)	SID (bits 7:0)	VCI (bits 7:0)	PTI	CLP	HEC (bits 7:0)

b) Modified ATM cell header for use with 12-bit SID

GFC	VPI (bits 7:0)	SID (bits 7:0)	VCI (bits 7:0)	PTI	CLP	HEC (bits 7:0)

c) Modified ATM cell header for use with 8-bit SID

G.998.1_F02

Figure 2/G.998.1 – Standard and modified ATM cell headers

6.2 Bonding Group ID (GID) and Management Entity (ME)

As shown in Figure 1, each side of a bonding group has a transmitting and a receiving entity. The bonding group operating from the Central Office (CO) side towards the Customer Premises Equipment (CPE) side has a unique Group ID (GID) assigned by the CO bonding management entity (bonding ME). The corresponding bonding group operating from the CPE side towards the CO side shall use the same GID (by definition), which it dynamically learns during initialization. All links within a bonding group shall use the same group ID in both the upstream and downstream directions. The ME also assigns the Tx link number to each of the links in the bonding group. The

[3] In this Recommendation, 8 and 12 bits of sequence index space have been defined. Note that the use of a particular SID is bounded by the aggregate rate, differential delay, and number of links. Implementations are not compelled to provide buffer space to accommodate the full range of sequence indices and are free to provide a sufficient but smaller number of buffers to suit their target application.

[4] Implementations should equalize latency on each link. However, when bonding DSL types that may have different latencies due to different values in PHY layer parameters, implementations should be able to tolerate at least 4 ms of differential delay. Differences in electrical length will not contribute significantly to the differential delay. No additional buffer is required for this variation.

Tx link numbers are assigned at the CO side and the CPE side will dynamically learn the Tx link numbers during initialization.

6.3 Autonomous Status Messages (ASMs)

Each bonding group has an associated set of Autonomous Status Messages (ASMs) with a unique GID that is used to communicate the status of the links in the group in each direction. These ASMs are used for both startup and maintenance of the links in a bonding group as defined in this clause.

Autonomous status messages shall always be transmitted onto all links within the group which have been provisioned. These messages shall be transmitted regularly on the available links with the Tx link number set to the number assigned to the physical link (line number and bearer number) on which the message is to be carried. During initialization, ASM transmission shall occur on each and every link in a group.

Receiver implementations shall always accept and rely upon non-errored autonomous status messages received on any incoming link that has a far-end Tx link status of 'Acceptable to carry bonded traffic' or 'Selected to carry bonded traffic' as defined in Table 3.

6.4 Link eligibility and link activation

The receiving entity is primarily responsible for determining which links are eligible to become active in the transmit group. In order to be eligible, a link shall be both:

a) of sufficient quality; and

b) determined by the receiver to be required at that time.

The receiver notifies the far-end transmitting entity using ASMs with the provisioned group ID with Rx link status of 'Acceptable to carry bonded traffic' as defined in Table 3. In all cases, a receiving entity should identify and count all HEC errors and consider all HEC errors in determining whether a link is suitable for inclusion within the active group or not. An implementation should not rely solely upon receipt of autonomous status messages to flag the link state as being acceptable[5], nor should an implementation rely solely upon the indication of a valid frame from the PHY layer[6,7].

When receiving an autonomous status message which indicates that a particular link has gone bad (Rx link status is 'Should not be used'), the transmitter should reconfigure itself to stop sending payload traffic on the broken link. However, the transmitter should continue sending autonomous status messages on all provisioned links, including the failed links, at the nominal rate. When receiving an autonomous status message which indicates the Rx link status is 'Acceptable to carry bonded traffic' and the link in question is currently not carrying bonded traffic, it is up to the transmitter implementation whether to use this link or not.

The transmitting entity is not bound to activate all links which have been flagged as eligible by the receiver. The transmitter may not activate a link which the receiver has not flagged by setting the

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[5] High-speed links will generally contain a very low proportion of control messages relative to payload messages. Basing link state on control messages alone could cause a high error rate to go unnoticed for an unacceptably long period.

[6] A simple network misconfiguration should be anticipated and tolerated. Although the PHY layers will each report valid incoming signals with potentially minimal errors, receiver implementations which do not authenticate the source of the ASM and disregard misconfigured links may experience complete loss of the bonding service.

[7] When DSL lines serving two different customers are inadvertently swapped, the PHY layers may not recognize the problem. In this case, receiver implementations should note the mismatch in group ID fields and take appropriate action.

Rx link status of 'Acceptable to carry bonded traffic' as defined in clause 9.[8] Bonded traffic shall be sent on a link only if the Tx link status and Rx link status are 'Selected to carry bonded traffic'.

6.4.1 Adding traffic to a provisioned link

The ASM transactions for adding bonded traffic to a link which is provisioned to be in the bonded group and not carrying bonded traffic is provided in Table 1. The traffic receiver sets Rx link status in its outgoing ASMs, and the traffic transmitter sets Tx link status in its outgoing ASMs. Also provided in the table is the action which should result.

Table 1/G.998.1 – Adding traffic to a provisioned link

Receiver; Rx link status	Transmitter; Tx link status	Resulting action
	Signal Rx candidate links to monitor; 'Acceptable to carry bonded traffic'	Rx monitors this link
When quality sufficient and Rx desires traffic on this link; 'Acceptable to carry bonded traffic'		Tx knows it can use this link
	If Tx desires to use this link; 'Selected to carry bonded traffic'	Tx awaits response from Rx
Confirm ready to receive bonded traffic; 'Selected to carry bonded traffic'		Bonded traffic flows on this link

6.4.2 Receiver-directed procedure to stop sending traffic

When a receiver determines that traffic should not be sent on a link in a given direction (for a reason such as insufficient quality), the following ASM transaction can be used to configure the transmitter so that no traffic is sent on this link:

– Rx sets Rx link status to 'Should not be used'.

– Far-end Tx should immediately stop sending traffic on that link, and should set Tx link status to 'Acceptable to carry bonded traffic' (or 'Should not be used' if it does not want Rx to consider this link again).

– The far-end Tx should continue to send ASM cells.

– Traffic may resume on this link by following the procedure outlined in Table 1.

While it is unclear why a receiver would need to change the status of a link from Selected to Acceptable, such a transition is not precluded. Specifically, a receiver with Rx link status of '11' may change Rx link status to '10'. In this event, the transmitter shall stop forwarding payload cells on this link. The transmitting entity shall keep its Tx link status as '11' ('Selected to carry bonded traffic'). Payload traffic may not resume until the Rx link status is '11' ('Selected to carry bonded traffic').

[8] There is no requirement that link usage is identical in both directions. If link quality is such that it is not used to carry traffic in one direction, it may still carry traffic in the other direction.

6.4.3 Transmitter-directed procedure to stop sending traffic

If a transmitter determines that a link should not be used in a given direction (because capacity not needed or other reasons at the discretion of the transmitter), the following ASM transaction can be used to inform the receiver that no traffic will be sent on this link.

– Tx sets Tx link status to 'Should not be used', and does not send bonded traffic on this link.
– Rx should change Rx link status to 'Should not be used'. Rx will not consider adding this link back to the group until Tx changes Tx link status to 'Acceptable to carry bonded traffic'.
– Traffic may resume on this link by following the procedure outlined in Table 1.

Note that at any point the transmitter can stop using any link to carry payload data without signalling this to the far end.

While it is unclear why a transmitter would need to change the status of a link from Selected to Acceptable, such a transition is not precluded. Specifically, a transmitter with Tx link status of '11' may change Tx link status to '10'. In this event, the transmitter shall stop forwarding payload cells on this link prior to the transition. As a result, the receiving entity shall set its Rx link status to '10' ('Acceptable to carry payload traffic').

6.5 Measurement of bonding group differential delay

In order to evaluate the differential delay between provisioned links, the CO and CPE ATM bonding functions shall maintain a local clock in 0.1 ms unit. The frequency offset between both clocks shall be lower than 200 ppm. The transmitter entity shall include a timestamp with the value of its local clock inside each ASM cell before transmission on a provisioned link. The timestamp format is defined in clause 9. An example algorithm to derive the differential delay from this timestamp is described in Appendix IV.

6.6 Compensation of differential delay by the CPE transmitting entity

To reduce the buffer requirement at the CO side, the CPE transmit entity shall be able to implement variable delays on a link basis between the SID tagging and the transmission through the gamma interface. The ASM cell shall incur an identical delay between the insertion of the timestamp and the transmission through the gamma interface as shown in Figure 3. At initialization or reconfiguration of the bonding group, the variable delays shall be set to 0 ms. The CO may request the CPE to implement a delay on a specific link. The value of this requested delay shall be indicated in the ASM cell transmitted on this link. To keep track of the delay compensation, the transmitter shall indicate in the ASM cell the actual delay implemented on this link.

Buffer space is required to minimize differential delay. In the worst case, this buffer is required on all lines except one. For an ADSL upstream transmitter, a buffer space of at least 8 kbytes per line shall be provided.[9] This is based on the ability to compensate for 20 ms differential delay at 3 Mbit/s. The compensation shall be implemented with a precision of at least 0.5 ms.

Note that resultant maximal differential delay in the upstream direction should be at most 1 ms, excluding ATM and other transmission delays, if all requested compensations can be implemented by the CPEs.

The buffer space and precision required to bond other DSL varieties is for further study.

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[9] For an ADSL downstream receiver, the amount of buffering needed depends on the application and is not herein specified.

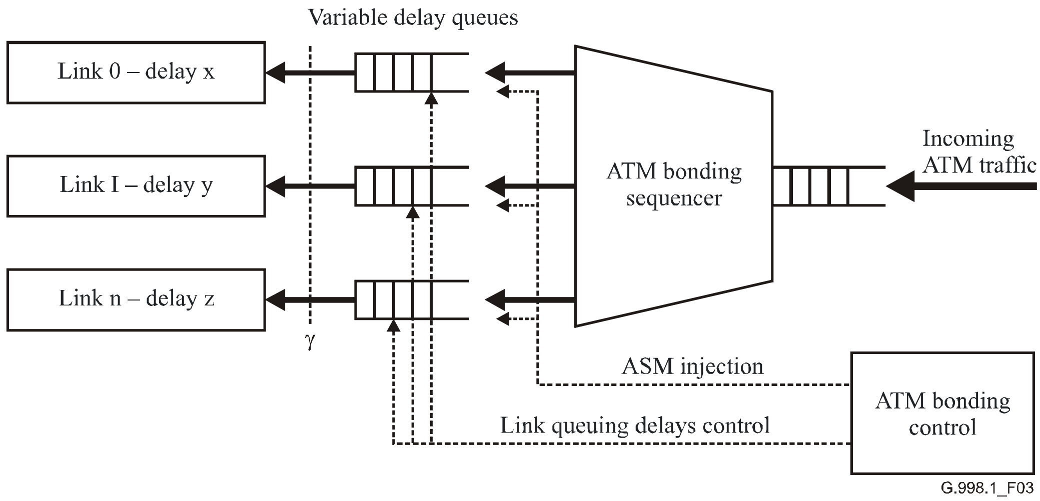

Figure 3/G.998.1 – Differential delay compensation in transmitter by variable delays

7 Reference models

7.1 User plane protocol reference model

An ATM bonding group is a bidirectional ATM stream transported by multiple bearers across multiple physical media in both upstream and downstream directions. The bonding layer has the capability to manage multiple bonding groups. A DSL bearer channel shall only belong to one bonding group at a given time. Multiple VC and VP connections can be supported in one bonding group subject to constraints of available VPI/VCI space supported in the modified cell header.

Figures 4 and 5 show the user plane protocol reference models of one bonded group and multiple bonded groups, respectively, that are consistent with the representation used in xDSL Recommendations. The bonding sublayer is located between the ATM transport layer and xDSL transceiver's ATM-TC sublayer.

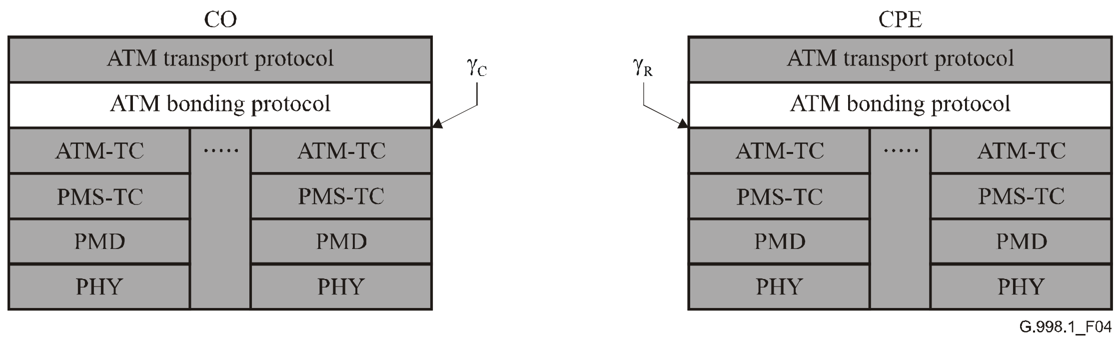

Figure 4/G.998.1 – User plane protocol reference model of one bonded group

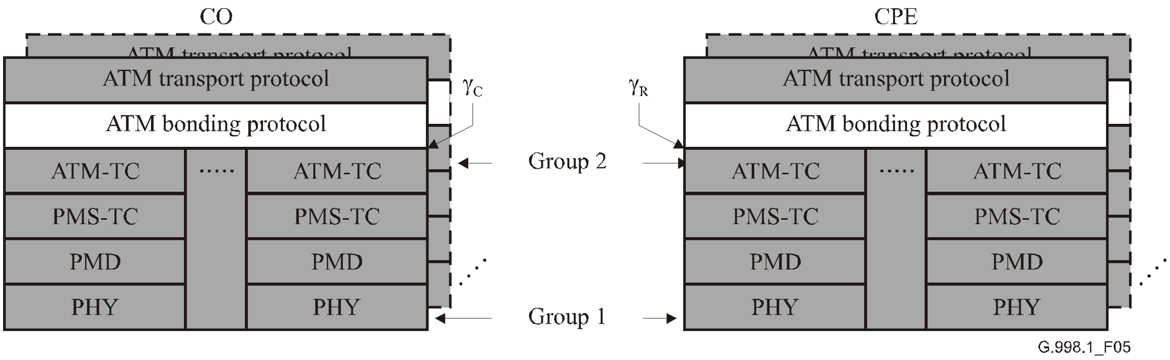

Figure 5/G.998.1 – User plane protocol reference model of multiple bonded groups

7.2 Bonding sublayer in layer reference model

Table 2 shows the bonding sublayer's layer reference model.

Table 2/G.998.1 – ATM bonding in layer reference model

	User plane functions	Layer management functions	Plane management functions
xDSL ATM bonding layer	• ATM cell stream split and reconstruction • ASM cell transmit and receive	• ASM handling	• Group configuration and removal • Group dynamic link management • Group rate change • Group status update • Group performance and fault monitoring

7.3 Functional reference model

Figure 6 illustrates the main functional blocks of the ATM bonding entity.

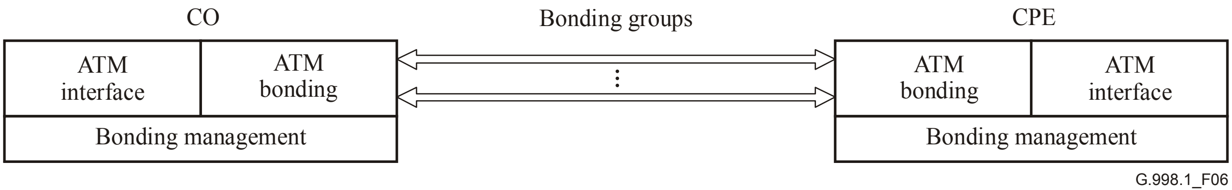

Figure 6/G.998.1 – ATM bonding functional blocks

7.3.1 ATM interface

The ATM interface block provides a bidirectional ATM connection to the higher ATM transport layer. In each direction, multiple ATM streams can be supported.

7.3.2 ATM bonding function

For the transmit direction in a bonding group, the ATM-bonding function block controls cell distribution onto member ATM-TC bearers that may have different net data rates, and places proper sequence IDs into the cells to allow recovery of cell sequencing at the receiver. In the receive direction, the function block merges cells received from the member bearers in the order defined by the sequence ID and reconstructs the original ATM stream.

Other than handling regular ATM cell streams, the block also handles proper transmission and reception of ASM cells on a per-group basis.

7.3.3 Bonding management function

The main function of the management block is to set up and remove bonding groups, as well as to manage the bonding group's operational behaviours, such as dynamic link drop/recovery, etc. The management block also monitors the group performance and fault conditions. In addition, the block does ASM message handling.

8 Cell header formats

8.1 Autonomous Status Messages (ASM)

The protocol for controlling the bonded links is carried in single-cell messages (autonomous status messages). These cells shall be addressed as if they originate from VP=0, VC=20. ASMs are not sequenced in the same manner as regular payload traffic. The sequence index bits should be set to '00' in all control cells.

Refer to the description of the autonomous status message format in clause 9.

8.2 Idle and unassigned cells

Idle and unassigned cells, as defined in ITU-T Recs I.432.1 and I.361, are handled normally by the ATM-TC of the transceiver. They are neither seen nor generated by the bonding layer.

8.3 OAM and ATM payload cells

A bonding group is logically the same as a single path for the purposes of ATM traffic. The treatment of OAM and ATM payload cells on a bonded group shall follow the same rules as if those cells were carried on a single path carrying multiple ATM streams.

8.4 HEC errors

It is important for the bonding control entity to identify, count, and respond to all HEC errors. HEC errors may occur within ATM payload, bonding control, idle, unassigned, and OAM cells. HEC errors shall be considered when determining whether a link is suitable for inclusion within the active group or not. How HEC errors are communicated to the bonding layer is left to the implementation.

9 Bonding group internal control protocol

9.1 Types of control message

The control protocol outlined in this Recommendation consists of single message type: an autonomous status message. This message conveys the status of the links to the far-end bonding management entity.

9.1.1 Length and format of control messages

The status message is contained in a single ATM cell, and bytes 50-53 are used to carry a CRC-32 on the payload of this cell. Bytes 46-49 are defined so that the ASM has the form of a single-cell AAL 5 message. An AAL 5 SAR is not required for compliance to this Recommendation.

9.1.2 Priority of control messages

It is the responsibility of the transmitter implementation to determine when to schedule and transmit control messages. The policy of when to insert a control message into the payload cell stream is left to the discretion of the implementer.

9.1.3 Frequency of autonomous status messages

During showtime, ASM messages shall be sent periodically on all provisioned links within each group. These messages are used for monitoring the status of the link and can be used by the bonding ME for dynamic link management and error control. According to implementation, ASMs may be transmitted as frequently as required. Status messages should be transmitted no less frequently than once per second per link in the bonded group. Transmitters should include means to ensure that in the long term[10], control messages are not transmitted at more than 1% of the available link capacity.[11] This limit does not apply during initialization.

It is not the intention to arbitrarily rule out links which operate at very low bit rates. Receiver implementations should endeavour to accept and process all incoming control messages, regardless of their instantaneous arrival rate. In the event that a receiver implementation cannot keep up with the rate of arrival of control messages, it is free to discard messages as necessary because the control protocol has been specified in a manner which is tolerant of receiver discards.

Transmission of status messages should be staggered across links to reduce the jitter impact upon the payload traffic. For example, if there are 32 links within a bonded group and the links are numbered from '0' to '31', status messages may be sent in a round-robin manner commencing with a message on link '0', then link '1', through to link '31' and then back to link '0' again. This would result in a bonded group of 32 links carrying at least 32 status messages every second; one status message per link.

However, there is no strict requirement for a transmitter implementation to follow a particular sequence when choosing the order of the links on which autonomous status messages are forwarded. Implementers are free to choose any order and frequency considered appropriate for the implementation.

Receivers should not anticipate a particular timing or order other than the minimum rate of one autonomous status message per second per link. Receivers should make allowance for the possible loss or corruption of autonomous status messages and should not base the assessment of link health on the arrival (or non-arrival) of autonomous status messages alone.

Because large frames carried within AAL 5 payloads are adversely impacted when one of the links within a bonded group degrades, one or more autonomous status messages should be sent as soon as a receiver identifies a degraded link. This, for example, could be implemented by immediately transmitting the next autonomous status message on the next scheduled link without waiting for its associated timer to expire.

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[10] It should be understood that, during initialization, ASMs may be transmitted at a frequency greater than 1%.

[11] This implies that each link should achieve a minimum allowable bit rate of 100 cells per second (42.4 kbit/s).

9.1.4 Format of the autonomous status message

The format of the autonomous status message is described in Table 3.

Table 3/G.998.1 – ASM message format

Octet	Label	Range	Comments
1-4	Cell header		VPI=0, VCI=20, PTI=1, CLP=0, GFC=0 The SID field should be set with all bits '0'. SID is not used in ASMs.
5	HEC	0..255	HEC calculated in the standard way across bytes 1..4
6	Message type	0..255	Defines message type: '00': Autonomous status message, 12-bit SID format '01': Autonomous status message, 8-bit SID format 'FF': Initialization or reconfigure group
7	ASM identifier	0..255	Modulo 256 message identifier. Incremented from 0 through 255 and back to 0. The field is used by the receiver to derive the age of ASMs. The bonding ME increments the 'ASM identifier' number for each new autonomous status message sent on a per-group basis. The receiver ignores (discards) autonomous status messages having an 'ASM identifier' earlier than other recently received autonomous status messages.
8 (bits 0-4)	Tx link number	0..n-1	This field is used for link identification. Links should be numbered sequentially commencing with '0'.
8 (bits 5-6)	Reserved		Reserved for future definition. Shall be set to '0' in all outgoing messages. Shall be ignored in all incoming messages.
8 (bit 7)	Insufficient buffers	Boolean	This field will be used to assist operators and end users identify situations where the receiver implementation does not support sufficient buffers to bond all available links. '0': All links flagged as available for bonding could be supported based upon current buffers, differential bit rate, differential delay, and jitter. '1': There are insufficient buffers to allow bonding of all links currently flagged as available for bonding.
9	Number of links	1..32	This field indicates the number of provisioned links in the bonding group.

Table 3/G.998.1 – ASM message format

Octet	Label	Range	Comments
10-17	Rx link status (2 bits per link, up to 32 links)	8 bytes	The status of each of the Rx links (up to 32) in the bonded group. The two MSBs (bits 7,6) in octet 10 correspond to the status of the first link (link '0'), the next two bits in octet 10 (bits 5,4) correspond to the status of the second link (link '1'), and so on. Octet 11 contains the status of link 4 (bits 7,6) through link 7 (bits 1,0), and similarly for octets 12-17. '00': Not provisioned '01': Should not be used '10': Acceptable to carry bonded traffic '11': Selected to carry bonded traffic
18-25	Tx link status (2 bits per link, up to 32 links)	8 bytes	The status of each of the Tx links (up to 32) in the bonded group. The two MSBs (bits 7,6) in octet 18 correspond to the status of the first link (link '0'), the next two bits in octet 18 (bits 5,4) correspond to the status of the second link (link '1'), and so on. Octet 19 contains the status of link 4 (bits 7,6) through link 7 (bits 1,0), and similarly for octets 20-25. '00': Not provisioned '01': Should not be used '10': Acceptable to carry bonded traffic '11': Selected to carry bonded traffic
26-27	Group ID	2 bytes	Integer numbers to uniquely identify bonding groups.
28-31	Rx ASM status (1 bit per link, up to 32 links)	4 bytes	The status of ASMs received on each link in the past one second: '0': At least 1 error-free ASM received '1': No error-free ASMs received
32	Group lost cells	0..255	Number of cells lost at the receiver bonding layer. Modulo 256.
33	Reserved	1 byte	Reserved for future definition. Shall be set to '0' in all outgoing messages. Shall be ignored in all incoming messages.
34-37	Timestamp	$0..2^{31} – 1$	Value of the ATM bonding function local clock expressed in 0.1 ms unit. If not supported in the CO, this value shall be set to 0 in ASM messages transmitted from the CO. The MSB is in octet 34, and the LSB is in octet 37.
38-39	Requested Tx delay	$0..2^{16} – 1$ (Note)	Requested delay in 0.1 ms unit to be implemented by the transmitter entity on the link carrying the ASM cell. This value shall be set to 0 on ASMs transmitted from the CPE. The MSB is in octet 38 and the LSB is in octet 39.

Table 3/G.998.1 – ASM message format

Octet	Label	Range	Comments
40-41	Actual Tx delay	$0..2^{16}-1$ (Note)	Actual delay in 0.1 ms unit implemented by the transmitter entity on the link carrying the ASM cell. This value shall be set to 0 on ASMs transmitted from the CO. The MSB is in octet 40 and the LSB is in octet 41.
42-45	Reserved	4 bytes	Reserved for future definition. Shall be set to '0' in all outgoing messages. Shall be ignored in all incoming messages.
46-47	Reserved	Shall be set to 0x00, 0x00	These values shall be filled in by the transmitter, but may be ignored by the receiver.[12]
48-49	Length of message	Shall be set to 0x00, 0x28	
50-53	CRC-32		Shall be calculated over payload octets 6-49 as defined in AAL 5.
NOTE – The valid range of this parameter is determined by memory available in the CPE as specified in 6.6.			

Explanation of the fields:

Cell header — The modified cell header format is intended to be bit-compatible with common PHY and ATM hardware devices. It is intended that devices implementing this bonding technique be able to be simply interfaced at the UTOPIA level with non-bonding aware PHY and ATM devices such as SARs, switches, traffic controllers, and the like.

Message type — The message type is provisioned at the CO and sent to the CPE in this field. The message type the CPE sends to the CO in this field shall be identical to the message type received from the CO. Both ends shall use the same length SID as determined by the CO and sent to the CPE in the message type field. The message type is determined during initialization and shall not be changed while the group is in service.

The value of '00' identifies this message as an autonomous status message and that 12-bit SID is used in this bonded group. The value '01' in this field identifies this message as an autonomous status message and that 8-bit SID is used in this bonded group. The value 'FF' in this field indicates that the bonding ME shall cease forwarding payload traffic and shall reinitialize. Implementations of this version of this Recommendation should examine the message type field, and if not '00', '01', or 'FF' the message should be silently discarded.

Implementations of future versions of this Recommendation should monitor the message type field of incoming control messages. Receipt of an autonomous status message containing a message type of '00' or '01'

[12] Note that bytes 46 and 47 correspond to the CPCS-UU and CPI bytes, as defined in AAL 5. They are set to 0. The length field, as used both here and in AAL 5, is set to 40 (decimal), or 28 (hexadecimal).

	indicates that the far end supports the 12-bit or 8-bit formats in the first version of this Recommendation, and the implementation should silently revert to the same version.
ASM identifier	This field defines the sequential order of autonomous status messages. The ASM identifier should increment from '00' through 'FF' and cycle back to '00'. It should be incremented for each newly transmitted autonomous status message on a per-group basis. No two consecutive autonomous status messages should be sent with the same ASM identifier, even Status Messages sent on different links within the bonded group. The receiver examines the ASM identifier field in order to identify out-of-order reception. In the event that an autonomous status message is received with an ASM identifier earlier than another recent autonomous status message, the autonomous status message with the earlier ASM identifier number should be discarded.
Tx link number	This field denotes the number assigned to the link at the CO by the ME during initialization. The CPE learns the Tx link number for each link from the ASMs received on the link from the CO. The CPE uses the same Tx link number for its ASMs. Link number assignments shall be consecutively numbered from '0'. These numbers shall not change for the life of the group, regardless of any change in link status. The Tx link number is configured statically when the bonded group is provisioned and shall not be changed while the group is in service.
Insufficient buffers	Before receivers may flag an Rx link as suitable for inclusion in the bonded group, it shall assess the prevailing differential bit rate, line rate, and jitter to determine the buffering requirements. If there are insufficient buffers available to support all links currently flagged as available for bonding, the receiver shall set the 'Insufficient Buffers' field to notify the far end of this condition.
Number of links	This field describes the number of links which have been provisioned in this bonding group. This is a static field which shall not be changed during the life of the group.
Rx link status	The most important function of the control protocol is for the two ends to be able to add links into the current group and for the two ends to be able to remove links from the group. This needs to be achieved as quickly and efficiently as possible in order to minimize lost traffic and maximize available time. Link numbers are defined by the management entity and provisioned at the CO. Two status bits are defined for each link. To convey status for 32 lines, 64 bits or 8 bytes are required. See definitions in the ASM definition. The first two bits in the first byte of the field correspond with the status of the first Rx link (link '0'). The second two bits correspond with the status of the second link (link '1') and so on through to the last two bits of the last byte which correspond with the status of the 32nd link (link '31').

The status indications are to be used as follows:

- **Not provisioned**: Link indicated as not provisioned, and will never be a part of the bonded group. Note that the number of provisioned links is equal to the field 'Number of Links'. It is the same in both directions, therefore, if Tx link status is 'Not provisioned', Rx link status shall also be 'Not provisioned'.
- **Should not be used**: Transmitter should not use link for bonding but is provisioned by NMS as a candidate link member (i.e., temporary outage). If the ATM path is still present on this link, a transmitter that receives ASMs with this Rx link status shall continue to send ASMs.
- **Acceptable to carry bonded traffic**: Used to request the transmitter consider this provisioned link for bonding.
- **Selected to carry bonded traffic**: Bonded traffic expected on this link.

Tx link status

To convey status for 32 lines, 64 bits or 8 bytes are required. See definitions in the ASM definition.

The first two bits in the first byte of the field correspond with the status of the first Tx link (link '0'). The second two bits correspond with the status of the second link (link '1') and so on through to the last two bits of the last byte which correspond with the status of the 32nd link (link '31').

The status indications are to be used as follows:

- **Not provisioned**: Link indicated as not provisioned, and will never be a part of the bonded group. See 'Rx link status'.
- **Should not be used**: Receiver should not consider the link for bonding, but is provisioned by NMS as a candidate link member.
- **Acceptable to carry bonded traffic**: Used to indicate which links the receiver should consider for bonding.
- **Selected to carry bonded traffic**: Transmitter is using or will use this link to carry bonded traffic.

During the life of a group, the status can be changed between any of the last three types. However, if the group initialized flagging a particular link as "Not provisioned", it shall never change from this indication.

Group ID

This field is configured statically when the bonded group is provisioned and shall not be changed while the group is in service. These fields may be used by an operator to help identify misconfiguration or to assist in management or debugging of the link.

Rx ASM status

This field conveys from the transmitter to the receiver whether ASMs are being received on each link. The first bit (bit 7) in the first byte of the field corresponds to the first link (link '0'). The second bit corresponds to the second link (link '1') and so on through to the last bit which corresponds with the status of the 32nd link (link '31').

The status indications are to be used as follows:

- '0': At least one error-free ASM received in the past one second interval.
- 1': No error-free ASM received in the last one second interval.

	This field is not valid for links with Tx link status of 'Not provisioned', as ASMs should not be expected on those links.
Group lost cells	This field conveys from the receiver to the transmitter the count of cells lost at the receiver bonding layer.
Reserved	Reserved fields should be filled with the value '0' and disregarded by the receiver. Reserved fields may be used for additional purposes in future versions of this protocol.
Timestamp	This field contains the value of the local clock maintained by the ATM bonding function at the transmission of the ASM cell (see 6.5). This field is required in ASMs transmitted by the CPE. If not implemented in the CO, ASMs transmitted from the CO shall set this field to 0.
Requested Tx delay	This field contains the value of the transmitter delay to be implemented by the transmitter on the specific link carrying this ASM cell (see 6.6). For ASMs transmitted by the CPE, this field shall be set to 0.
Actual Tx delay	This field contains the value of the transmitter delay implemented by the transmitter on the specific link carrying this ASM cell (see 6.6). For ASMs transmitted by the CO, this field shall be set to 0.
Length	Length of payload of ASM cell including reserved bytes but not CRC. Set to value 0x28 in all ASM messages.
CRC-32	The value in this CRC field shall be the same as if a standard AAL 5 SAR had been used to generate the single cell status message.

10 Initialization

There are two sides of a bonded group of links, a "CO" side and a "CPE" side. The initialization procedure is defined below:

1) PHY transceivers are trained individually. When each bearer channel becomes operational, both the CO and the CPE management entities know the parameters (data rate, margin, etc.).
2) After the PHY enters showtime, the CO shall force its CPE peer bonding entity into an initialization state by sending an ASM with message type 'FF' and the appropriate group ID on each of the active links. If a bonding ME receives an error-free ASM with a message type of 'FF', that bonding ME shall immediately cease forwarding user payload traffic, and shall re-initialize.
3) The CPE bonding ME shall establish the grouping of its bearer channels into bonding groups by deriving this information from the incoming ASMs from the CO. This process is initiated by the CO bonding ME.
4) As soon as each PHY is in showtime, the CO bonding ME shall commence transmission of autonomous status messages with message ID other than 'FF' on the downstream links of a bonding group[13]. The corresponding 'Tx link status' field within the ASMs shall be set to indicate that the link is available for service but is not currently bonded. The CPE bonding ME shall remain silent on each of its links until it has received at least one error-free ASM on each provisioned link, the number of such links is equal to the 'Number of links' field in each received ASM message, and the group ID fields have the same value.

[13] When each line is carrying multiple bearers, each bearer is required to have a unique group ID.

As the CPE bonding ME receives error-free ASMs, it uses the ASMs to learn the group ID, cell format, and the member links in the bonding group. The CPE shall commence transmission of its own ASMs on a particular link following receipt of a validated and error-free ASM on all provisioned links.

5) Each bonding ME shall use the incoming 'Rx link status' indications (within the incoming ASMs from its peer) to choose which Tx links are candidates to carry payload traffic. In order for a bonding ME to commence forwarding payload traffic on a link, it shall first receive at least one error-free ASM from its peer on any of the incoming links which has the 'Rx link status' field, corresponding to the link in question, that indicates 'Selected to carry bonded traffic'.

   Neither the CO nor CPE bonding MEs are permitted to start to forward payload traffic on an outgoing Tx link until after it has received at least one ASM on that particular link.

6) The CPE shall employ the upstream bearer having the same index (bearer number) as the downstream bearer on which the ASM was received.

7) As additional ASMs are received during the life of the group, the 'Group ID', 'Number of links' and 'Tx link number' fields should be compared with their previously received counterparts. An alarm may optionally be raised if a mismatch is noted, but in any case, forwarding of payload traffic should be interrupted and all bonded links should be placed out of service.

   After the bonding has been interrupted, the bonding MEs shall re-initialize by setting the 'Message Type' to 'FF'.

8) If it is necessary for the operator to reconfigure any parameters, including a change to the 'Group ID', the CO bonding ME shall re-initialize by setting the 'Message type' to 'FF'.

9) If at any time a bonding ME needs to change any of its 'Rx link status' indications, it is free to do so unless otherwise constrained by another requirement in this list. Having made the change, that particular 'Rx link status' field shall not be changed again until at least three ASMs containing that change have been transmitted on each in-service Tx link.

10) If a bonding ME receives an error-free ASM with an 'Rx link status' field indicating that a currently in-service Tx link should not be used by the bonded group to carry bonded traffic, that bonding ME is required to cease forwarding user payload traffic on that Tx link as quickly as practical and to update its own corresponding 'Tx link status' field.

11) All receivers shall perform buffer requirements calculations based upon prevailing line rate, line delay, and jitter characteristics to determine whether the available buffer pool is sufficient to bond each of the links currently flagged as available for bonding. It is the receiver's responsibility to ensure that the transmitter is never permitted to bond a combination of links which could exceed the receiver's buffering capabilities. The receiver shall set the 'Insufficient buffers' field as defined in the ASM message whenever this situation is detected.

11 External management

This clause is not intended to provide a complete MIB specification for external management.

11.1 OAM interface primitives

Figure 7 shows the interface signals between the ATM bonding entity and external management functions. Each signal carries multiple primitives or parameters.

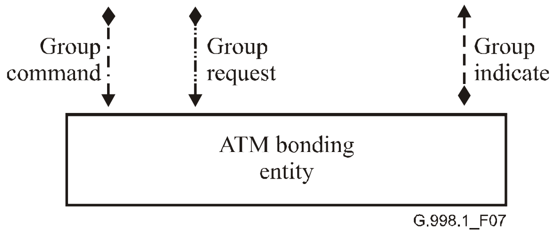

Figure 7/G.998.1 – OAM interface signals

The group command signal passes control information to the bonding entity to create or remove bonding groups. Primitives and parameters are listed in Table 4.

Table 4/G.998.1 – Group command signal

Primitives	Parameters	Note
Group config/reconfig	Bonding group ID	
	Line number(s)	Line number + Bearer number identify a member link
	Bearer number(s)	
	Max aggregate rate	Can be set as 'infinity' to be ignored. Different elements for upstream and downstream.
	Min aggregate rate	Any rate achieved below min rate should fail a bonding group. Different elements for upstream and downstream.
	Differential delay tolerance	Covers end-to-end delay variance for aggregation buffer sizing. Different elements for upstream and downstream.
Group remove	Bonding group ID	

The group request signal is used to inquire about bonding group OAM status. Primitives are listed in Table 5.

Table 5/G.998.1 – Group request signal

Primitives	Note
Group operation inquiry	Response in Table 6.
Group performance inquiry	Response in Table 6.

The group indicate signal is used to report bonding group OAM status. Primitives and parameters are listed in Table 6. Performance measurements shall be accumulated in intervals of 15-minute and 24-hour periods.

Table 6/G.998.1 – Group indicate signal

Primitives	Parameters	Note
Group operation status	Group status	Operational, unavailable.
	Achieved aggregate rate	Current achieved group aggregate rate. Different elements for upstream and downstream.
Group performance	Group cell loss count	Cells lost at the bonding layer in the accumulation interval. Different elements for upstream and downstream.

Performance data for the bonded links can be derived from the MIB elements for each individual PHY as defined in ITU-T Rec. G.997.1.

11.2 OAM channel between NMS and bonding entity

Figure 8 shows an example OAM channel between an NMS and the bonding entity to pass bonding-related OAM information. In this example, SNMP is used for bonding unit management and it is transported to NT using ATM.[14] Use of SNMP is not required for compliance to this Recommendation.

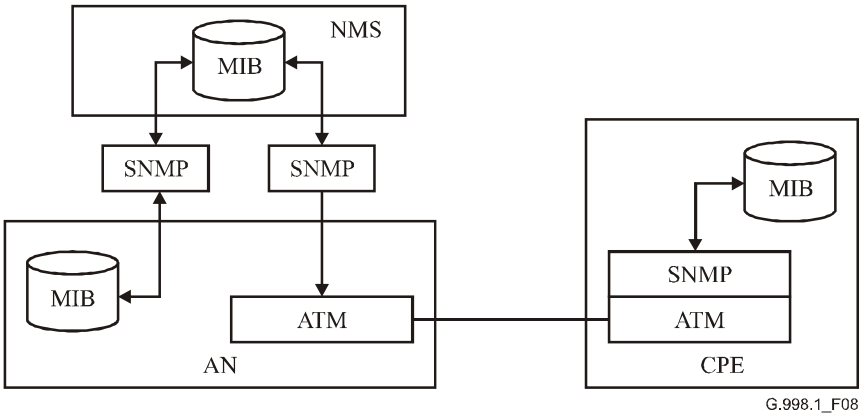

Figure 8/G.998.1 – OAM channel between NMS and bonding entity

11.3 Cell rate adjustment

After a bonding group is successfully configured/reconfigured, the achieved aggregate rate should be reported to Connection Admission Control (CAC) for connection management. During a bonding group's normal operation, the achieved aggregate rate may change due to temporary link failure/recovery. Bonding entities should report any rate change via standard interface signals. Since treatment of CAC and message passing mechanism is implementation dependent, traffic management handling necessitated by rate change is left to the discretion of implementers.

[14] Bonding MIB elements may be transported to CPE through an ATM path to enable CPE-based multi-line optimization.

11.4 MIB elements

11.4.1 Group provisioning

1) *Group ID*

   An ID to uniquely identify a bonding group.

2) *Line number*

   An ID number to uniquely identify a DSL line.

3) *Bearer number*

   A bearer number as defined in ITU-T Rec. G.994.1. Combination of line number and bearer number identifies a link to bond.

4) *Maximum aggregate data rate (bit/s)*

   The maximum net data rate a bonding group is allowed to achieve to carry an ATM stream. Links shall not be disabled to satisfy this parameter. Otherwise, implementation of this functionality is outside the scope of this Recommendation. If set to 'infinity', this parameter is ignored. Different elements for upstream and downstream.

5) *Minimum aggregate data rate (bit/s)*

   The minimum net data rate a bonding group should achieve to carry an ATM stream. Different elements for upstream and downstream.

6) *Differential delay tolerance (ms)*

   The maximum differential delay among member links in a bonding group. Different elements for upstream and downstream.

11.4.2 Group performance

1) *Achieved aggregate data rate (bit/s)*

   The net data rate a bonding group actually achieves. It may change subject to dynamic link usage conditions. Different elements for upstream and downstream.

2) *Group status*

   Two group statuses are defined, namely operational and unavailable. A group is considered unavailable when it does not satisfy the parameters provisioned for the group.

3) *Group running time*

   The accumulated time when a bonding group is in normal operation (the status is operational). Derived from group status.

4) *Group Rx cell loss count*

   The total number of cells that are lost at aggregation output from a bonding group for the accumulation interval. Different elements for upstream and downstream.

11.4.3 Group failures

1) *Current group failure reason*

   Indicating the reason for current group failure status: Minimum data rate not met, differential delay tolerance exceeded. Implementations with other failure mechanisms can return a value of Other.

2) *Group failure count*

   Count the number of times that a group is declared unavailable in the accumulation period.

3) *Group unavailable seconds*

   The time in seconds during which a bonding group is unavailable in the accumulation period.

Appendix I

Optional initialization procedure facilitating spectral optimization

Successful bonding group setup relies on careful planning and provisioning across all levels in an access system. The DSL Recommendations series (G.99x) provides sufficient procedures for an NMS to enable an ATM bonding group. The general process is outlined below[15]:

1) Based on application requirements, derive the aggregate rate and delay variance tolerance requirement.

2) Select the lines to be bonded and obtain each line's DS and US rate capacities and delay information. If necessary, pre-train the candidate lines through the standard full initialization procedures, shortened/fast initialization procedures, or loop diagnostic procedures.

3) Process, in the NMS, the above information and develop provisioning profiles for the candidate DSL transceivers. Each provisioning profile would contain all of the necessary US/DS configuration parameters defined in ITU-T Rec. G.997.1. Among these, the min/max net data rate, minimum impulse protection[16] and min/max delay[17] parameters, if applicable, should be tuned to collectively reflect the bonding group's aggregate rate and delay variance tolerance requirements.

4) The provisioning profiles are passed to xTU-Cs. The bonding-tuned DSL configuration parameters are exchanged between xTU-Cs and xTU-Rs through the G.994.1 handshake procedure so that the DSL transceivers can be initialized in such a way as to support the bonding group's aggregate rate and delay variance requirements.[18]

5) After the lines are up and running, the NMS issues a bonding configuration command to NE bonding entity to begin bonding initialization procedure.

6) If bonding initialization is successful, the bonding ME signals the system with a Group Operation Status update to be ready for ATM connections. If unsuccessful, repeat steps 1-5 with appropriate DSL configuration adjustments.

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[15] This guideline is for information only, not a normative part of the Recommendation. In general, a bonding group can always be setup on already trained-up lines without any change if the resulting aggregate rate and delay variance happen to be acceptable.

[16] ITU-T Rec. G.992.3 recommends that Minimum Impulse Protection value can overrule max delay constraint when they are in conflict.

[17] ITU-T Rec. G.997.1 currently does not include MIB element for min delay. It needs to be defined.

[18] Optionally, bonding-tuned configuration parameters can also be passed to FE bonding entity through bonding OAM channel so that receiver-based multi-line joint bonding optimization can be applied to achieve better rate/power efficiency through some DSL line double-train procedure. The procedure is vendor dependent and is up to implementer's discretion.

Appendix II

Sample initialization for the ATM bonding protocol

As an example of an initialization procedure, assume:

- Two lines (L1, L2), each of which is trained up with two bearers (B0, B1) both upstream and downstream.
- A bonding group is provisioned as: {DS: L1B0 L2B0; US: L1B0 L2B0}

A second bonding group could be provisioned as {DS: L1B1 L2B1; US: L1B1 L2B1}: This has no real bearing on the rest, as the second group is independent of the first group.

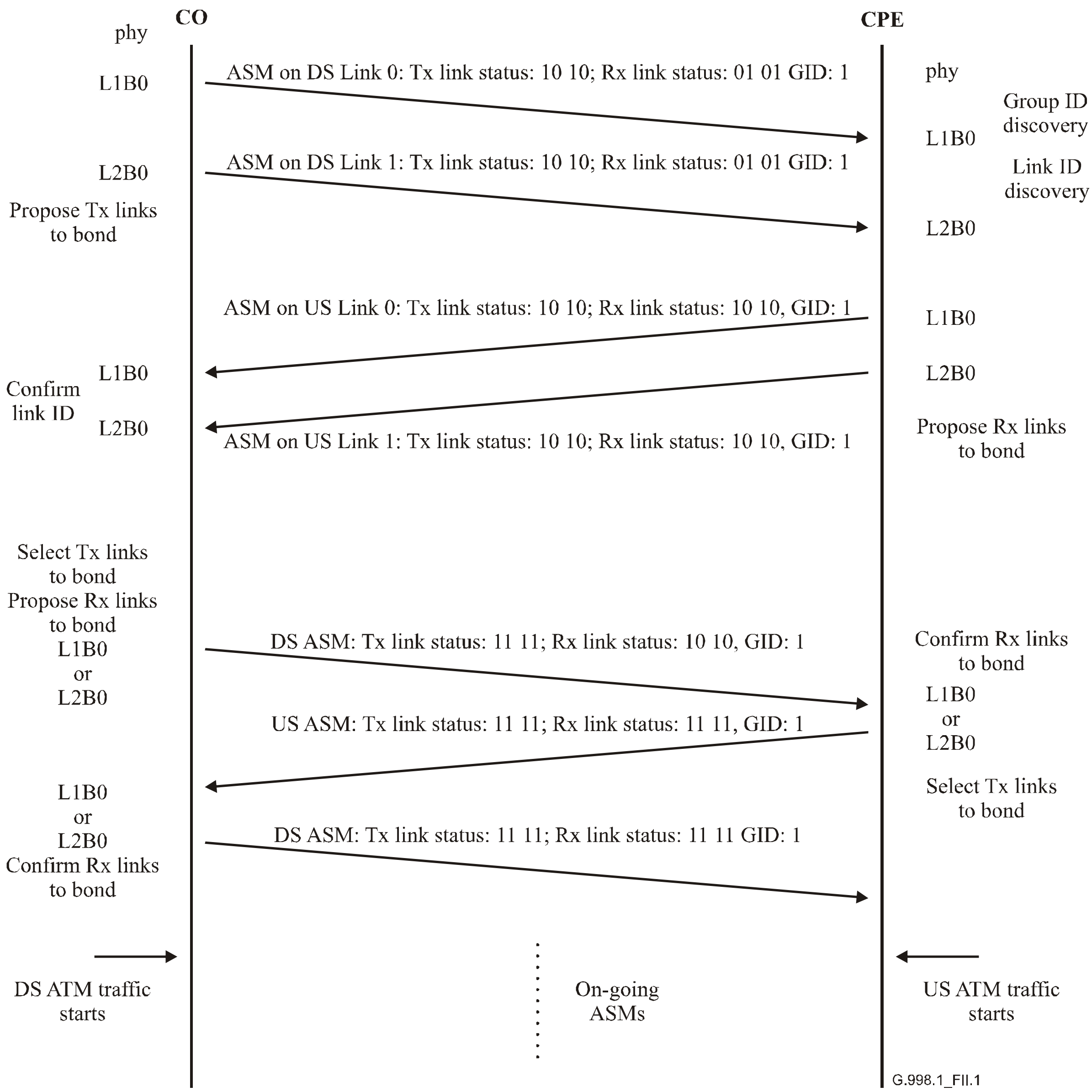


Figure II.1/G.998.1 – Example ASM flow during initialization

Notes on the timing diagram in Figure II.1:

The process starts with the CO sending an ASM message on each link in the bonded group. This message has Tx link status set to '10' or '01' for each member of the group, and has the group ID, cell header format, and the link number set to the group, cell header format, and link selected. The Rx link status is set to '01' (or '00' if the link is not provisioned) for each link at this point.

1) After the first error-free downstream ASM message is received at the CPE, the CPE knows the group ID, the cell header format, the physical line/bearer the message arrived on, the number of bearers in the proposed group as well as the bearer for the upstream for that link in that group. It does not know what physical line/bearer the other links in the group will map to, so it cannot decide on the proposed Rx link status for those links yet.

2) After the CPE has discovered all the link mappings, it sends a proposed set of links for bonding in the downstream direction by setting Rx link status to '10'. This set is the same or a subset of the links with received Tx link status set to '10'. It is normally the same set unless the CPE wants to exclude one of the links from the group for some reason.

3) This ASM message is sent on all the links with the proper link number. This confirms the link mappings and conveys the proposed Rx links for bonding in the downstream direction. At this point there is a complete map of links to physical line/bearers at both the CO and the CPE.

4) At this point, the CO selects the set of lines it wants to bond on the downstream from the proposed Rx set from the CPE by setting the Tx link status to '11' for those links. At the same time, it sends a proposed set of upstream Rx links suitable for bonding (Rx link status to '10'), which is the same or a subset of the links with received Tx link status of '10'.

5) The CPE confirms the downstream bonding group selection by sending an ASM message with the Rx link status set to '11' and also selects the upstream links it wants to bond by setting the Tx link status to '11'.

6) If the received Rx link status at the CO is set to '11' on all the links in a group and the CO previously sent Tx link status of '11' on those links, the bonding group in the downstream direction is confirmed and downstream traffic can be initiated on all the bonded links. In the case of a mismatch in these status fields, the bonding group in the downstream direction may still be confirmed subject to constraints on the aggregate downstream rate as no traffic will flow on the link where Tx link status is '11' and Rx link status is not '11' as per 6.4. In this case, the number of links carrying downstream bonded traffic will be less than provisioned, similar to the case where a link is removed from the set carrying bonded traffic during showtime.

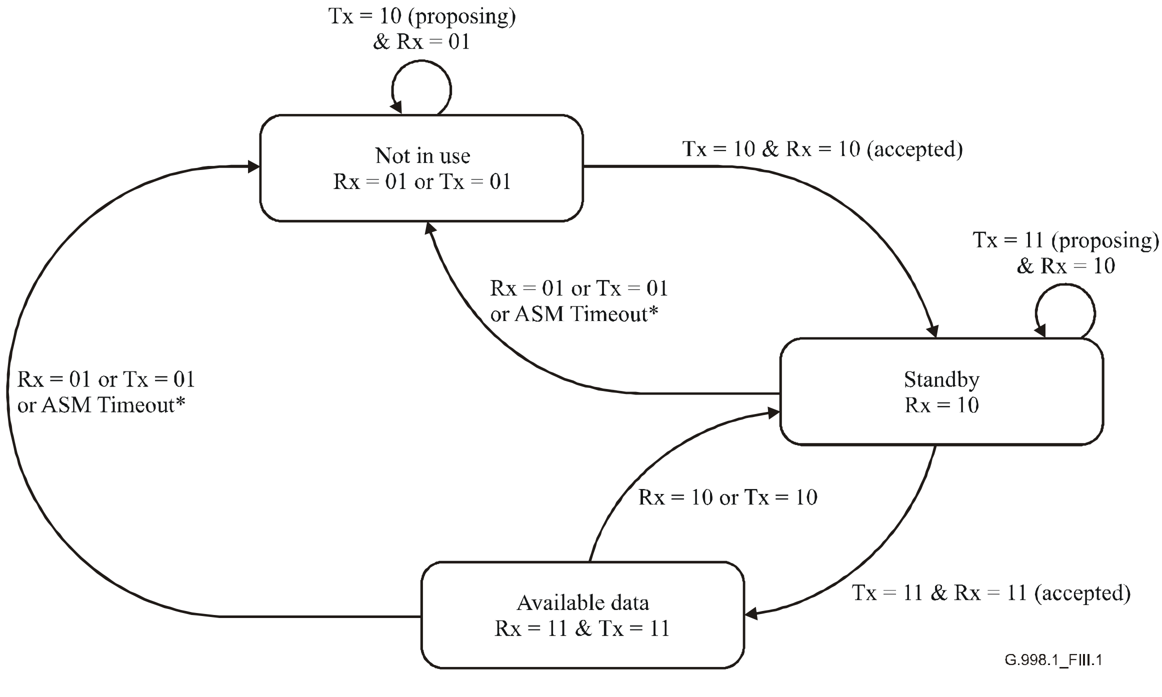
7) At this point the CO also confirms the upstream bonding group selection by sending an ASM message with the Rx link status set to '11'.

8) If the Rx link status and previously sent Tx link status match at the CPE, the bonding group in the upstream direction is confirmed and upstream traffic can be initiated. In the case of a mismatch in these status fields, the bonding group in the upstream direction may still be confirmed subject to constraints on the upstream aggregate rate as no traffic will flow on the link where Tx link status is '11' and Rx link status is not '11' as per 6.4. In this case, the number of links carrying upstream bonded traffic will be less than provisioned, similar to the case where a link is removed from the set carrying bonded traffic during showtime.

Appendix III

Link status state machine

Figure III.1 shows the transition behaviour of a provisioned link. The necessary conditions to allow transition from one link state to the next state based on Tx and Rx status are provided. Regarding the transmitter, when both Tx link status and Rx link status are '11' and the transmitter receives anything for the Rx link status except '11', the transmitter stops forwarding bonded traffic on that link. In all other cases, reception of these Rx link status signals is not sufficient to force a state transition as state transitions are at the discretion of the local end. The near-end transmitter or receiver can transition to a lower Tx or Rx status autonomously. Table III.1 provides additional information on the non-defined status combinations of the link. The only condition in which bonded data is being delivered on a loop is when Tx=11 and Rx=11. Although the condition Tx=00 and Rx=00 is not in Table III.1 and is therefore allowed, it is not shown in the link state diagram because it represents a non-provisioned link, i.e. links not in the group.



Note that moving to higher link state requires Tx & Rx conditions while moving to lower link state requies Tx or Rx conditions.
* While ASM Timeout is not explicitly defined in this Recommendation, this example state machine implementation shows how an ASM Timeout may be used to transition states.

Figure III.1/G.998.1 – Link status state machine diagram

Table III.1/G.998.1 – Non-defined link status

Tx	Rx	Reason not defined
00	not '00'	Not allowed. An unprovisioned link will always be unprovisioned. Rx and Tx match if unprovisioned.
not '00'	00	
01	10	Rx cannot consider link for bonding if not proposed by Tx.
01	11	Rx cannot have 'Selected' status unless Tx has 'Selected' status.
10	11	Rx cannot have 'Selected' status unless Tx has 'Selected' status.
11	01	Tx cannot have 'Selected' status unless confirmed by Rx.

Appendix IV

Example of algorithm to derive the end-to-end delay

The receiving bonding application will choose one of the bonded links as the reference link.

Assume link 0 is the reference link.

The computation of the differential delay without compensation can be computed as follows:

1) Compute a propagation delay without compensation.
2) Compute the differential delay without compensation.
3) Compute the average differential delay without compensation.

Since the final goal is to evaluate the differential delay, the propagation delay without compensation for link I is computed as follows:

$$Pd(I,t) = timestamp(K(I,t)) - arrival(K(I,t)) - appliedDelay(K(I,t))$$

where:

Pd(I,t)	is the propagation delay without compensation on link *I* at time *t*
K(I,t)	is the index of the last ASM cell received on link *I* at time *t*
timestamp(k)	is the timestamp placed in the ASM with index *k*
arrival(k)	is the value of the local time when ASM with index *k* has been received
appliedDelay(k)	is the value of the *appliedDelay* field in the ASM with index *k*

About every second, instantaneous differential delay without compensation is computed:

$$Idd(I,t) = Pd(I,t) - Pd(0,t)$$

where:

Idd(I,t)	is the instant differential delay without compensation for link *I* at time *t*. The differential delay is computed with link 0 as the reference
Pd(I,t)	is computed as explained above

The average differential delay without compensation can be computed as the average instant differential delay without compensation computed over the *n* last seconds. The purpose of this average is to remove the jitter part of the delay. The compensation is not included in order to have an average independent of the different extra delays applied on each line. The differential delay of line *I* after compensation between lines is equal to:

$$diffDelay(I,t) = \overline{Idd}(I) + appliedDelay(I,t) - appliedDelay(0,t)$$

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