



Flexible Bandwidth Services with DSL Bonding

Technology White Paper

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Issue 1: August, 2002

PMC-2021395

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Abstract

This paper reviews the service requirements and topologies for bonded DSL. It describes DSL bonding techniques and compares the common approaches for various DSL technologies. Of these approaches, IMA (Inverse Multiplexing for ATM) has wide applicability to DSL technologies, builds upon the most commonly deployed layer 2 access technique- ATM, and provides an immediate solution to service providers' and customers' requirements. In particular, IMA-over-SHDSL is gaining wide traction with DSLAM vendors and service providers as a flexible, available solution to business customer requirements and to transport problems for subtended DSLAMs.

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Revision History

Issue No.	Issue Date	Details of Change
1	August, 2002	Document created.

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1 Introduction

Demand for broadband services continues to expand while economic forces constrain the deployment of last-mile fiber solutions. Squeezing bandwidth from existing copper facilities remains an important objective for service providers. Copper-based service offerings in the access space include traditional leased line services over T1/E1, as well as a variety of data access services provided over Digital Subscriber Line (DSL). However, customers who require bandwidths greater than those provided by T1/E1 or DSL must choose from limited options. This paper describes one solution – DSL bonding - that allows service providers to deliver an economical upgrade path for customers in need of greater bandwidth. It also describes the use of DSL bonding as a transport technology in support of the broadband rollout.

Compared to traditional T1 and E1 circuits, Digital Subscriber Lines (DSLs) have several advantages for service providers and for customers. Both symmetric and asymmetric DSLs provide attractive rate/reach profiles compared with T1/E1. DSLs provide flexible framing structures, including ATM, TDM and packet framing, and flexible rates that can exceed those of T1/E1. However, DSL bandwidths at extended-reach distances do not approach the T3/E3 range.

Customers are left with few alternatives in the “bandwidth gap” between T1/E1 or DSL and T3/E3. In this range, a service provider can offer $n \times$ T1/E1, $n \times$ DSL, or can provision a T3 facility over fiber or coaxial cable. The cost for a T3 is very high, and unless the facility will be fully utilized a T3 is not an attractive option for most customers. Today’s most cost effective technology is often $n \times$ DSL. Bonding of these DSL lines – the aggregation of several DSL lines together to form a single logical link of higher combined bandwidth – is ideal for traffic aggregation and service management.

2 Bonded DSL Service Requirements

DSL Bonding can potentially be applied wherever DSL services are deployed, including:

- High-speed transport services
- Business access services
- Residential/SOHO services

The following sub-sections explain how DSL Bonding further enhances these applications, and provide a summary of applicable DSL technologies in each case.

2.1 High-Speed Transport Services

2.1.1 Service Description

In cases where existing fiber is not available, service providers utilize DSL as an access trunk technology to support backhaul of traffic from subtended DSLAMs or other remote network elements. For these applications, symmetrical DSLs such as SHDSL provide a more cost-effective alternative to traditional T1/E1 technology because of their much better transmission rate/reach characteristics.

2.1.2 DSL Bonding Applicability

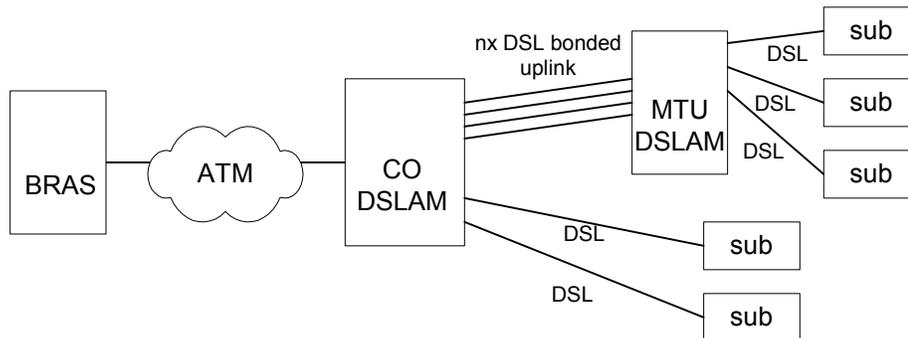
For network backhaul of ATM-based or packet-based traffic, such as is used in DSLAMs, next-generation Digital Loop Carriers (DLCs) and 3G wireless base stations, bonding of a number of DSL lines allows traffic to be aggregated over a single “virtual” link. The statistical multiplexing inherent in this aggregated connection provides much greater efficiency than that which could be achieved over multiple separate links. An example in Figure 1 shows a subtended DSLAM, deployed close to subscribers in a Multi Tenant Unit (MTU) building, backhauled to a Central-Office-based DSLAM using a bonded DSL uplink.

2.1.3 Applicable DSLs

Typically, symmetrical DSLs (often SHDSL), are used for backhaul and uplink services. Because of its symmetry, flexible framing structures, and coverage of the common DS1/E1 access rates, SHDSL, and bonded SHDSL, is particularly well suited to deployment for high-speed transport.

However, bonded ADSL or VDSL has a strong potential appeal to provide the uplink in the case of a subtended residential DSLAM that is providing ADSL or VDSL service. In this case, a bonded ADSL- or VDSL-based uplink would have aggregate uplink and downlink rates that match the traffic characteristics of the ADSL or VDSL subscribers served from the subtended DSLAM.

Figure 1 DSL Bonded Uplink for Subtended DSLAM



2.2 Business Services

2.2.1 Service Description

Business services to medium-to-large enterprise customers require data rates that span the range from DS1 to DS3 (1.544 Mbit/s – 44.736 Mbit/s) in 24-channel networks or from E1 to E3 (2.048 Mbit/s - 34.368 Mbit/s) in 32-channel networks. Service delivery can be using traditional TDM access methods or using Frame Relay (FR), ATM or IP networking technologies. Examples of business service applications include leased line replacement, corporate private networking, Internet access, and Voice/Data Integration.

2.2.2 DSL Bonding Applicability

A major driver for DSL Bonding services is allowing medium-to-large enterprise customers to grow their bandwidth flexibly and incrementally beyond that provided over a single DSL line. Consider the upgrade options available to an enterprise currently served by T1/E1 provided over a single DSL. First, the enterprise could upgrade to a single T3/E3 connection, typically provided over fiber. This option involves lengthy installation delays and high installation costs; worse, the monthly investment would not be justified, as much of the T3/E3 bandwidth would be unused. A second solution might be two separate DSL lines; although the installation costs and speed would be more attractive, this option would not provide the enterprise an integrated and managed service over a single interface. An alternative and better solution, DSL Bonding allows two or more DSL lines to be aggregated to provide a single interface whose bandwidth can be appropriately scaled to serve present and future needs, while still leveraging the simplicity and low cost of DSL installation.

2.2.3 Applicable DSLs

Symmetrical DSLs (SHDSL and SDSL), and in some cases ADSL or VDSL can be used for business access services.

SHDSL is well suited to business access services for the reasons cited in Section 2.1.3. As SHDSL services and platforms roll out worldwide, bonded SHDSL will be a natural candidate for business access services requiring more than 2.3 Mbit/s.

Bonded ADSL may also be useful in the business context. Many small businesses currently have Internet connections served by ADSL. As usage of the Internet connection increases, or where

new services like VoDSL are added to a business's service portfolio, increasing the ADSL bandwidth through bonding may have strong appeal.

2.3 Residential/SOHO Services

2.3.1 Service Description

ADSL is the most common DSL technology available to Residential/SOHO customers. The primary application is high-speed Internet access, with available data rates that depend upon constraints of the local network.

Many service providers are also exploring the delivery of video services over DSL. The FS-VDSL standards organization has published a recommendation on video distribution over VDSL; this group believes that video distribution services are the anchor application for a full services delivery model that also includes Internet access, voice and other services. Others plan to offer video services over ADSL. In general, these "next wave" residential broadband services are suited to shorter-reach DSL deployments, such as apartment buildings served from the basement, or neighborhoods served from the curbside, as the high bandwidths required restrict the available range of ADSL, VDSL and other DSL techniques.

2.3.2 DSL Bonding Applicability

Although residential customers using ADSL for internet access typically do not require bandwidth greater than that available via single pair, DSL bonding provides operators with an alternative deployment scenario for high-bandwidth services to customers located at the extremes of DSL reach from the Central Office (CO). These customers may be serviced by deploying regenerators in the network to extend the reach and/or bandwidth of the DSL line. However, by bonding a number of lower-speed DSL lines the operator may meet the customer's service requirements without the need to deploy out-stationed equipment in the loop plant with its associated operational costs.

For "next-wave applications", video distribution could also benefit from DSL bonding. Once again, the service rate/reach equation can be favorably shifted through the use of bonded pairs to address outlying subscribers. Furthermore, the use of bonded ADSL has the potential to offer immediate services in cases where VDSL may not yet be available.

DSL bonding for residential applications requires that sufficient copper pairs be available to provision a second DSL line. While this is not always the case, an ADSL rollout can have the effect of freeing up such pairs. Heavy users of dial-up Internet service often subscribe to a second line. As such subscribers make the transition to ADSL, which typically provides both voice and data on their primary phone lines, these secondary residential line pairs are being freed up. The redeployment of these lines for revenue generating services like bonded DSL may be attractive to service providers wishing to retain some of the revenue these lines were generating before their ADSL deployment.

2.3.3 Applicable DSLs

Suitable DSLs for bonding in the residential and video applications include both ADSL and VDSL.

3 DSL Bonding Techniques

DSL Bonding can be implemented using several standards-based techniques. The following three techniques will be discussed in some detail because of the benefits they can offer current access networks.

- PHY Layer bonding [1]. PHY (or Physical) Layer bonding involves grouping the raw physical transport data rates of a number of DSL lines together such that it provides a single higher bandwidth connection. PHY Layer bonding has the advantage of protocol transparency. However, it is relatively inflexible in terms of how individual lines may be grouped. SHDSL is the only DSL technology that provides PHY Layer bonding as a standardized function. SHDSL currently limits bonding to a maximum of 2-pairs but there is ongoing standards activity to increase this beyond the 2-pair limit.
- Inverse Multiplexing for ATM (IMA) [2]. IMA adds an intermediate protocol layer between the PHY and ATM layers that is implemented at the Customer Located Equipment (CLE) and within the service provider's Access Node. Using this intermediate protocol layer, IMA may group up to 32 individual DSL lines together to form a single, aggregated ATM transport link. Although IMA introduces some small operational overhead, the IMA sublayer is transparent to the ATM layer above the TC sublayer, and to other higher protocol layers.
- Multilink PPP (ML-PPP) [3]. ML-PPP can be used to group multiple PPP links into a single virtual bundle. In many implementations, PPP already forms part of the IP-over-DSL stack. Therefore, ML-PPP is another candidate technique for providing an aggregated transport link. Like IMA, ML-PPP bonding must be implemented at the CLE. However, there are a number of points within the operator's network where ML-PPP can be implemented; for example at the service aggregation point within the Access Node, or in an associated LAC (L2TP Access Concentrator), RAS (Remote Access Server), or SMS (Subscriber Management System). In cases where the ISP and DSL service provider are separate, ML-PPP could be implemented by either entity.

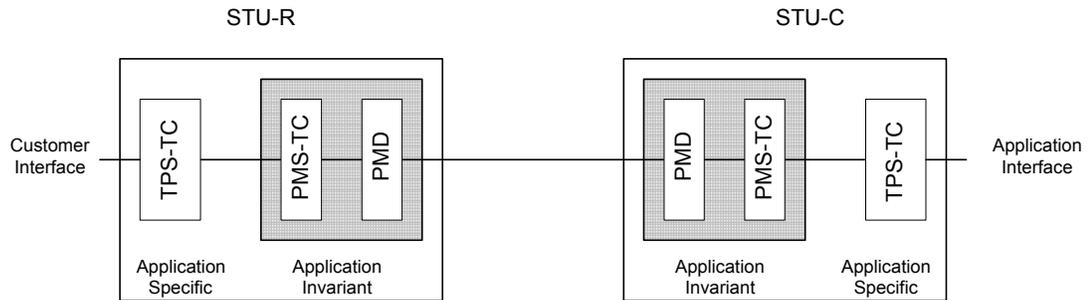
The following sections describe these three DSL bonding techniques in more detail.

3.1 PHY Layer Bonding for G.SHDSL

PHY Layer bonding, or 4-wire mode, is defined for SHDSL in the G.991.2 standard [1].

Figure 2 shows a simplified functional model of the SHDSL transceiver (modem) without PHY-layer bonding. As shown in the figure, the Transmission Protocol-Specific Transmission Convergence (TPS-TC) layer performs the mapping of application specific user data to and from the generic SHDSL transport frame structure. Types of user data supported include fractional and full rate T1 and E1, unaligned T1 and E1, ATM, and clear channel data. The application invariant layers below the TPS-TC generate the basic transport frames and transmit them as a bit stream over the DSL link.

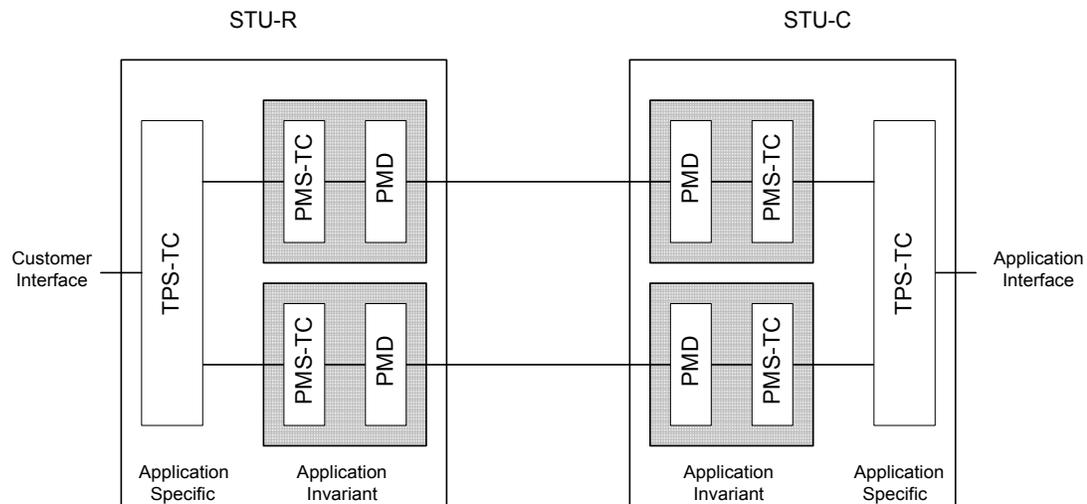
Figure 2 SHDSL STU functional transceiver (single pair SHDSL)



Acronyms
 STU-R SHDSL Transceiver Unit at the Remote End
 STU-C SHDSL Transceiver Unit at the Central Office
 TPS-TC Transmission Protocol-specific Transmission Convergence (TC) Layer
 PMS-TC Physical Medium Specific TC Layer
 PMD Physical Media Dependent

In the case of PHY Layer bonding, a special TPS-TC layer frames data into the payload structures of two SHDSL lines. This is shown in Figure 3. The standard supports the PHY bonding of most of the application specific data types, with the exception of unaligned T1 and E1. In the case of ATM, a dual-pair PHY bonded solution would provide a single ATM link with maximum aggregate rate of 4.608 Mbit/s.

Figure 3 SHDSL STU functional transceiver (PHY-bonded dual-pair)



3.2 ATM Layer Bonding (IMA)

Inverse Multiplexing for ATM (IMA) is fully specified in the ATM Forum standard AF-PHY-0086.001 [2]. IMA is applicable to any ATM UNI/NNI including the DSL loop in cases where ATM framing is used over DSL.

IMA introduces a common multiplexing sublayer between the ATM layer and the individual ATM transmission convergence sublayers of physical links being grouped. In the transmit direction, the IMA sublayer allocates ATM layer cells among the links of an IMA group in round-robin fashion. In the receive direction, the IMA sublayer recombines cells received on the links within an IMA group into a single cell stream, and delivers that stream to the ATM layer. To handle synchronization, a framing structure is introduced in which IMA Control Protocol cells are transmitted periodically on each link rather than payload cells. Thus the use of IMA introduces a very small bandwidth overhead.

Figure 4 and Figure 5 show two possible IMA-over-SHDSL configurations. Although illustrated for SHDSL, the same configurations are equally applicable to other DSL technologies. In both configurations, an IMA sublayer implementation is shown which spans n SHDSL transceivers, where $1 \leq n \leq 32$. In Figure 4 (Configuration #1), the ATM Transmission Convergence (TC) sublayer is internal to the DSL transceiver and the TC sublayer interfaces to the IMA sublayer via a UTOPIA interface. In Figure 5 (Configuration #2), the ATM TC sublayer is grouped together with the IMA sublayer, and the TC sublayer interfaces to the transceiver via a standard TDM interface.

Although the figures show the same configuration used at both remote and central office equipment, this is not required.

The sub-sections that follow review some of the IMA-over-DSL technical parameters, and describe the differences between Configurations #1 and #2.

Figure 4 IMA-over-SHDSL (Configuration #1)

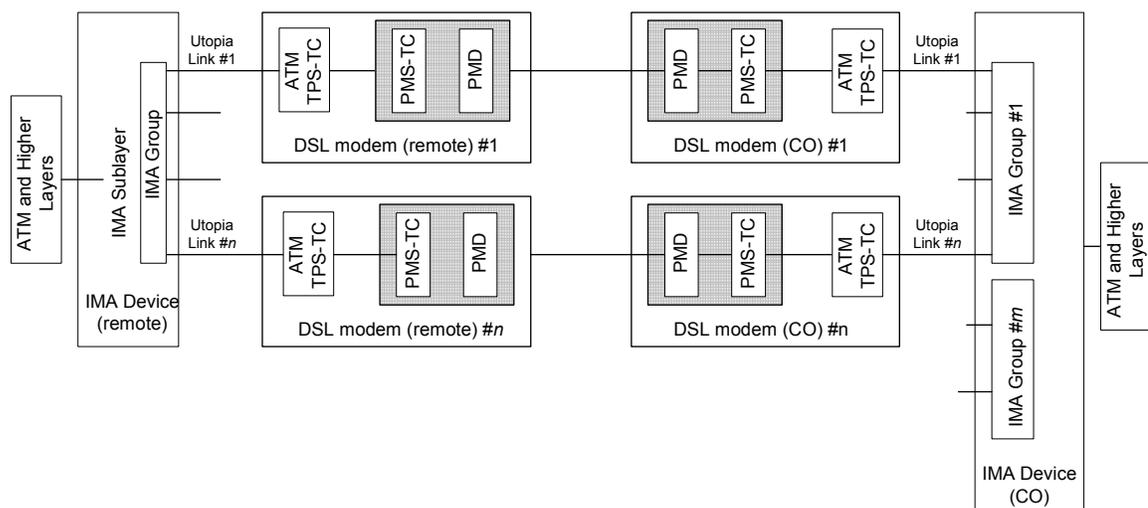
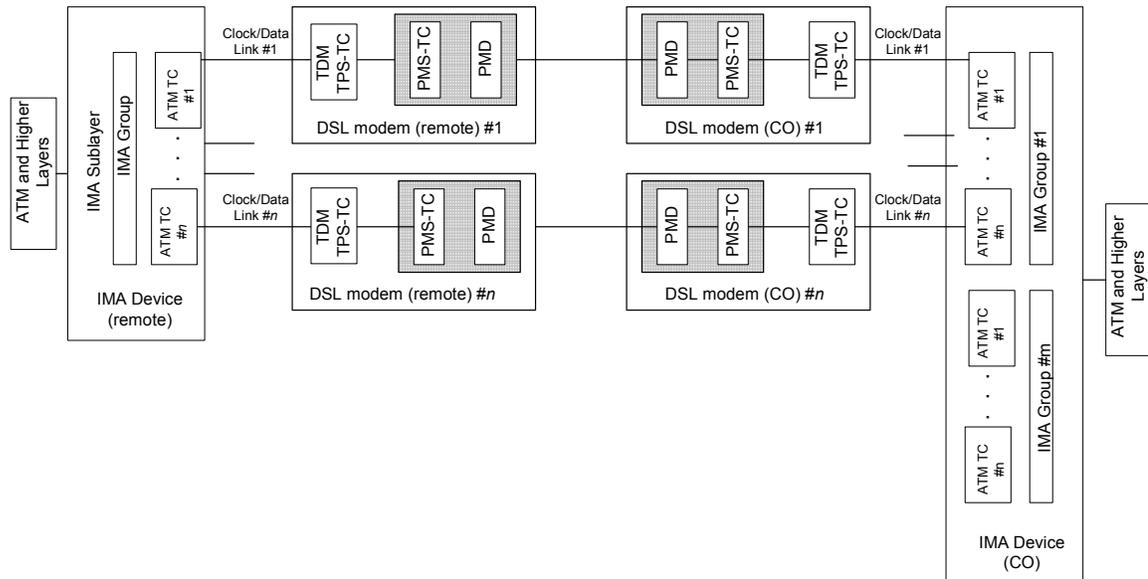


Figure 5 IMA-over-SHDSL (Configuration #2)



3.2.1 Number of links per IMA group

The IMA standard supports between 1 and 32 links per group (normally, DSL bonding would be applied to smaller numbers of links that to 32). Examples of aggregate and net rates for IMA link group spanning this range are shown in Table 1 for SHDSL and ADSL.

Table 1 Examples of IMA/DSL Link Groupings

Links per group	SHDSL (ATM TC mode)		ADSL	
	Gross aggregate bit rate (Mbit/s)	Net aggregate bit rate after IMA overhead assuming IMA frame size M=128 (Mbit/s)	Gross aggregate bit rate for downlink/ uplink (Mbit/s)	Net aggregate bit rate after IMA overhead assuming IMA frame size M=128 for downlink/ uplink (Mbit/s)
$n = 1$	2.304	2.304	6.144/ 0.640	6.144/ 0.640
$n = 2$	4.608	4.570	12.288/ 1.280	12.186/ 1.269
$n = 5$	11.520	11.424	30.72/ 3.200	30.465/ 3.173
$n = 8$	18.432	18.279	49.152/ 5.120	48.744/ 5.078
$n = 16$	36.864	36.558	98.304/ 10.240	97.488/ 10.155
$n = 20$	46.080	45.698	122.88/ 12.800	121.860/ 12.694
$n = 32$	73.728	73.116	196.608/ 20.480	194.977/ 20.310

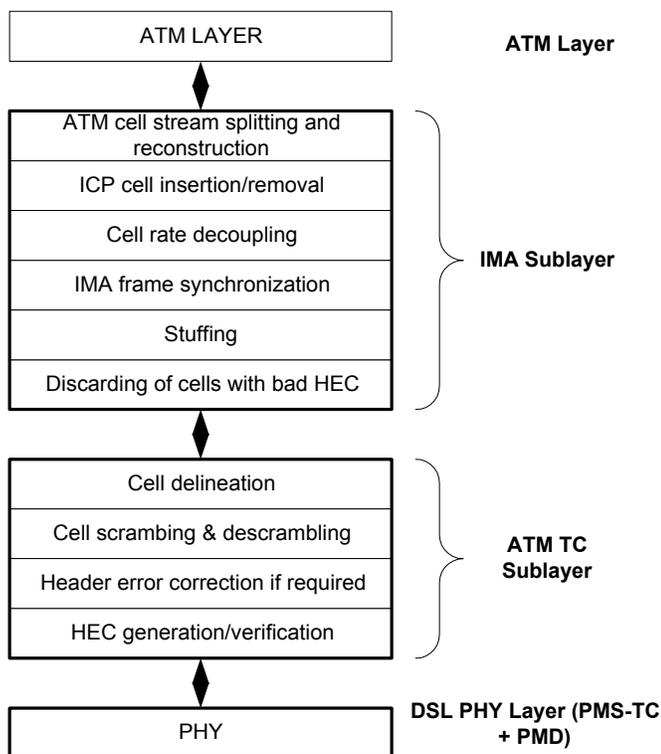
As an example, consider provision of DS3 service (44.736 Mbit/s). Such a service could be fully emulated with an IMA group formed of 20 SHDSL lines. Another example is emulation of a 10Mbit/s ethernet link; in this case an IMA group of 5 SHDSL lines provides sufficient bandwidth.

3.2.2 Interaction of SHDSL Framing Modes and IMA layer

This section looks at interactions between the IMA sublayer and the various framing modes of SHDSL. SHDSL supports both ATM and TDM framing modes; both can be used in IMA-over-SHDSL applications.

In the following discussion, it will be helpful to refer to Figure 6, showing a protocol stack view of IMA over DSL. As can be seen, the IMA sublayer sits between the ATM layer and the ATM TC layer. This section discusses the two configurations for the location of the IMA and ATM TC sublayers and the corresponding use of the SHDSL framing modes.

Figure 6 ATM/IMA/DSL protocol stack



Configuration #1

Many DSL transceivers already include ATM TC functionality. For transceivers with internal ATM TC functions, the IMA sublayer can be implemented externally as shown in Configuration #1 (Figure 4). Communication between the transceiver ATM TC layer and the external IMA sublayer is typically via a shared ATM cell interface such as Utopia L2. Configuration #1 allows for flexible combinations of IMA groups across SHDSL links within the Access Node.

However, use of a shared cell interface in Configuration #1 introduces several complications in IMA-over-SHDSL system design:

- When IMA is used, the ATM TC layer must not implement cell rate decoupling. As can be seen in Figure 6, cell rate decoupling (insertion of IDLE cells) in the downlink direction is managed by the IMA sublayer rather than the ATM TC layer. In practice, the IMA implementation must prevent cell underflow down to the ATM TC layer so that the ATM TC layer will not be forced to insert IDLE cells. This requires a low-delay-jitter cell interface between these two layers and may require additional cell buffering within the transceiver than would otherwise be necessary.
- The ATM TC layer in the uplink direction must be configurable to not discard cells containing HEC checksum errors or an indication must be provided to the IMA sublayer that a cell with a HEC error was discarded.
- For applications using IMA-over-SHDSL in ITC mode, delay jitter on the cell interface between the IMA and TC sublayers may increase the required cell buffering for the IMA implementation and may reduce the ability of the IMA protocol to track and correct for timing differences between the TRL (Timing Reference Links) and other links. These issues will not impact those applications using CTC mode for IMA-over-SHDSL.

Configuration #2

Configuration #2 (Figure 5) of IMA-over-SHDSL also makes use of external IMA processing separate from the transceiver functions but groups the ATM TC sublayer with the IMA processing. Configuration #2 allows for flexible combinations of IMA groups across SHDSL links within the Access Node while alleviating the system design complications associated with Configuration #1.

In addition, Configuration #2 has the ability to directly support IMA over DS1, E1, and other commonly deployed PHY technologies.

In Configuration #2, the interface between the transceivers and the IMA function is typically a point-point “clock and data” serial interface.

3.2.3 IMA Link Differential Delay Compensation

IMA requires the ability to equalize delay among the links within a group. A minimum capability of 25 ms of link delay compensation for IMA over DS1/E1 links is specified in [2]. For IMA over DSL, link delays differentials are likely to be much smaller than this value. Reducing link delay compensation requirements to a lower value for DSL decreases the complexity and cost of implementation.

3.2.4 IMA Transmit clock mode

IMA supports both Common Transmit Clock (CTC) and Independent Transmit Clock (ITC) modes. While CTC requires that the payload clocks of all links within the IMA group be clocked from the same clock source, ITC allows payload clocks across the links to be clocked from independent sources.

Clocking schemes within the Access Node typically distribute central office clocks to all DSL transceivers within the Access Node. Also, transceivers at the remote termination are typically loop timed. These arrangements suggest that CTC mode will be typically used for IMA over DSL applications.

3.2.5 IMA Group Symmetry modes

IMA group symmetry options as defined in Section 5.2.2.7 of [2] are shown in Table 2. Several asymmetric operation modes, in which fewer links are used in one direction than the other, are defined for IMA, but these modes are not typically used with DSL service.

Table 2 Group Symmetry Modes in IMA/DSL

Mode	Description	Requirement in IMA over DSL context
Symmetrical Configuration and Operation	IMA is configured in each direction for all physical links	This mode will typically be used.
Symmetrical Configuration and Asymmetrical Operation	IMA is configured in each direction for all physical links, but may be inactive on some links	Not typically used.
Asymmetrical Configuration and Operation	IMA is configured independently in each direction for all physical links.	

3.2.6 Independent Uplink/Downlink Rates with IMA

The IMA specification [2] does not preclude operation of IMA with independent data rates in the uplink and downlink directions. For application of IMA-over-ADSL, independent uplink/downlink rate capability will be required. See Section 3.2.7 for further discussion of issues related to IMA-over-ADSL.

3.2.7 Operation of IMA-over-ADSL

IMA-over-ADSL is a candidate for increasing service bandwidth and/or reach to customers. The following are a number of technical issues that must be considered for IMA-over-ADSL:

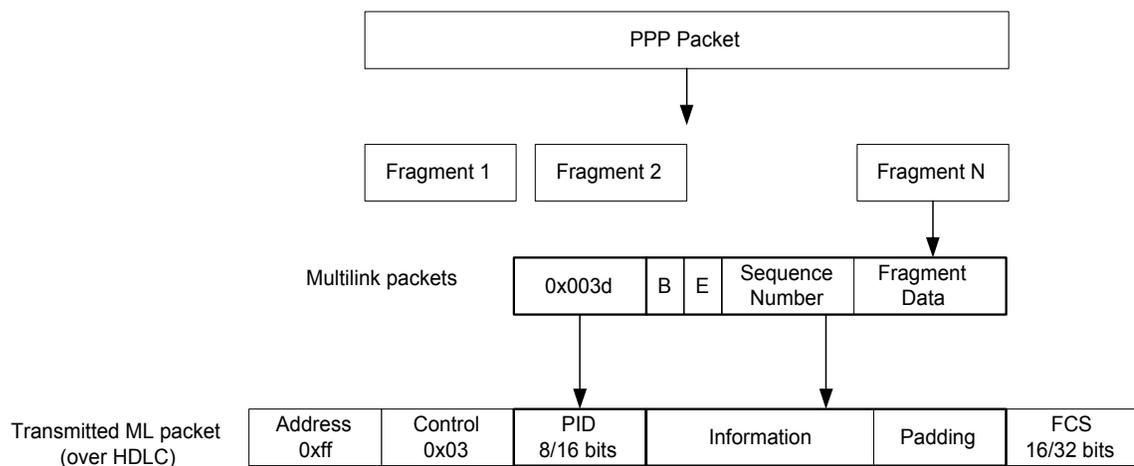
- Uplink and downlink link rates are different in ADSL. The IMA implementation must be capable of handling this difference.
- Allocation of ATM channels to ADSL fast path or interleaved path should be coordinated among the links to prevent excessive differential delay for the IMA sublayer.
- The IMA specification assumes that the different links operate at the same nominal link cell rate. However, ADSL transceivers negotiate a channel rate as a result of transceiver training, channel analysis and a capabilities exchange. Final bit rates for both uplink and downlink channels are determined by the transceiver in the central office. In order to ensure proper operation of IMA, final bit rate settings must be coordinated among all the central office transceivers within an IMA group.
- Dynamic link rate changes should be prevented for proper IMA operation.

3.3 Multilink PPP

Several DSL Forum protocol models for accessing data networks utilize the PPP protocol to carry packets over the “U” interface [5]. These protocol models are PPPoA, PPPoE, and L2TPoA. Because of the widespread use of PPP, it is interesting to consider how ML-PPP could be used for DSL Bonding.

ML-PPP as defined in RFC 1990 [3] can be used to group multiple PPP links into a single virtual bundle. In the transmit direction, ML-PPP takes a PPP packet, optionally fragments it and prepends a new ML-PPP header. Each resulting fragment (or whole packet) is transmitted across a separate physical link. At the receiver, the per-fragment headers are used to reconstruct the complete packets. This process is represented schematically in Figure 7.

Figure 7 ML-PPP Operation



3.3.1 Differences between ML-PPP and IMA

Some of the differences in the way that data is multiplexed between IMA and ML-PPP are:

- While IMA uses a fixed round-robin distribution method, the distribution of fragments to links is not standardized in ML-PPP. Therefore, the freedom to accommodate links of different bandwidth already exists in ML-PPP and ML-PPP supports dynamic link rate changes.
- Whereas IMA confines overhead information to a periodic framing structure, ML-PPP inserts additional header structures between Layer 3 and PPP on each packet fragment sent.
- Both IMA and ML-PPP include provisions for equalization of differential delay across the links. Estimation of delay differences is standardized in IMA but implementation specific in ML-PPP.

- ML-PPP fragmentation and reassembly operates on a single virtual bundle. Therefore, delays can occur to all traffic in that bundle when a single fragment is lost or delayed. IMA groups are maintained using a framing mechanism that is resilient to the loss or delay of individual cells.
- ML-PPP coexists with “normal” PPP on the same links, allowing the user to route delay sensitive traffic over a single link via PPP, bypassing the ML-PPP bundle and any associated delay in ML-PPP processing. This facility may be useful in support of interactive voice service over links with differential delay. By contrast, all ATM traffic passing through an IMA enabled set of links will be processed by the IMA sublayer. However, in typical DSL application the IMA implementation will not add unduly to delay.
- ML-PPP when implemented with multi-class extensions [4] provides additional support for traffic of different priorities or classes.
- Because ML-PPP is not restricted to a point-to-point topology, it provides the flexibility to locate the ML-PPP function in the DSLAM or at other upstream locations in the access network.

3.3.2 Application of ML-PPP over DSL

Figure 8 Potential Application of ML-PPP over DSL

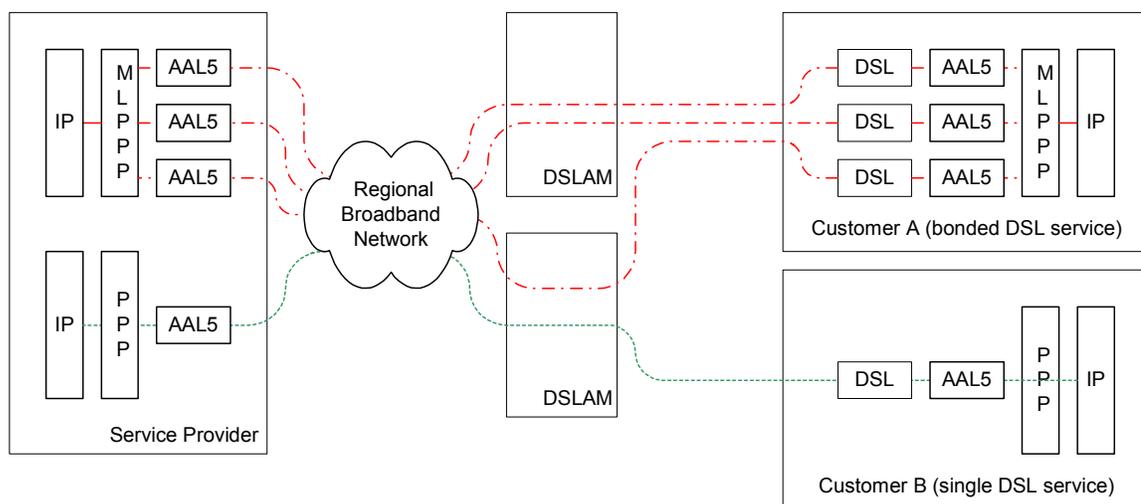


Figure 8 shows an example of ML-PPP over DSL. Customer B receives a PPP-over-ATM based service on a single DSL link, and Customer A receives service on three DSL links that are aggregated using ML-PPP. At the premises of Customer A, an Integrated Access Device combines the DSL modem and ML-PPP functions (and possibly a router function). Each of Customer A's DSL links carries ML-PPP fragments over AAL5. At the service provider's termination point, the ATM, PPP, and ML-PPP connections are shown terminated in the same network box for simplicity, but other equipment configurations are possible.

3.3.3 ML-PPP Protocol Issues

Typically, ML-PPP is used with PPP in HDLC framing. (PPP in HDLC framing, and ML-PPP could be used upstream from the DSLAM). However, on the DSL loop, the most common protocols stacks are

- PPP over AAL5 over ATM (PPPoA)
- PPP over Ethernet over AAL5 over ATM (PPPoE).

ML-PPP protocol could be applied directly to PPP packets carried over AAL5. Similarly, the ML-PPP protocol could be applied to PPP packets carried over the PPPoE, but it is not clear that PPPoE would be used in applications requiring DSL bonding.

4 Technical Comparison

4.1 Protocol Transparency

For services that are limited to 2-pair SHDSL, PHY-layer bonding is the most protocol-transparent option as it supports TDM, ATM and Packet modes directly. However, most data oriented applications over DSL already use ATM, so IMA is an evolutionary technical solution for these applications. ML-PPP is suited only to applications built over the PPP protocol; as one example residential/SOHO Internet access is commonly deployed using one of the PPP over the loop variants.

4.2 Access Node Configuration Flexibility

PHY Layer bonding for SHDSL is of very limited flexibility in the DSLAM. Only 2 pairs may be bonded, although future versions of the standard will support more than 2 pairs. In order to bond any two pairs, both pairs must be physically terminated by the same transceiver. Changes to configuration would require physical reconfiguration of the pairs through cross-connect facilities.

IMA bonding is much more flexible than PHY Layer bonding and provides the following benefits:

- For a line card, implementing IMA external to the transceiver provides greater flexibility in forming groups and supporting link additions and deletions from groups as required.
- IMA may also be implemented using a “server card” approach, where cell traffic from line cards may be flexibly aggregated at a central location within the access node. The server card approach has the advantage of allowing IMA groupings across any set of links irrespective of their individual line card locations. In the server card approach, if the interface between the line cards and server card is ATM cells then close attention must be paid to the delay jitter across the interface between server and line cards. In this sense Configuration #2 has particular advantages over Configuration #1. For a server card approach based on a clock/data interface, the individual streams may be aggregated for transport to the IMA server card using a higher speed TDM bus or using a TDM based switching fabric.

ML-PPP bonding shares the same advantage as IMA in that it provides greater flexibility for grouping links irrespective of their physical termination. Furthermore, ML-PPP allows the aggregation of links that do not pass through the same DSLAM. ML-PPP may be implemented internal to the access node or can be implemented at upstream platforms such as LAC, RAS or SMS.

4.3 Added Delay

PHY Layer bonding does not add significantly to fixed delay.

IMA implementations add slight fixed delay from the following sources:

- Transmission processing including buffering to maintain constant cell rate across IMA links;
- Receive processing including buffering to smooth out differential delay.

The total added delay is implementation specific, but is typically extremely low.

ML-PPP implementations add fixed delay from the following sources:

- Transmission processing including fragmentation across the links;
- Receive processing including buffering to smooth out differential delay across lines.

The total added delay is also implementation specific.

4.4 Different Link Bandwidths

PHY Layer bonding and IMA both require that each link within a group has the same data rate. In the case of IMA, small differences in clock rate can be accommodated through the use of ITC mode but common clocking arrangements in the Access Node suggest this capability will not typically be required.

ML-PPP does not require that links have the same bandwidth. The ability of ML-PPP to accommodate a wide range of bandwidth differences is implementation-specific.

4.5 Support of Asymmetric Uplink/Downlink Bandwidths

While no PHY layer bonding is specified for ADSL or VDSL, both IMA and ML-PPP can be implemented over ADSL and VDSL.

Nothing in the IMA specification precludes implementation of IMA over asymmetric link bandwidths. Furthermore, recent standards definition of the next generation of ADSL technology (“ADSL2”) has included text to specifically enable IMA operation.

ML-PPP is also capable of asymmetric operation over ADSL and VDSL

4.6 Implementation Complexity

While a thorough comparison of the implementation complexity of these techniques would require evaluation of vendor-specific implementations, a few general comments in this regard are made here.

PHY Layer bonding is typically implemented as an application-specific TPS-TC in a multi-PHY SHDSL transceiver. From a system point of view, the PHY-bonded SHDSL lines appear as a single transparent transmission link.

IMA is a data processing function that is readily available in off-the-shelf hardware chips that provide support for many physical lines or modems in a single device. Such chips interface directly with DSL transceivers on line cards; they can also be deployed on server cards within the Access Node.

ML-PPP for PPP in HDLC framing is also readily available in off-the-shelf hardware chips that provide support for many HDLC channels in a single device. However, direct application of ML-PPP to the DSL Forum protocol stacks (PPPoA, PPPoE, L2TPoA) may require additional software or hardware support to configure the packet formats to that particular stack.

5 Summary

DSL bonding applications are likely to be driven by both business and residential service requirements and by transport applications within the access network. The primary technical options include PHY-Layer bonding for SHDSL, IMA for SHDSL, ADSL and other ATM-based DSLs, and ML-PPP for any DSL using PPP as the link layer protocol.

From the analysis presented in this paper:

- PHY-layer bonding is protocol transparent, but it is restricted in its flexibility and is currently only standardized for 2-pair SHDSL.
- IMA-over-SHDSL is very flexible in terms of link grouping. It is well suited to meeting business service requirements and represents an evolutionary upgrade path for SHDSL operators with an installed base of ATM services and equipment. It is also a suitable solution for uplink transport of subtended DSLAMs and other access network elements.
- IMA-over-ADSL and IMA-over-VDSL may provide an alternative solution for delivery of higher rate business services, delivery of high bandwidth residential services such as video broadcast, and for service reach extension. It also may be used as a transport facility matched to the particular requirements of subtended ADSL and VDSL DSLAMs.
- ML-PPP provides a packet-based alternative to IMA. ML-PPP has advantages including flexibility of configuration and tolerance of different link speeds within a bundle.

6 References

- [1] ITU-T G.991.2, “Single-pair high-speed digital subscriber line (SHDSL) transceivers”, 2001
- [2] ATM Forum AF-PHY-0086.001, “Inverse Multiplexing for ATM (IMA) Specification Version 1.1”, March 1999
- [3] IETF RFC 1990, “The PPP Multilink Protocol (MP)”, 1996
- [4] IETF RFC 2686, “The Multi-Class Extension to Multi-Link PPP”, 1999
- [5] DSL Forum Technical Report TR-043, “Protocols at the U Interface for Accessing Data Networks using ATM/DSL”, August 2001