Technology Backgrounder

Digital Subscriber Line (DSL) Transmission Methods

1. Overview

Many DSL technologies have been developed in the recent years. Their purpose it to enable using the wide installed base of copper (twisted pair) cables laid by the telephone companies to provide the ubiquitous phone service (plain old telephone service – POTS) for high-speed digital transmission.

The two main DSL methods are SHDSL and ADSL:

- Single-pair high-speed digital subscriber line (SHDSL) technology, supports symmetrical transmission rates of up to 2.312 Mbps. SHDSL has been standardized in ITU-T Rec. G.991.2.

- Asymmetrical digital subscriber line (ADSL), supports up to 8 Mbps in the downlink direction and up to 1 Mbps in the uplink direction. The line code used by ADSL interfaces is the Discrete Multitone (DMT) code. ADSL has been standardized in ITU-T Rec. G.992.1.

The various DSL interfaces are used to provide the uplink to the ATM network, and cover ranges up to a few km over typical unloaded twisted pairs.

2. SHDSL Transmission Methods

SHDSL Transmission System Versions

SHDSL standards describe two types of transmission systems:

- 2-wire (2W) SHDSL system – uses a single unloaded twisted pair.

- 4-wire (4W) SHDSL system – uses two unloaded twisted pairs, and distributes the payload among the two pairs using the same modulation methods as the 2W system. The 4W system has longer range, because it operates at lower line rates.

This section presents only the 2W system, however the information is also applicable to 4W systems.

SHDSL Transmission Subsystem Structure

The basic SHDSL transmission subsystem includes two units interconnected by a single pair of wires, usually a regular unloaded twisted pair. The pair is used for duplex transmission.

Two different types of SHDSL units are defined by ITU-T Rec. G.991.2:

- SHDSL central unit (STU-C), usually located at the network side, at the central office (CO), which controls the operation of the whole subsystem, supervises the link setup process and provides the timing reference.

- SHDSL remote unit (STU-R), which terminates the line at the user's side, on the customer's premises (CPE).

SHDSL Modulation Method

SHDSL uses multi-level pulse-amplitude modulation (PAM) together with trellis coding. Using advanced digital signal processing (DSP) techniques enables symmetric data transmission at rates in the range of 192 to 2304 kbps (corresponding to lines rates of 200 to 2312 kbps).

The modulation method is spectrally compatible with other transmission technologies deployed in the access network, including other DSL technologies.

The SHDSL operation must compatibility with regional standards, as specified in Annex A (North America) and Annex B (Europe) of ITU-T Rec. G.991.2 (this includes both operational differences and performance requirements).

SHDSL Signal Structure

The SHDSL line signal is organized in frames. The line signal structure enables the transmission of both payload and overhead data. The main types of overhead data are:

- Synchronization word, for frame alignment.

- Error detection and correction data also used for performance monitoring data.

- Embedded operations channel (**eoc**) - enables supervision and management of the whole SHDSL transmission subsystem (STU-C and STU-R), and initiation of diagnostic loopbacks and tests.

The transmit SHDSL data stream is generated by a framer, which also demultiplexes the received data stream. The framers used in some RAD's products (such as LA-110) can be configured to generate two types of data streams: N × 64 kbps data stream or serial ATM data stream.

SHDSL Line Transmission Process

The SHDSL line transmission process includes two stages: start-up and data transmission.

To enable link establishment under various conditions, the SHDSL subsystem operates in a master-slave mode, where the STU-C unit serves as the master, and the STU-R unit is the slave.

The STU-C unit performs the following functions:

- Controls the link start-up procedure.

- Provides the timing reference for SHDSL transmission.

- Manages the communication on the **eoc** channel.

The start-up process is automatically initiated by the STU-C upon power-up, and uses advanced digital signal processing techniques together with a special link activation process. It includes the following sequence of operations:

- Data rate negotiation, which attempts to set up the link at the highest rate possible (the maximum allowed rate is selected by the user, as part of the link configuration parameters). This process has three main steps:

  - Analysis of line transmission characteristics (line probing) whenever a link must be setup between two SHDSL modems.

  - Exchange of transmission parameters (handshaking) between the two modems.

  - Transmission of special signals that enable training of echo cancellers and equalizers, and the synchronization of SHDSL receivers to transmitters in both directions of transmission.

- Automatic detection and compensation of tip/ring polarity reversal on the line.

After start-up, the SHDSL links support transmission of payload, as well as an *eoc*. Data transmission is automatically started after start-up is successfully completed.

The total overhead carried by an SHDSL signal is always 8 kbps. For example:

- When the payload data rate is 192 kbps (3 × 64 kbps), the line rate is 200 kbps

- When the payload data rate is 2304 kbps (36 × 64 kbps), the line rate is 2312 kbps.

SHDSL Transmission Parameters

The user must specify the following set of SHDSL transmission parameters:

- Maximum link rate: this is the rate at which the SHDSL modems will attempt to set up the link. A lower rate increases the maximum range, therefore when the link cannot be set up at the requested rate, the SHDSL modems automatically negotiate to select the highest possible rate.

- Transmission mode. ITU-T Rec. G.991.2 specifies three sets of regional signal characteristics for SHDSL modems, however only two of the sets are currently offered for the LA-110:

  - The set of characteristics specified in Annex A is required for compatibility in North American networks

  - The set of characteristics specified in Annex B is required for compatibility in European networks.

- Power backoff. When the estimated power loss on the link between the two SHDSL modems is low, it may be desirable to use less than the maximum allowed signal power. You can enable this option, called power backoff, to reduce the interference caused by your signal to other equipment using pairs in the same cable without degrading the link transmission quality.

3. ADSL Transmission Methods

ADSL Modulation Method

The characteristics of the ADSL signals are defined in the ITU-T Rec. G.992.1 standard. The ADSL line code is the Discrete Multitone (DMT) code.

The DMT line code is designed to provide a good match for the twisted-wire pair channel. One of the main characteristics of the twisted-wire pair channel is the extreme variation in its transmission function versus frequency within the range of interest. For example, for operation over POTS infrastructure, the range is from 25 kHz, which is the lowest frequency that can be used without significant interference from the phone signals carried by the line, up to approx. 1.1 MHz.

To overcome this variation, discrete Fourier transform (DFT) techniques are used to decompose the modulated signal into many mutually orthogonal signals, located at a spacing of 4.3125 kHz (in accordance with the ITU-T Rec. G.992.1 standard, the downstream signal is decomposed into 256 discrete subcarriers, and the upstream signal – into 32 subcarriers).

Each subcarrier carries a certain fraction of the payload. The subcarrier modulation method is a special form of quadrature amplitude modulation (QAM). Due to the relatively high bandwidth efficiency of QAM, each subcarrier essentially uses its own frequency band. Since this band is relatively narrow, it is possible to process each subcarrier independently of the other subcarriers, so as to compensate in a nearly optimal way for attenuation, group delay, and intersymbol interference (ISI).

Figure 1 shows a typical allocation of DMT subcarriers, which is suitable for ADSL transmission systems operating over a POTS infrastructure. The recommended operating parameters over POTS infrastructure are defined in Annex A of the ITU-T Rec. G.992.1 standard.

As seen in *Figure 1*, the frequency ranges of the downstream and upstream channels overlap partially. This capability is obtained by using echo cancellers.

Another approach for duplex transmission over one pair is frequency division multiplexing (FDM). The FDM method is used when it is necessary to separate (i.e., prevent the overlapping of) the frequency ranges used to transmit and receive. For example, the frequency range required for ISDN signal transmission is up to 95 kHz.

To support this frequency range, it is necessary to configure the ADSL transmission subsystem for operation in the FDM mode. *Figure 2* shows a typical range of subcarriers for each direction for operation over ISDN infrastructure. The reduced number of subcarriers decreases the maximum range by approximately 10%, relative to the range over POTS infrastructure. The recommended operating parameters using FDM over ISDN infrastructure are defined in Annex B of the ITU-T Rec. G.992.1 standard.
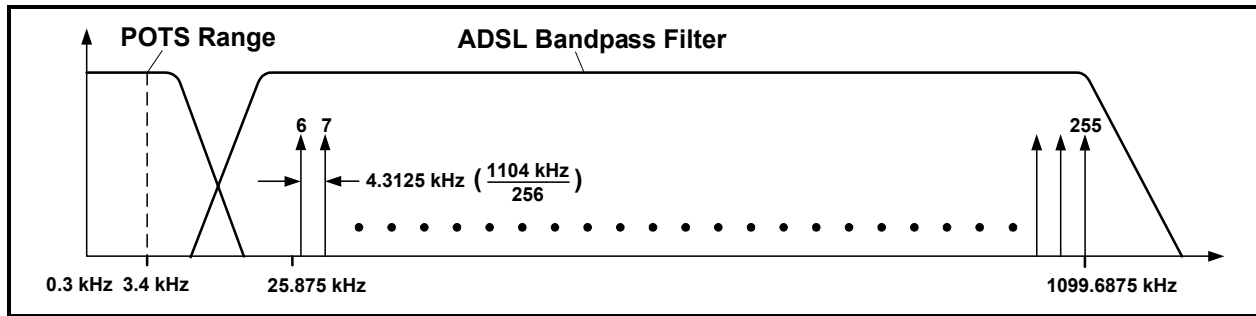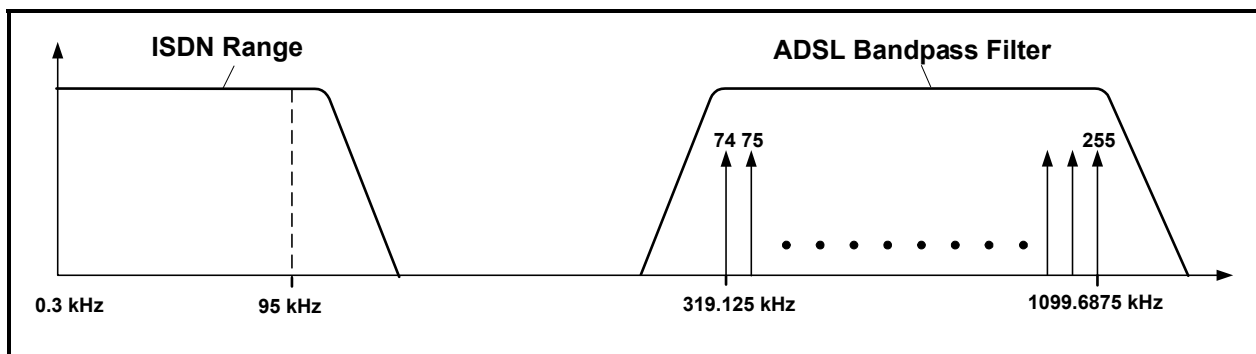
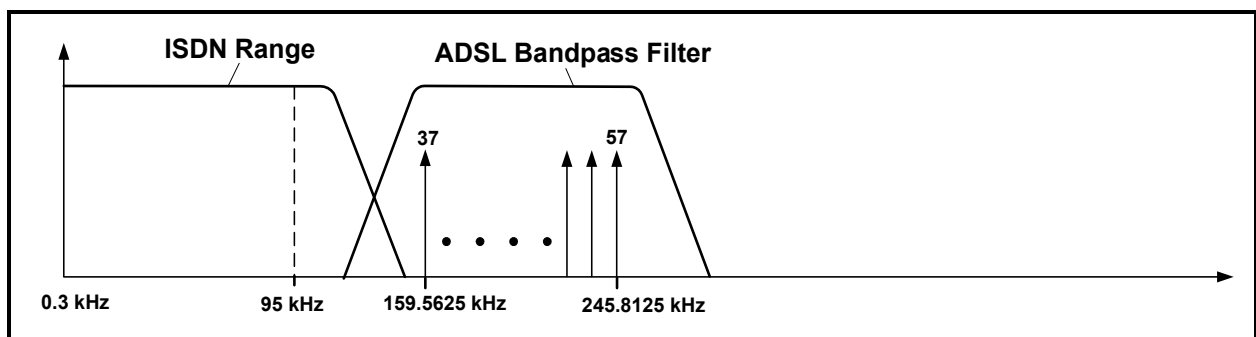A. Downstream Subcarriers
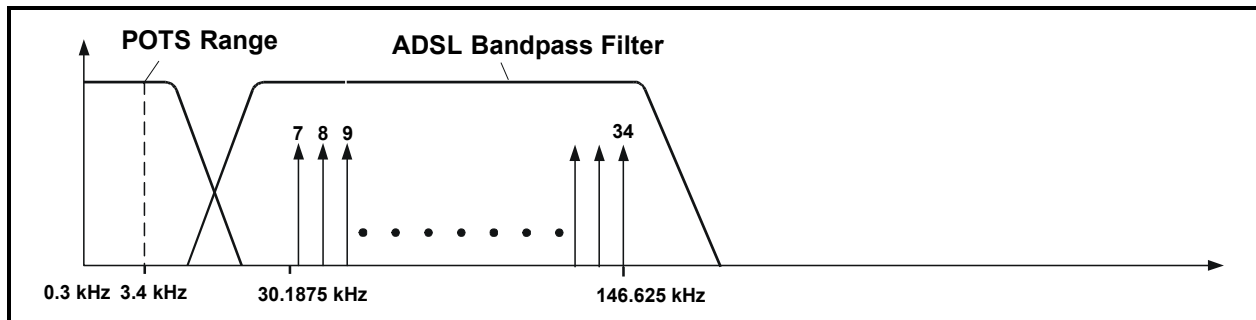
B. Upstream Subcarriers

Figure 1. Typical Allocation of DMT Subcarriers (POTS Infrastructure)

A. Downstream Subcarriers

B. Upstream Subcarriers

Figure 2. Typical Allocation of DMT Subcarriers (ISDN Infrastructure)

ADSL Payload Channels

The ADSL signal is formatted in frames and superframes, which include various types of overhead and payload transport channels. The frame structures depend on the type of payload, and therefore this section covers the characteristics relevant to the transport of ATM signals.

The ADSL transmission subsystem supports the transmission of the following main types of payload channels:

- Downstream channel, designated AS0: simplex high-speed channel, used to transmit data from the ATU-C to the ATU-R. ADSL systems support all the downstream data rates specified in the ITU-T Rec. G.992.1 standard, as well as other data rates which are multiples of 32 kbps. The maximum downstream data rate for ATM signals is 6.144 Mbps.

- Upstream channel, designated LS0: simplex high-speed channel, used to transmit data from the ATU-R to the ATU-C. ADSL systems support all the downstream data rates specified in the ITU-T Rec. G.992.1 standard, as well as other data rates which are multiples of 32 kbps. The maximum upstream data rate for ATM signals is 640 kbps.

The data rates of the payload channels are usually not synchronized to the ADSL line data rate. This is achieved by inserting padding bits and idle ATM cells in the data stream, but in this case it is necessary to use a synchronization mechanism that restores the original data rate at the other end of the link.

An alternative approach is to lock the payload channels rates to the ADSL line rate: in this case, the channel rates are determined by the line rate, minus a fixed rate of overhead data.

ADSL Subsystem Overhead

The ADSL subsystem overhead includes the following main types of data, used for synchronization and ADSL link management:

- Synchronization word

- ADSL overhead channel (*aoc*), which enables the ATU-C and ATU-R units to exchange status data.

  For example, during the ADSL link start-up process the *aoc* is used to send the system configuration parameters, evaluate the transmission capabilities of the interconnecting line, select the optimum data rate (necessary when using the rate-adaptive mode), and perform the handshaking required to start service.

  Other *aoc* functions include:

  - Transmission of performance statistics from the ATU-R to the ATU-C.

  - Activation of test loopbacks, and bit error rate (BER) measurement.

  - Checking of ATU-R software version, and automatic updating by downloading the ATU-C software to the ATU-R when versions differ.

  - Handshaking with the remote unit.

- Embedded operations channel, *eoc*, used for communication between the ATU-C and ATU-R. The *eoc* is used for in-service and out-of-service maintenance, and for the retrieval of ATU-R status information and ADSL performance monitoring parameters.

  The communication through the *eoc* is always initiated by the ATU-C. The ATU-C serves as the master of the *eoc* link, and sends commands to the ATU-R. The ATU-R serves as slave on the *eoc* link, and it only responds to the commands. The only exception is for the "dying gasp" message: this message is sent by the ATU-R when an imminent power failure is detected and is inserted in the upstream link as soon as appropriate bytes are available, irrespective of the commands sent by the ATU-C.

- CRC check bytes for error detection.

- Fixed indicator bits for OAM.

- FEC redundancy bytes for error correction.

ADSL Framing Modes

The channels and overhead described above are inserted in frame structures defined by ITU-T Rec. G.992.1. Two types of framing are used on the ADSL link: full overhead and reduced overhead. Furthermore, two versions of full overhead and two versions of reduced overhead are defined.

The four resulting framing modes, referred to as framing modes 0, 1, 2 and 3, are defined in *Table 1*.

An ATU-C configured for ATM transport must support the framing structures 0 and 1; support of reduced overhead framing structures 2 and 3 is optional.

Table 1. ADSL Framing Modes

Framing Structure	Description
0	Full overhead framing with asynchronous bit-to-modem timing. This requires the synchronization control mechanism to be enabled.
1	Full overhead framing with synchronous bit-to-modem timing. In this case, the synchronization control mechanism is disabled.
2	Reduced overhead framing with separate fast and sync byte in the fast and interleaved latency buffer respectively (requires 64 kbp framing overhead)
3	Reduced overhead framing with merged fast and sync byte, using either the fast or the interleaved latency buffer (requires only 32 kbps framing overhead)

The ATU-C indicates during link initialization the highest framing structure number it supports. If the ATU-R indicates a lower framing structure number during initialization, the ATU-C selects the framing structure number indicated by the ATU-R.

ADSL Coding Methods

To ensure reliable transmission, ADSL transmission include several functions:

- Modulation/demodulation, using DFT.

- Evaluation of the transmission function of the channel

- Distribution of payload among the various subcarriers. This algorithm analyzes the signal-to-noise (SNR) for each subcarrier, and assigns the optimal amount of payload information to be carried by each subcarrier. As a result, each subcarrier carries 2 to 15 bits per symbol, resulting in a payload of up to 60 kbps per subcarrier. Since the error events for each subcarrier are essentially independent, this method achieves a coding gain near the maximum theoretical gain.

- Error detection and correction algorithm. The algorithm applies forward error correction coding to overcome random errors and impulse noise error events, that are common to the residential twisted-wire pairs. The coding methods include concatenated trellis and Reed-Solomon block coding, and interleaving:

  - The ADSL systems use a variable rate Reed-Solomon code. The code provides a redundancy in the range of 2 to 24 bytes at block lengths of up to 255 symbols (bytes). The amount of redundancy can be configured by means of the configuration files. This gives the operator the flexibility to adjust the error protection to the typical requirements of the installation, to provide the customers extra protection where loop conditions call for.

  - The trellis code, specified in the ANSI DS1.413-1995 standard, is used as the inner code in the concatenated coding scheme of ADSL systems, with the Reed-Solomon code serving as the outer code. The trellis code operates on the data spread on the various subcarriers, and thus does not add extra latency. The trellis code improves the noise margin measured for stationary added noise (such as white noise and typical NEXT and FEXT noise) without requiring additional bandwidth.

  - Protection against impulse noise is obtained by using interleaving. Interleaving can be independently enabled/disabled by the user for each channel and transmission direction. The interleaving parameters require a trade-off between protection and latency.

Adaptation to a Changing Environment

Due to the advanced coding techniques described above, ADSL systems can transport the required payload in very noisy environments.

To evaluate its operating environment, the system measures the noise environment during start-up and selects accordingly optimized operational parameters. Moreover, the system uses a special adaptation algorithm to select automatically the highest rate that can be supported by the line; for this purpose, the user can specify a minimum acceptable data rate and the adaptation algorithm uses this value in case the line quality is not sufficient to support the nominal data rate of the intended application.

To ensure continued protection during normal operation, the system continues to monitor on-line the noise environment, and to adapt itself to slow changes in the environment. This function, called bit swapping, is automatically performed by exchanging messages through the *aoc* channel. For example, the addition or deletion of a narrow band noise will immediately be detected and the ADSL systems will use the handshaking protocols defined in the standard to make the arrangements required to optimally protect the data at all times. These changes are performed without disrupting the service and without any resynchronization and training procedures.

When operating in the rate-adaptive mode, the rate adaptation algorithm will not only perform bit swapping, but at start-up will also select automatically the highest data rate that can be supported while maintaining a user-specified noise margin.

Network Timing Reference (NTR)

Some services, for example, Voice and Telephony over ATM (VToA), require that a reference clock be available for the higher layers of the protocol stack, that is, above the physical layer. This reference click is used to guarantee end-to-end synchronization of transmit and receive sides.

To support the distribution of a timing reference over the network, the ADSL system may transport to the ATU-R an 8 kHz timing marker, designated NTR, which supplied to the ATU-C.

The enables the ATU-C to provide timing information, which then becomes available to the equipment connected to the ATU-R. This reference timing has an accuracy corresponding to the accuracy of the clock provided to the ATU-C. The maximum frequency variation of the NTR is ±32 ppm.