Enabling Network Upgrades for Advanced Multimedia Service Delivery

VDSL Pair Bonding Extends Broadband Delivery and Increases Speeds for Advanced Multimedia Service Delivery

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Video is changing everything. Service providers throughout the world, motivated equally by the need to diversify their revenue streams as well as maximize their return from capital investments, are faced with the difficult challenge of cost-effectively upgrading their existing networks while providing customers with the robust network required to handle the increasing bandwidth demands of triple play services, high-definition video, and other advanced multimedia services.

VDSL is the current access technology of choice for triple play services and Ikanos' industry-leading advances in DSL technology are enabling continuous increases in throughput speeds as well as extending services to more homes. Ikanos' cutting-edge VDSL technology conquers some of the performance-inhibiting hurdles inherent in DSL technology and increases network performance by addressing the interference associated with crosstalk-dominated noise that has historically limited data transmission rates as loop lengths increased.

VDSL pair bonding from Ikanos increases the maximum attainable bit rate available to VDSL end-users. Pair bonding also increases the service area for a given deployment. Additional performance gains can be achieved when vectoring is implemented, either alone or in tandem with Ikanos' pair bonding. Alone or combined, these techniques allow service providers to design and deploy multimedia service networks that incorporate fiber in their backbone while allowing them to use their existing copper infrastructure for last-mile connections to their customers. These hybrid networks deliver dramatically improved capacity, performance, and stability.

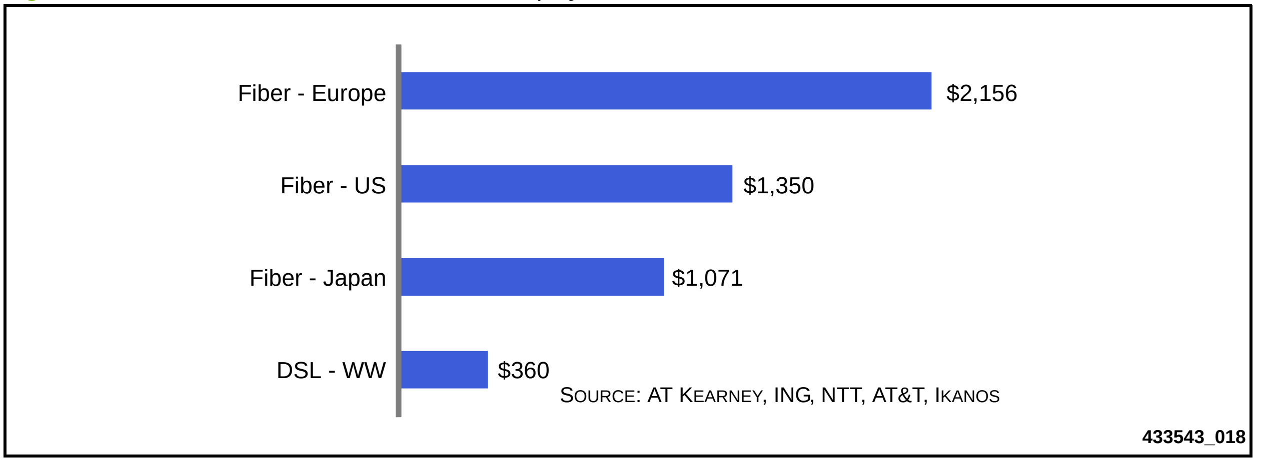
This paper provides an overview of VDSL pair bonding. It discusses the performance benefits achieved by pair bonding over existing technologies. Additionally, a financial analysis is included in which available network options are explored.

Introduction

The widespread popularity of broadband multimedia services is a double-edged sword for telecommunications service providers. Declining voice traffic revenues, rising consumer expectations, and fierce competition from cable operators make service bundles, in particular those that include high-definition television, an essential survival strategy. Delivering such video-intensive services requires an increase in bandwidth of at least 20 to 100 Mbps. Until recently, conventional wisdom held that only a fiber to the home (FTTH) network architecture could deliver this level of performance. And unfortunately the wholesale deployment of FTTH is so costly that it strains even the deep pockets of the world's largest telecommunications service providers.

Figure 1 illustrates a cost-comparison of the estimated installation costs associated with fiber and DSL installations for several international markets. From the data presented, it is clear that completely replacing an existing network is extremely costly and time-consuming. As a result, most service providers are pursuing a hybrid fiber to the node (FTTN) architecture which provides subscribers with copper-based last-mile links and xDSL technology.

Figure 1 *Cost Per Household for Broadband Deployment/Installation*



Using the installed base of copper local loops eliminates the costly process of pulling fiber through a neighborhood and bringing it to each home. Additional savings are realized because most xDSL customer premises equipment can be installed by the subscriber.

VDSL

Significant advances in the next-generation of DSL technology (i.e., VDSL,) have improved the reach, stability, and overall capacity of legacy copper infrastructures so that the deployment of FTTN networks that reliably deliver 50 to 100 Mbps is achievable at a fraction of the cost of a purely optical solution.

VDSL is key to the deployment of triple play services within a twisted-pair access network. The increased bandwidth provided by VDSL allows the deployment of a high-speed access channel for video applications over internet protocol (IPTV) while supplying sufficient capacity for the simultaneous support of high-speed Internet access and voice over internet protocol (VoIP) applications.

Though it offers quick and easy deployment of advanced broadband services, telco copper is limited by the laws of physics. The amount of bandwidth available to users is limited by their distance from the fiber termination point, quality of the wire, and the amount of crosstalk on the line. Factors include:

- Increased signal power loss is introduced with increasing frequency and distance.
- Multi-pair cables are subject to both near-end and far-end crosstalk coupling that increases with increasing frequency, making higher frequency signals more susceptible to degradation from crosstalk.

In general, the combination of signal loss introduced by a twisted pair cable and crosstalk introduced by signals in adjacent wire pairs within the same cable limit the range at which high-speed VDSL services may be deployed. Therefore, for a specified service quality objective on a single access wire pair, service providers limit deployment to customers within a set maximum radius from the central office (CO) or remote terminal (RT).

Advanced Noise-Mitigating Technology

To minimize the impact of signal power loss and crosstalk, Ikanos has developed cutting-edge noise-mitigating technologies which enhance link robustness, reliability, and availability under severe and time-varying noise environments. These ground-breaking technologies enable dramatic improvement in broadband throughput over distances approaching one mile which is more than sufficient to service the vast majority of customers in urban and suburban locations.

Key advances include:

- Ikanos quality video (iQV™), software which dynamically increases line stability,
- Pair bonding, and
- Vector processing, a standards-based crosstalk cancelling technology.

The focus of this white paper is the style of pair bonding known as VDSL ethernet in the first mile (EFM) bonding and how it provides the most cost-effective means of upgrading broadband networks to extend VDSL service beyond current geographical constraints.

Pair Bonding

When additional bandwidth and increased distance are required, Pair bonding can be incorporated to support another data channel over a second twisted-pair found in the last-mile runs of most residences and commercial installations. Bonding logically combines the capacity of the two channels in a transparent manner so the subscriber sees a single connection that is theoretically capable of delivering up to 200 Mbps in performance.

Customers located close enough to the CO may be served directly by equipment located inside the CO. To reach customers located further away, the service provider may deploy a fiber fed cabinet that contains the VDSL equipment serving the customers located within a maximum serving radius from the cabinet. Depending on the cabinet’s location, there may be a certain percentage of end-users whose access line(s) fall outside the maximum reach limit for service deployment on a single wire pair. Customers located outside this serving radius will likely not receive the objective service quality on a single pair due to large loss and possible excessive level of crosstalk in the long loop. For customers having more than one wire pair available to the home, pair bonding may be used to provide the service with extended reach, where the bit rates on each loop are lower than the objective rate but the combined bit rate exceeds the objective rate for the service.

With proper understanding of the rate versus reach tradeoffs, bonding may be used to extend the reach of basic xDSL service to customers outside the single wire pair serving radius, or to provide higher capacity to end users than on a single xDSL access link within the single pair serving radius.

The Ethernet Pair Bonding Technique

This section provides a very brief overview of the ethernet pair bonding mechanism defined in G.998.2. For complete information, refer to G.998.2 Ethernet Bonding Recommendation[a], and the Ethernet in the First Mile Standard[b]. This standards-based approach to ethernet bonding is applicable to any physical layer transport type (e.g., VDSL, ADSL2, SHDSL, etc.) To the upper layers in the protocol stack, the bonded links appear as one single high-speed link transporting ethernet packets.

Figure 2 provides a functional block diagram of the bonding process at the transmitter. The bonding block receives ethernet packets from the ethernet layer above. The bonding block first removes any overhead associated with the ethernet packet, specifically any inter-packet gap (IPG) bytes and the preamble. The packet segmentation block takes the resulting ethernet data frame and breaks it up into smaller data fragments. Two bytes of overhead are added to each data fragment, and they are then distributed among the N lines in the bonded group for simultaneous transmission to the far-end. The bonding receive function at the far-end receives the fragments on all of the lines in the bonded group and then reassembles the original packets based on the information received in the overhead bytes.

Figure 2 *Functional Block Diagram of Ethernet Bonding*

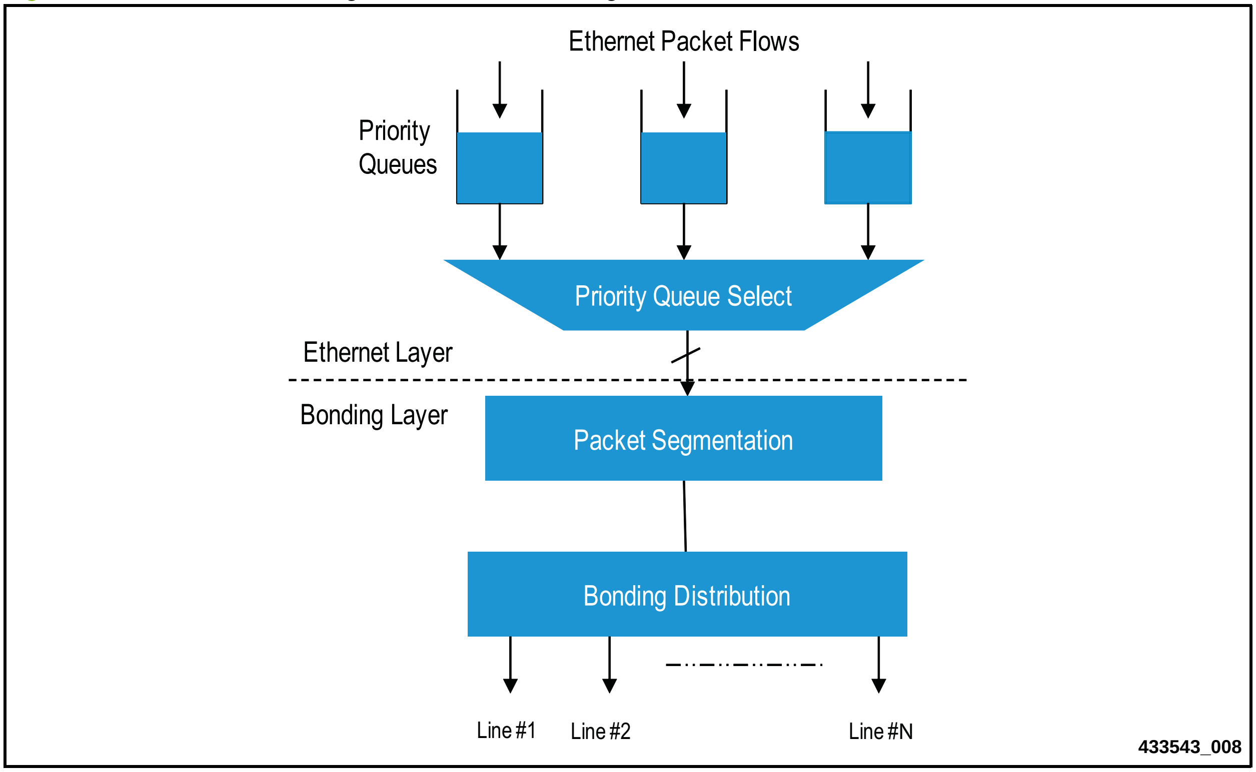


Figure 3 shows a diagram of the fragmentation process. Only the ethernet data frame is broken up into smaller data fragments. Two bytes of overhead are added to each fragment:

- 14 bit sequence identifier (SID);
- One bit for a start of packet (SOP) indication;
- One bit for an end of packet (EOP) indication.

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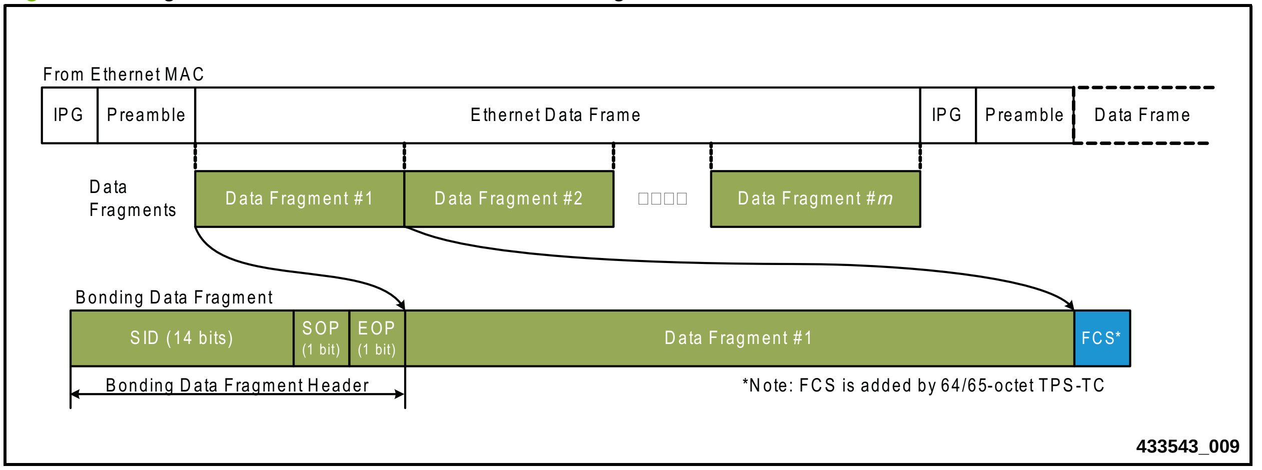
a. ITU-T Recommendation G.998.2, "Ethernet-based multi-pair bonding," January 2005.
b. IEEE 802.3ah (2004), "Carrier Sense Multiple Access with Collision Detection (CSMA/CD) access method and physical layer specification – Amendment: Media Access Control Parameters, Physical Layers, and Management Parameters for Subscriber Access Networks."

The minimum data fragment size is 64 bytes and the maximum fragment size is 512 bytes.

Figure 3 *Fragmentation of Ethernet Packets for Bonding*



When transmitted on a line using VDSL, the packet transfer mode transmission convergence (PTM-TC) layer function transports the bonding fragments by adding one byte of overhead for every 64 bytes of data received from the bonding layer. This PTM-TC function is referred to as 64/65-octet encoding, which is used to convert the data blocks received from the bonding layer into a bit rate for transmission using VDSL. Also, at the end of each data block, the 64/65-octet encoder appends 2 or 4 bytes of CRC (i.e., a frame check sequence [FCS],) for the detection of any errors in the received sequence.

Recommendation G.998.2 and IEEE 802.3ah define a differential delay requirement of 15,000 bit times between any two lines in a bonded group and a maximum bit rate differential of 4:1 between the highest and lowest bit rates in the bonded group. Amendment 1 to G.998.2 has updated the differential delay requirements when VDSL transceivers are used on each link to accommodate for various transceiver characteristics, namely transceiver jitter caused by transmitter and receiver buffering, symbol rate, sync symbols, and FEC. With this amendment, a two-pair bonding group transmitting 100 Mbps net data rate at a 4:1 ratio would need to support a differential delay of 65,000 bit times.

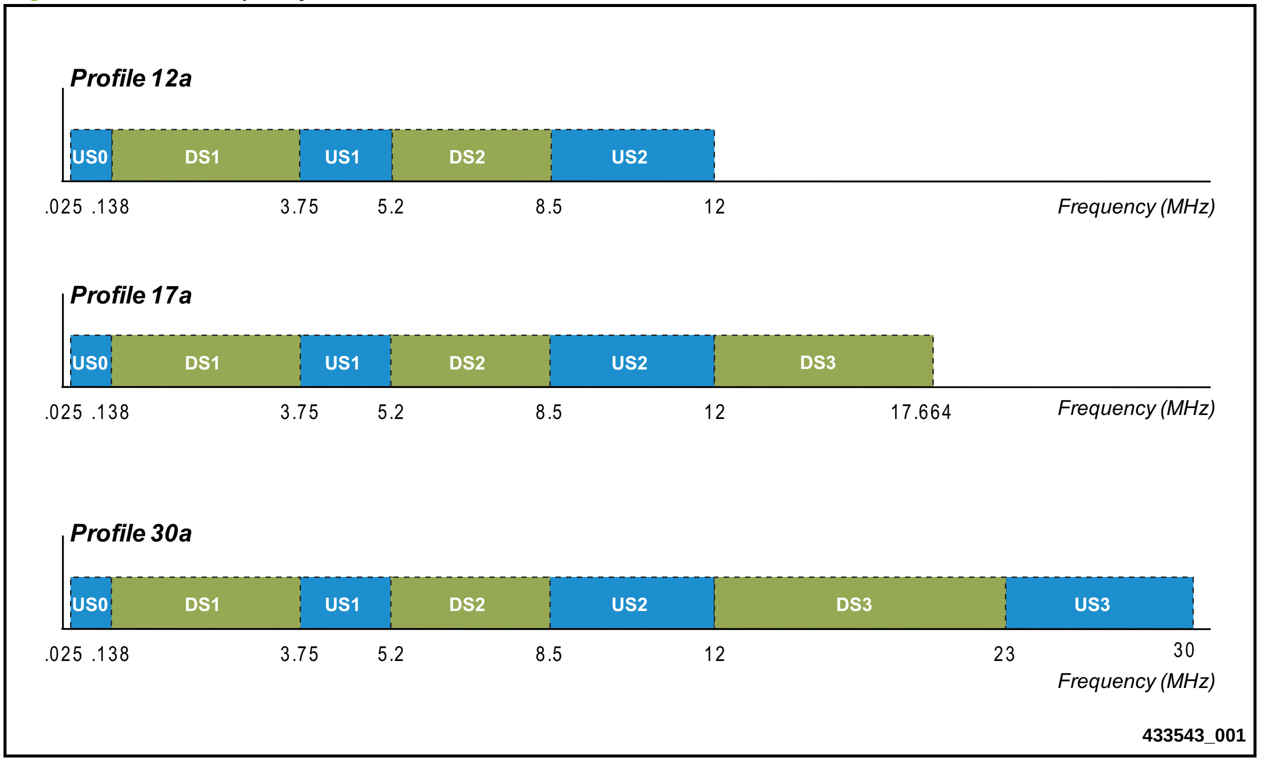
Limits of a VDSL Deployment on a Single Link

To demonstrate the gains of pair bonding with VDSL, we first investigate the performance achievable when operating on a single link using profiles 12a, 17a, and 30a [a]. Then we compare the resulting Rate vs. Reach performance with a pair-bonded VDSL system using the same VDSL profile.

The VDSL frequency plan for transmission of the upstream and downstream signals that is used in North America, and also in many places within Europe and Asia, is illustrated in Figure 4. This band plan is referred to as Frequency Plan 998, and it serves as the foundation for the performance analyses described in this paper. Profile 8 uses the frequencies up to 8.5 MHz, which provides a significantly greater emphasis to the downstream. Profile 12 uses the frequency band from 8.5 – 12 MHz for upstream transmission, giving this profile a more symmetric weighting to upstream and downstream bandwidths. Also shown in Figure 4 are the plan 998 frequency allocations for profiles 17a and 30a which address shorter reach and higher capacity applications (e.g., profile 17a targets primarily FTTN applications, while profile 30a targets primarily fiber to the building (FTTB) applications.)

The power spectral density (PSD) of the upstream and downstream frequencies is defined in Annex A of the VDSL Recommendation G.993.2 [a]. For the analyses provided in this paper we truncate the PSD to be such that the maximum transmit power is limited to +14.5 dBm for both the upstream and downstream channels.

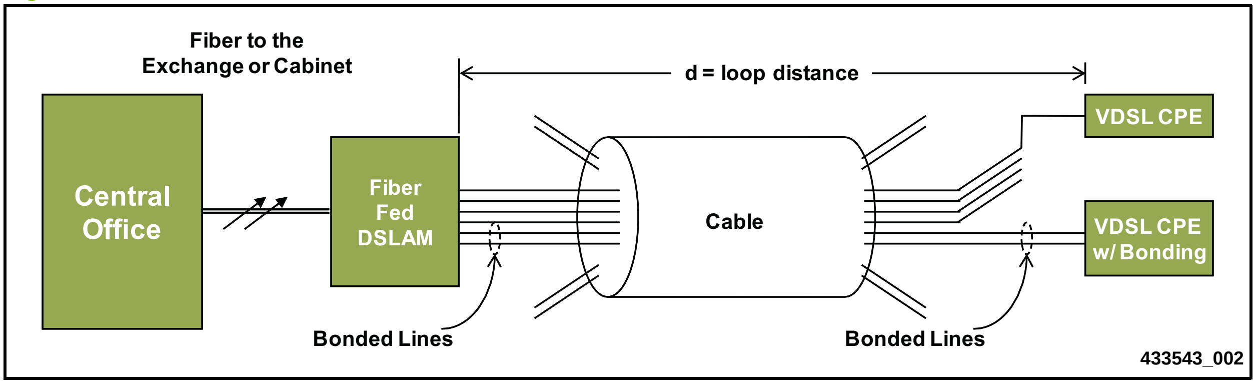
Figure 4 *VDSL Frequency Plan 998*



a. ITU-T Recommendation G.993.2, “Very high speed digital subscriber line transceivers 2 (VDSL2),” February 2006.

On the network side, customers may be served by VDSL equipment located in cabinets residing in the CO or in an RT. The network equipment containing the VDSL nodes is generally referred to as a digital subscriber line access multiplexer (DSLAM). When the DSLAM is located in the CO, we refer to the configuration as fiber to the exchange (FTTEx); when the DSLAM is contained in a remote terminal cabinet, we refer to the configuration as FTTN. Figure 5 shows the general architecture for VDSL access using FTTEx or FTTN. In either case, each subscriber line served from the DSLAM must be less than or equal to a maximum distance (i.e., serving radius,) so as to meet a predefined service quality. An example deployment range for a profile 12a VDSL circuit may be 3000 ft, or approximately 1 km.

Figure 5 *General VDSL Access Architecture*



For VDSL deployments up to about 5000 ft (1.5 km,) the rate is primarily limited by far-end crosstalk (FEXT) inside the cable. Impulse noise is also present on the line, but this does not affect reach as much as it affects the bit rate. Mitigation of impulse noise is generally addressed with forward error correction at the expense of channel efficiency. Impulse noise mitigation is outside the scope of this paper.

We compute transmission performance on a single wire pair of VDSL profile 17a via computer simulation using the following system assumptions:

- Reference Channel Model for estimation of rate vs. reach performance: 25 pairs of AWG 26 (approximately 0.4 mm diameter) cable
- Frequency plan 998
- Background noise: -140 dBm/Hz additive white Gaussian noise (AWGN)
- Far-end crosstalk considered at 1% worst case [a]
- Crosstalk scenarios:
  - AWGN only (no crosstalk)
  - 1 self far-end crosstalk (SFEXT) disturber + AWGN
  - 12 SFEXT disturbers + AWGN
  - 24 SFEXT disturbers + AWGN
- Coding Gain: 3 dB
- SNR Margin: 6 dB
- Bit loading: 2-15 bits
- PSD is per G.993.2 Annex A with transmitter power limited to +14.5 dBm for both upstream and downstream.

Figure 6 shows the 1% worst case achievable profile 17a downstream bit rates on single wire pairs in a

a. ITU-T Recommendation G.993.2, “Very high speed digital subscriber line transceivers 2 (VDSL2),” February 2006.

25-pair cable for different levels of self-crosstalk.

NOTE:
This curve provides the baseline of achievable bit rates on a single wire pair without any compensation for crosstalk.

Figure 6 *Total Downstream Rate for Annex A Profile 17a Under Different FEXT Conditions*

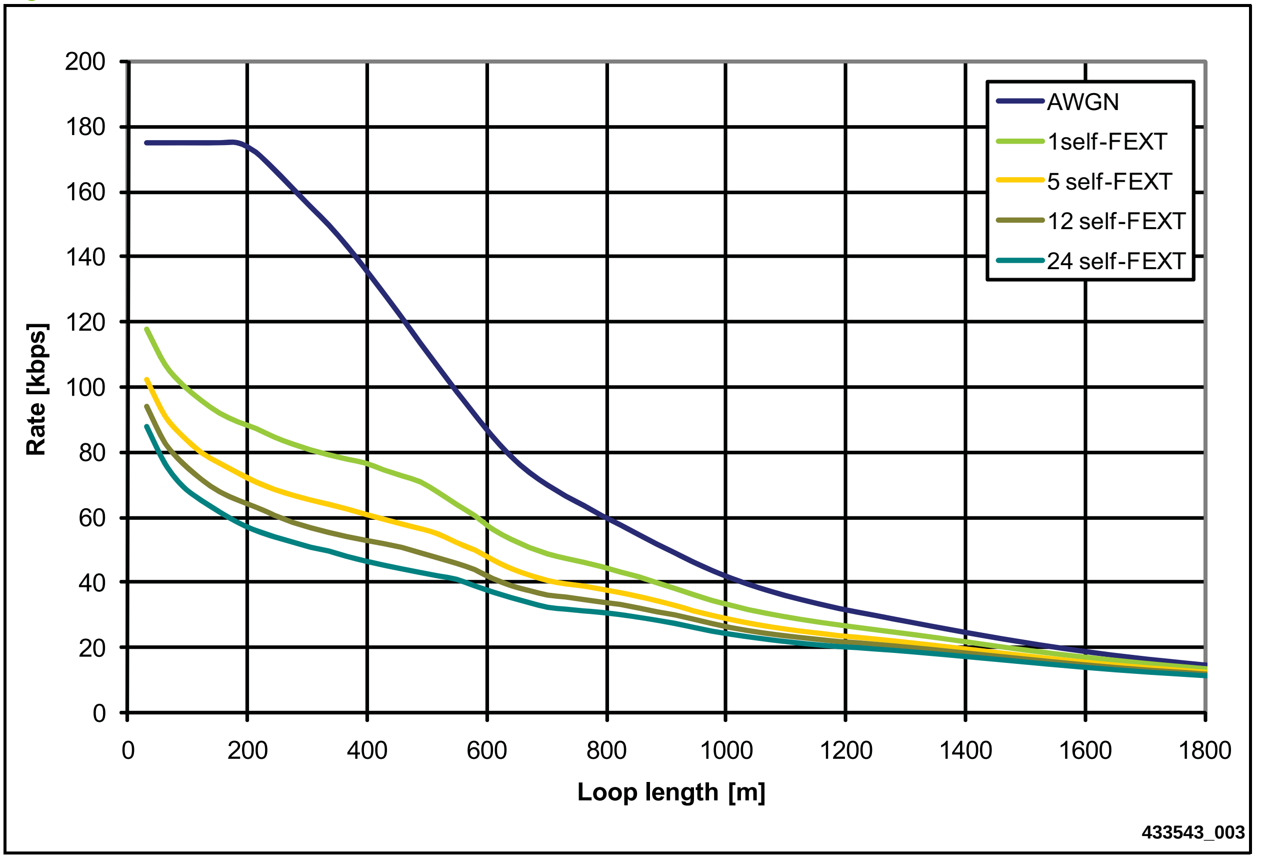
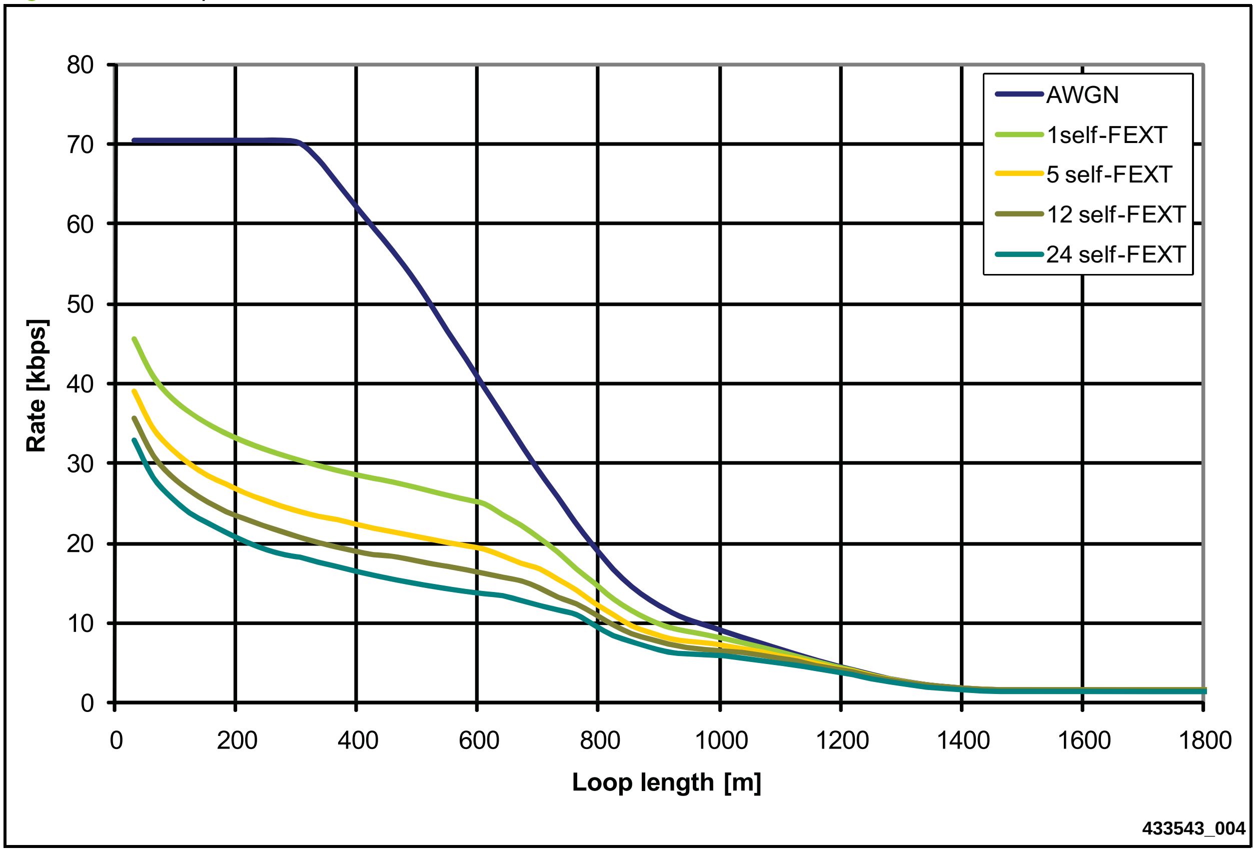


Figure 7 shows the 1% worst case achievable profile 17a upstream bit rates on single wire pairs in a 25-pair cable for different levels of self-crosstalk.

NOTE:
This curve provides the baseline of achievable bit rates on a single wire pair without any compensation for crosstalk.

Figure 7 *Total Upstream Rate for Annex A Profile 17a Under Different FEXT Conditions*



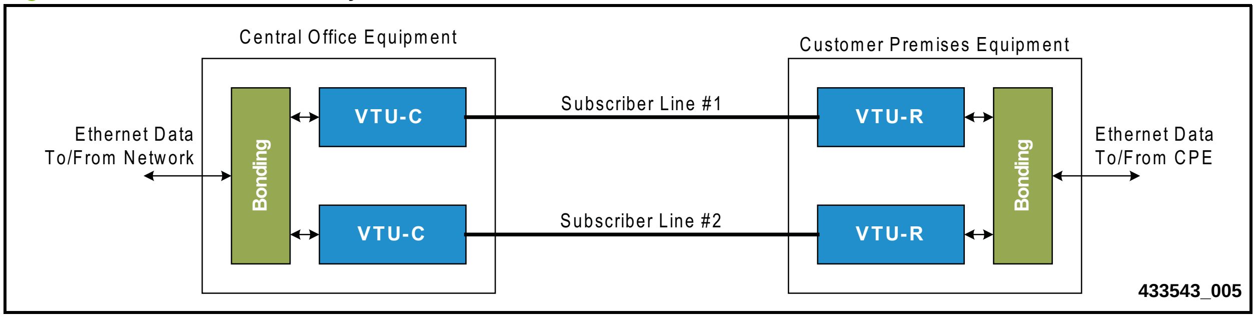
With regards to the profile 17a performance reference curves in Figure 6 and Figure 7, we note the following:

- The AWGN curve is the best rate that can be achieved when there is no crosstalk in the cable.
- At the shorter distances, the bandwidth of the received signal having sufficient signal-to-noise ratio to carry information is rather large, which allows for the higher achievable bit rates. Since the far-end crosstalk coupling increases with the square of increasing frequency, the effect of self-far-end-crosstalk has a very significant impact on bit rate, as can be seen in the two figures.
- At longer distances, the received signal bandwidth is narrower and the overall crosstalk coupling is less than that at higher frequencies. Hence, the lower bit rates at the longer distances are dominated more by loop attenuation and background noise than by self-crosstalk.
- For Profile 17a, the downstream band DS3 has bit loading capacity up to about 2300 ft (700 m.) Beyond this distance, service may be provided using profile 12a.
- In Profile 12a, the upstream band US2 has bit loading capacity up to about 3000 ft (920 m,) beyond which service may be provided with profile 8.
- Finally, the downstream band DS2 has bit loading capacity up to about 3800 ft (1150 m) and upstream band US1 has bit loading capacity up to about 4750 ft (1450 m.) Note that both of these bands are contained in profile 8.

Performance Gains with Bonding

A high-level block diagram of a pair-bonded VDSL system is shown in Figure 8. Each subscriber line is terminated with a VDSL transceiver at each end. The bonding function operates at the Ethernet packet level above the physical VDSL transceiver level. At the transmit side, Ethernet packets are divided into smaller packet fragments and distributed for transmission across the lines in the bonded pair. At the receive end, the bonding block collects the fragments and reconstructs the original packet. The net available throughput is the sum of the bit rates of the two lines. The Ethernet Pair Bonding Technique provides a brief overview of the actual Ethernet bonding operation.

Figure 8 *Pair-bonded VDSL System Architecture*



The focus of this paper is the performance gains achieved with pair bonding of profile 12a and 17a transceivers since these are the most widely-deployed profiles. Two deployment scenarios are examined:

- Profile 17a without bonding vs. profile 17a with bonding;
- Profile 12a without bonding vs. profile 12a with bonding.

It should also be noted that for the downstream channel, pair bonding of profile 12a is the same as pair bonding of profile 8a.

In the analysis, the following conditions are assumed:

- 25-pair cable deployed with 2 wire pairs to each of 12 users. One wire pair is not used.
- In the “without bonding” (or “un-bonded”) case, we serve each user with a single line (i.e., profile 12a, 17a, or 30a,) system. The extra wire pair to each end user is not utilized, so the lines will see a worst case of 12 self-crosstalk disturbers.

NOTE:

Technically this should be 11 self-crosstalk disturbers, but for convenience, we approximate this to using the 12 self-crosstalk disturber model.

- In the “with bonding” (or “bonded”) case, we serve each end user with pair-bonded systems using profile 12a, and so both pairs of wire are utilized. With all wire pairs in the cable in use, the wire pairs in each of the pair-bonded systems will see a worst case of 24 self-crosstalk disturbers.

NOTE:

Technically this should be 23 self-crosstalk disturbers but for convenience we approximate this to using the 24 self-crosstalk disturber model.

The above assumptions are considered in the performance data provided below.

Figure 9 shows a composite of the downstream bit rates for single pair operation (based on 12 Self-FEXT disturbers) for profiles 12a, 17a, and 30a, together with pair-bonded profile 12a and 17a (based on 24 self-FEXT disturbers.)

Figure 9 *Downstream Rate Comparison: Profile 17a Single Pair versus Profile 17 Bonded (Annex A)*

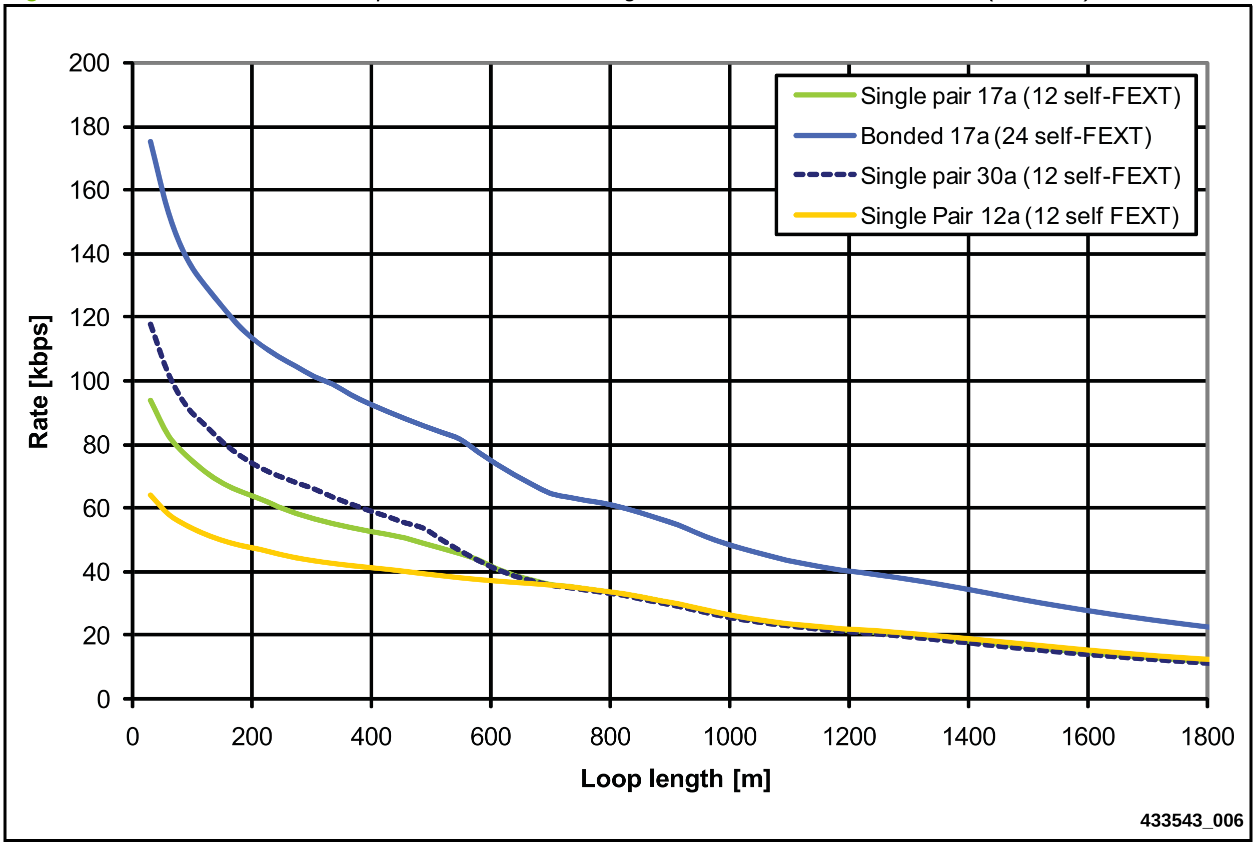
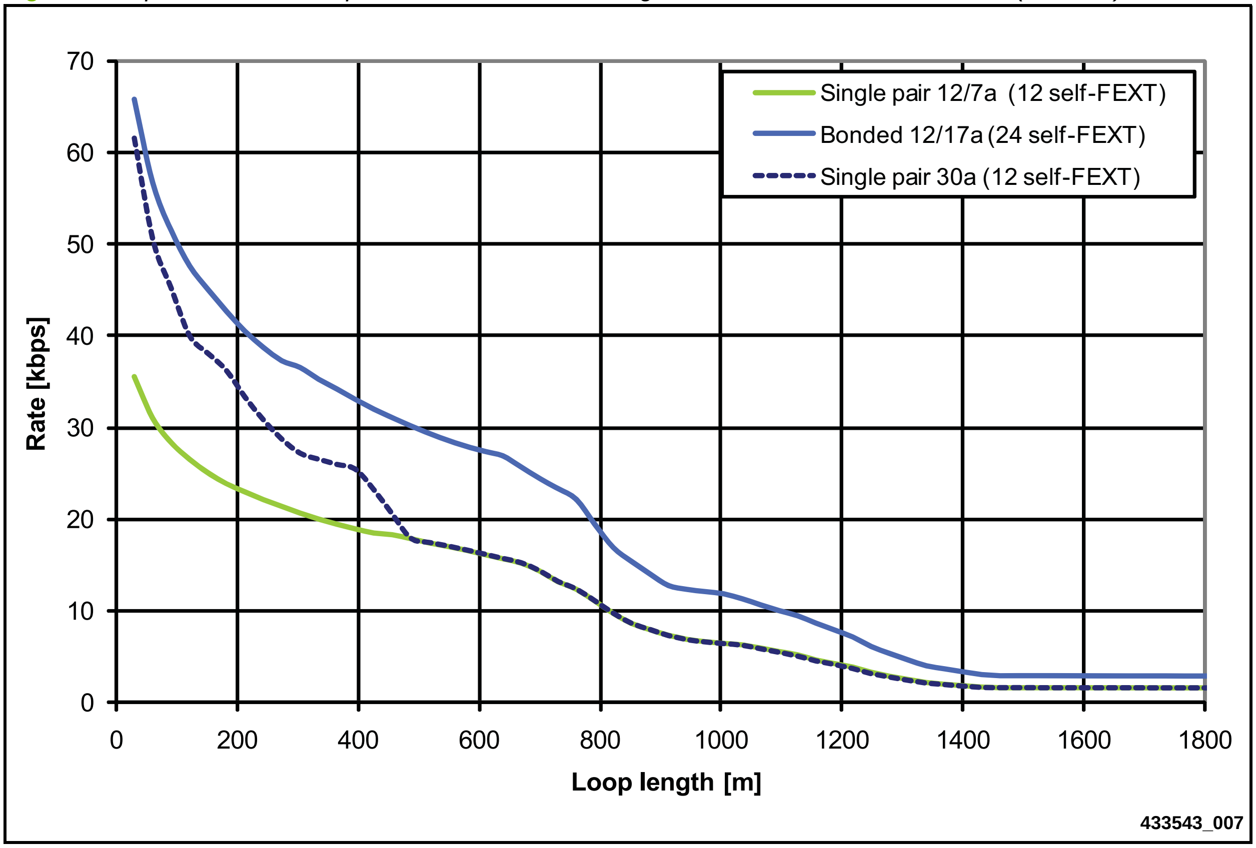


Figure 10 shows a composite of the upstream bit rates for the same configurations. Note that the curves for upstream profile 12a and 17a are the same.

Figure 10 *Upstream Rate Comparison: Profile 12a/17a Single Pair versus Profile 17a Bonded (Annex A)*



The following sections provide descriptions of the achievable performance gain of pair-bonded profile 17a and 17a over single pair operation.

Profile 17a Unbonded versus Profile 17a Bonded

The green curve (i.e., third curve from the top,) in Figure 9 shows the achievable downstream line bit rates as a function of distance for VDSL systems deployed on a single loop using profile 17a. Again, the light blue curve (i.e., the top curve,) shows the achievable bit rates for VDSL systems deployed using pair-bonded using profile 17a. Figure 10 provides the corresponding performance for the upstream channel. The top curve (i.e., the blue curve,) shows the pair-bonded profile 12a/17a upstream bit rates, and the green curve (i.e., third curve from the top,) shows the single pair upstream profile 12a and 17a bit rates.

To show the possible gains in reach, we chose two reference service deployment scenarios:

- 70 Mbps down and 30 Mbps up (indicated as 70/30 Mbps);
- 50 Mbps down and 10 Mbps up (indicated as 50/10 Mbps).

The following observations and conclusions can be made:

- For the 70/30 Mbps service, profile 17a may be deployed up to a distance of approximately 200 ft (80 m.) In this case, the upstream limits the reach. The downstream rate of 70 Mbps may be deployed up to 400 ft (120 m.)
- With pair-bonded profile 17a, the reach for the 70/30 Mbps is service extended up to approximately 1600 ft (490 m,) limited by the upstream channel capacity. Note that the downstream channel at 70 Mbps may reach up to approximately 2100 ft (640 m.)
- For the 50/10 Mbps service, profile 17a may be deployed up to a distance of approximately 1500 ft (450 m,) limited by the downstream channel capacity. Note that the upstream channel at 10 Mbps may reach up to approximately 2600 ft (790 m.)
- With pair-bonded profile 17a, the reach for the 50/10 Mbps is service extended up to approximately 3100 ft (940 m,) limited by the downstream channel capacity. Note that the upstream channel at 10 Mbps may reach up to approximately 3600 ft (1100 m.)

The above gains in reach for pair-bonded profile 17a over unbonded profile 17a are summarized in Table 1, including the percentage gain in the largest distance that can support both upstream and downstream reference rates for each scenario.

Table 1 Distance Gains: Pair Bonded Profile 12a Over Profile 17a

Deployment Scenario	Profile 17a Unbonded		Profile 12a Bonded		Percentage Distance Gain	
	DS	US	DS	US	DS	US
70/30 Mbps	400 ft (120 m)	200 ft (60 m)	2100 ft (640 m)	1600 ft (490 m)	425%	700%
50/10 Mbps	1500 ft (450 m)	2600 ft (790 m)	3100 ft (940 m)	3600 ft (1100 m)	107%	38%

To illustrate the gains in bit rate, we chose the same reference distance values as selected earlier. That is:

- 660 ft (200 m) for in building, or FTTB, applications,
- 2000 ft (600 m) and 2600 ft (800 m) for FTTN applications, and
- 3900 ft (1200 m) for long reach applications of VDSL.

The results are summarized in Table 2. Note that the gains in bit rate are greatest at the longer loop lengths.

Table 2 Bit Rate Gains: Pair Bonded Profile 12a Over Profile 17a

Distance	Profile 17a Single Pair (Mbps)		Bonded Profile 17a (Mbps)		Percentage Rate Gain	
	DS	US	DS	US	DS	US
660 ft (200 m)	65	24	111	40	71%	67%
2000 ft (600 m)	41	16	74	27	80%	69%
2600 ft (800 m)	33	10	60	17	82%	70%
3900 ft (1200 m)	21	4	40	7	90%	75%

Profile 12a Unbonded vs. Profile 12a Bonded

The yellow curve (i.e., fourth curve from the top,) in Figure 11 shows the achievable downstream line bit rates as a function of distance for VDSL systems deployed on a single loop using profile 12a. The light blue curve (i.e., top curve,) shows the achievable bit rates for VDSL systems deployed using pair bonding with profile 12a.

Figure 11 *Downstream Rate Comparison: Profile 12a Single Pair versus Profile 12 Bonded (Annex A)*

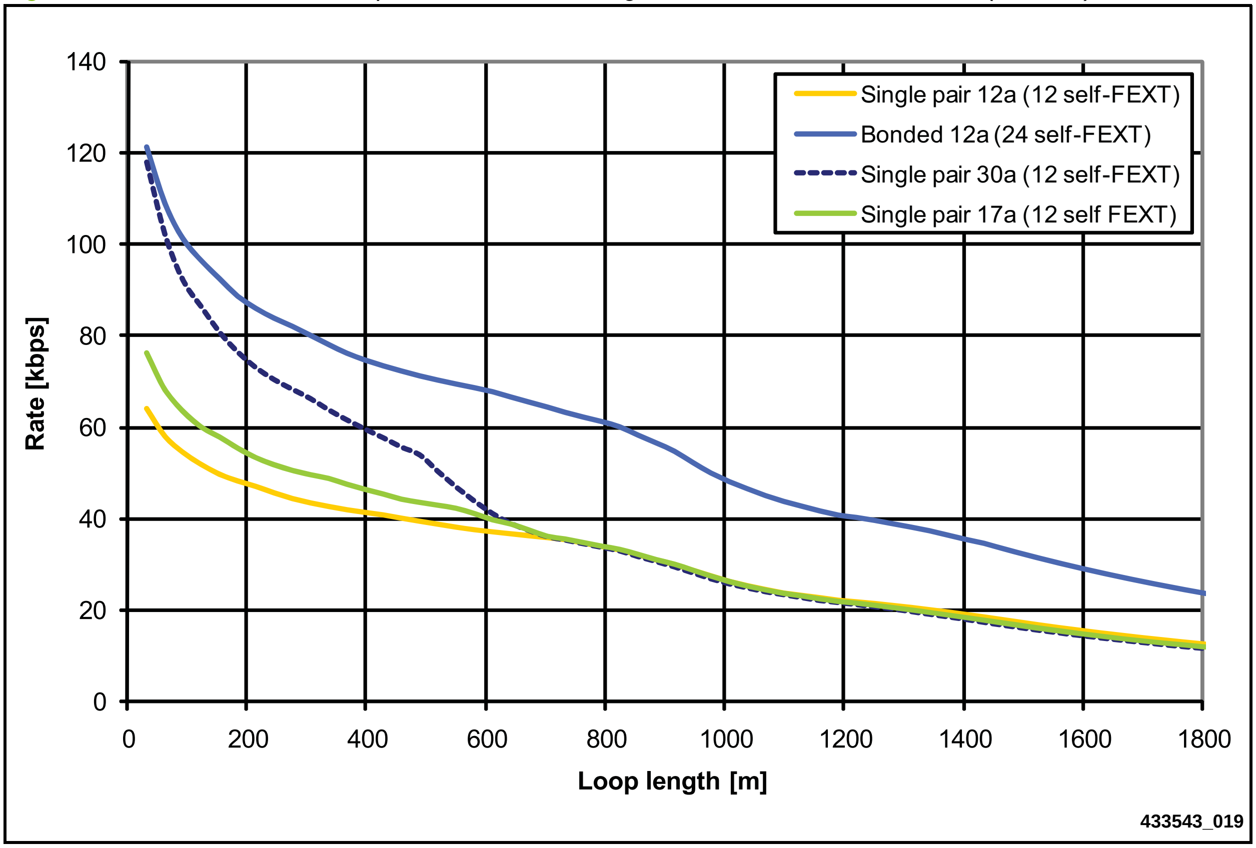
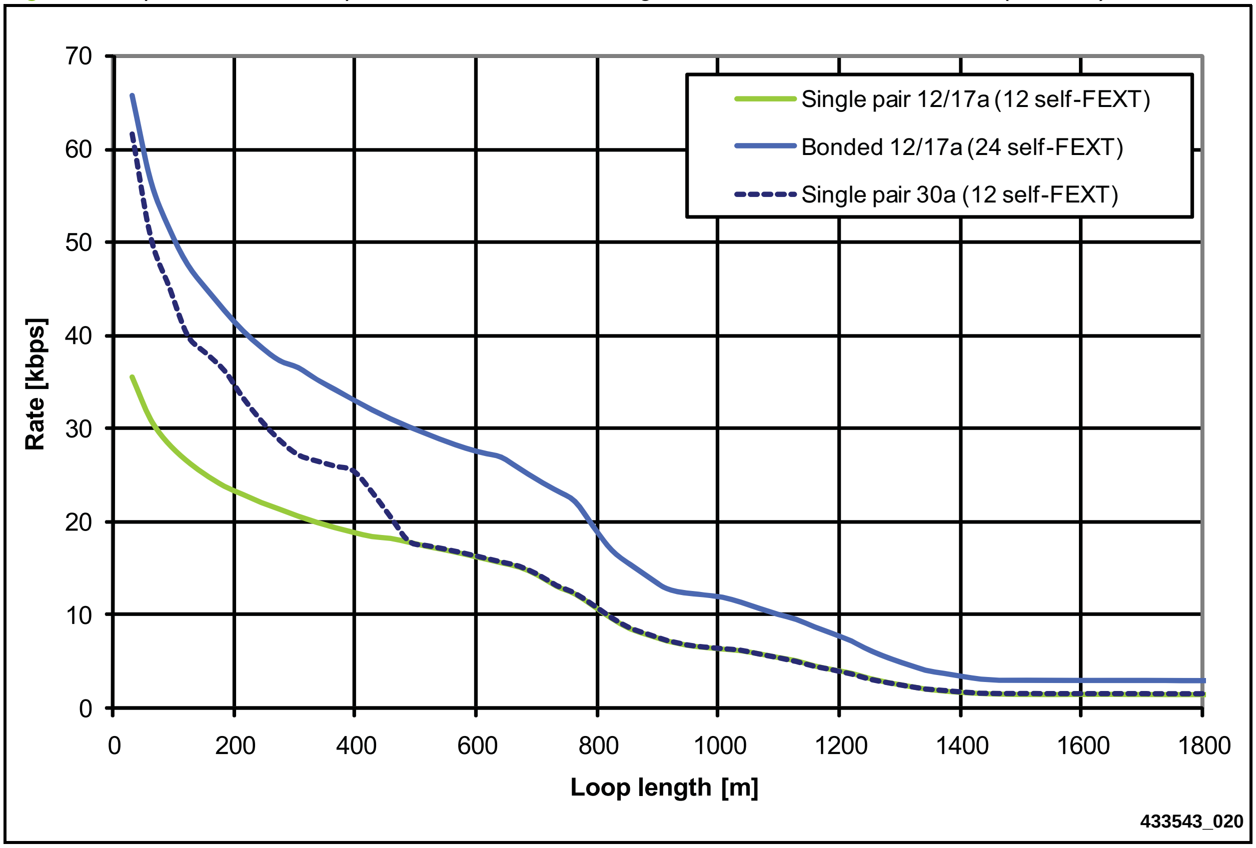


Figure 12 provides the corresponding performance for the upstream channel. The top curve (i.e., the blue curve,) shows the pair bonded profile 12a upstream bit rates and the third curve from the top (i.e., the green curve,) shows the single pair upstream profile 12a (i.e., the same as for profile 17a,) bit rates.

Figure 12 *Upstream Rate Comparison: Profile 12a/17a Single Pair versus Profile 12 Bonded (Annex A)*



When compared with the deployment of a single pair profile 12a system, the bit rate gain is approximately 2:1. The reason for the factor's being slightly less than two is that for the pair bonding case, a 24 self-crosstalk disturber model is assumed where for the unbonded case, 12 self-crosstalk disturbers are assumed.

For the distance gains, we chose two reference service deployment scenarios:

- 50 Mbps down and 10 Mbps up (indicated as 50/10 Mbps),
- 25 Mbps down and 2 Mbps up (indicated as 25/2 Mbps).

The following observations and conclusions can be made:

- For the 50/10 Mbps service, profile 12a may be deployed up to a distance of approximately 425 ft (130 m,) limited by the downstream channel capacity. Note that the upstream channel at 10 Mbps may reach up to approximately 2700 ft (830 m.)
- With pair-bonded profile 12a, the reach for the 50/10 Mbps service is extended up to approximately 3200 ft (970 m,) limited by the downstream channel capacity. Note that the upstream channel at 10 Mbps may reach up to approximately 3600 ft (1100 m.)
- For the 25/2 Mbps service, profile 12a may be deployed up to a distance of approximately 3400 ft (1040 m.) In this case, the downstream limits the reach.
- With pair-bonded profile 12a, the reach for the 25/2 Mbps service is extended up to approximately 5700 ft (1740 m,) limited by the downstream channel capacity.

The above gains in reach of pair-bonded profile 12a over unbonded profile 17a are summarized in Table 3, including the percentage gain in the largest distance that can support both upstream and downstream reference rates for each scenario.

Table 3 Distance Gains: Pair-bonded Profile 12a Over Profile 12a

Deployment Scenario	Profile 12a Unbonded		Profile 12a Bonded		Percentage Distance Gain
	DS	US	DS	US	
50/10 Mbps	420 ft (130 m)	2700 ft (830 m)	3200 ft (970 m)	3600 ft (1100 m)	646%
25/2 Mbps	3400 ft (1040 m)	4400 ft (1350 m)	5700 ft (1740 m)	>6000 ft (1800 m)	67.3%

To illustrate the gains in bit rate, we chose the same reference distance values as selected earlier. That is:

- 660 ft (200 m) for in building, or FTTB, applications,
- 2000 ft (600 m) and 2600 ft (800 m) for FTTN applications, and
- 3900 ft (1200 m) for long reach applications of VDSL.

The results are summarized in Table 4. Note that the gains in bit rate are greatest at the longer loop lengths.

Table 4 Bit Rate Gains: Pair-bonded Profile 12a Over Profile 12a

Distance	Profile 12a (Mbps)		Bonded Profile 12a (Mbps)		Percentage Bit Rate Gain	
	DS	US	DS	US	DS	US
660 ft (200 m)	48	23	87	41	81%	78%
2000 ft (600 m)	37	16	68	27	84%	68%
2600 ft (800 m)	34	11	61	19	79%	73%
3900 ft (1200 m)	21	4	40	8	90%	100%

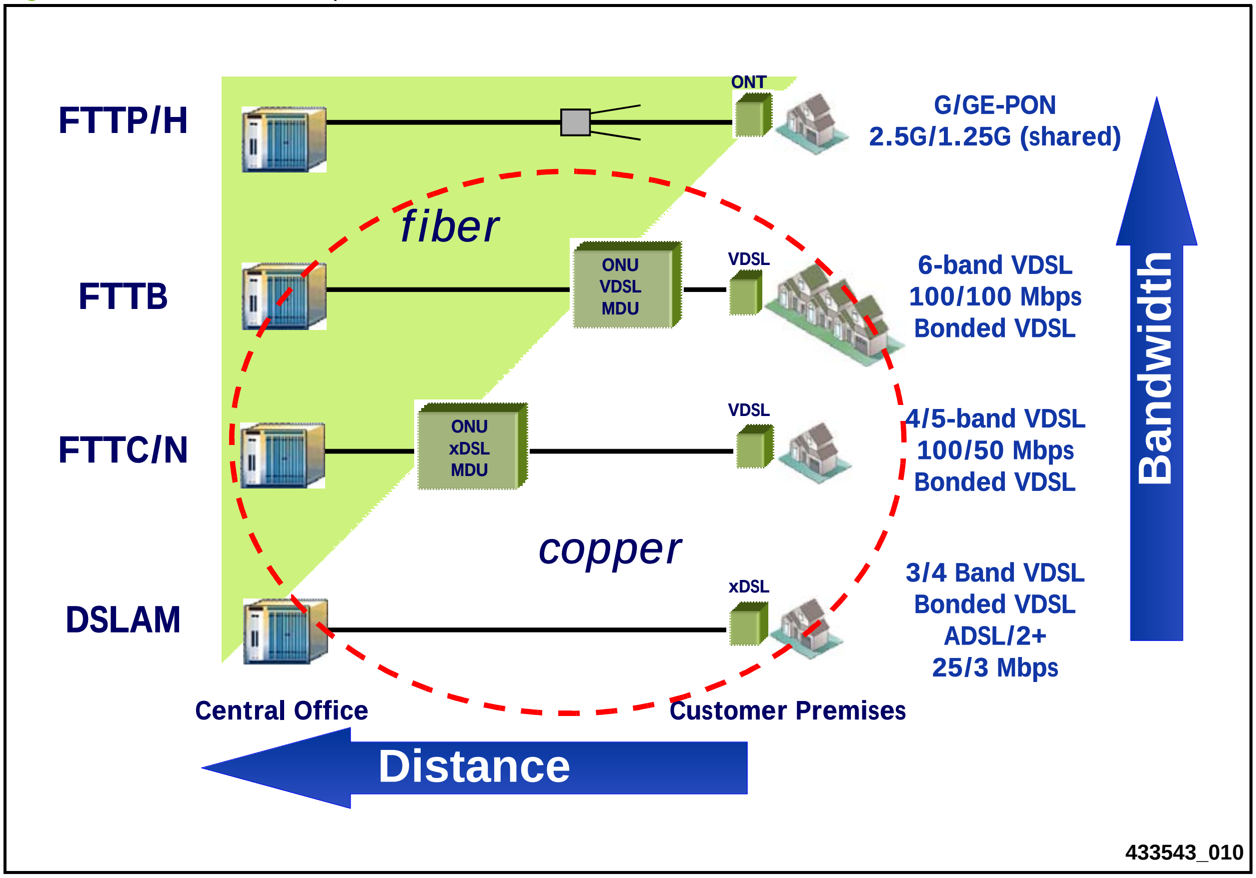
Case Study: VDSL Pair Bonding for Broadband Network Upgrades

This case study illustrates how VDSL pair bonding influences investment choices for operators looking to upgrade their customer network. It focuses on the financial cost-analysis performed by a fictional operator, W-Telecom, using a concrete example of a network in transition by examining the financial implications of each of the following last mile upgrade options when upgrading legacy customers to triple play service rates:

- Ethernet passive optical network (EPON);
- VDSL;
- VDSL pair bonding.

Figure 13 illustrates the four classical architectures of last mile access technologies based on fiber and copper.

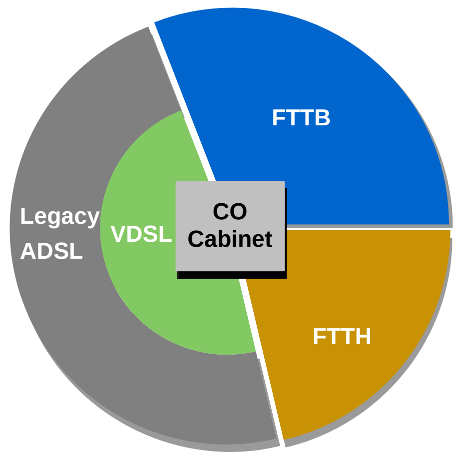
Figure 13 *Last-Mile Access Options*



W-Telecom's Network in 2010

Figure 14 illustrates graphically the relative distribution of W-Telecom's current last mile customer deployments.

Figure 14 *W-Telecom Last Mile Customer Deployments in 2010*



From Figure 14, it is seen that, in 2010, approximately:

- One-third of its deployments is FTTB.

  These deployments, even when installed post-construction, have proven to be cost-effective due to multiple customers being serviced by a single fiber installation/deployment.

- One-fifth of its deployments is FTTH.

  These deployments are primarily found in neighborhoods and buildings where fiber was installed as part of the initial construction.

- One-half of its deployments is a combination of VDSL/legacy ADSL where:
  - Most ADSL customers that are geographically located close enough to the CO/Cabinet have already been upgraded to VDSL service.
  - The remaining legacy ADSL customers are primarily single family homes located too far from a DSLAM to be upgraded to VDSL.

Table 5 provides detailed customer deployment information, including revenue dollars per unit.

Table 5 W-Telecom Customer Deployment Information

	ADSL	VDSL	FTTB	FTTH	Total
Subscribers (in thousands)	1,407	1,943	2,010	1,340	6,700
	21%	29%	30%	20%	
Rates (Mbps)	4 - 20	20 - 50	10 - 50	30	
ARPU	25	30	28	40	
Revenue generated (USD, thousands)	$422,100.	$699,480.	$675,360.	$643,200.	$2,440,140.
Maximum distance from CO/Cabinet	1.25 Miles (2 km)	0.75 Miles (1.2 km)	0.2 Miles (0.3 km)	9 Miles (15 km)	

W-Telecom's plan to cost-effectively upgrade their legacy ADSL deployments to allow triple play service rates is driven by the following factors:

- The bandwidth available to legacy ADSL customers is too low for high end services (e.g., IPTV), resulting in low average revenue per user (ARPU).
- Upgrading legacy ADSL customers to a guaranteed 30 Mbps service will increase ARPU by $15, thus generating an additional $250 million of revenue annually.
- The operator's technology upgrade requirements include:
  - Maximizing the return on investment,
  - Leveraging the existing infrastructure,
  - Their upgrade must be field proven.

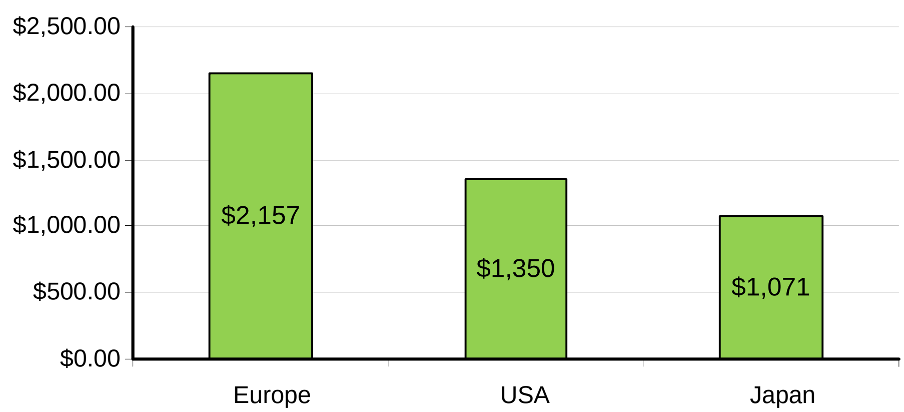
Upgrade Cost Analysis by Last Mile Technology

This section provides the cost analysis for each of the last mile technologies being considered.

EPON Upgrade Cost Analysis

Despite equipment cost reductions and improvements in installation time, fiber installation costs continue to remain above $1,000 (USD) in the majority of industrialized economies. Figure 15 compares the installation cost per subscriber, in US Dollars, for Europe, the US, and Japan.

Figure 15 *Typical Cost for Fiber (US Dollars per Subscriber*



SOURCE: AT KEARNEY, ING, NTT, AT&T, IKANOS

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Table 6 calculates the total investment (in thousands of US dollars) for W-Telecom to upgrade their legacy ADSL customers to EPON service based on typical installation costs cited in Figure 15.

Table 6 Extended Upgrade Investment Using Typical EPON Installation Costs from Figure 15

	Europe	USA	Japan
Subscribers to Upgrade 1.4M	1,407	1,407	1,407
Cost per Subscriber	$2,157.	$1,350.	$1,071.
Total Investment to Upgrade Legacy Subscribers (USD, thousands)	$3,034,899.	$1,899,450.	$1,506,897.

VDSL Upgrade Cost Analysis

As seen in Figure 16, 30/5 Mbps service is guaranteed for a maximum loop length of 3000 ft (914 m) under the following conditions:

- Profile 17a;
- 12 Self-Crosstalk disturbers;
- 26 AWG wire;
- UPBO is off.

Refer to Performance Gains with Bonding, for additional information.

Figure 16 *Rate versus Reach for VDSL Profile 17a; 12 Self-Crosstalk Disturbers; 26 AWG; UPBO Off*

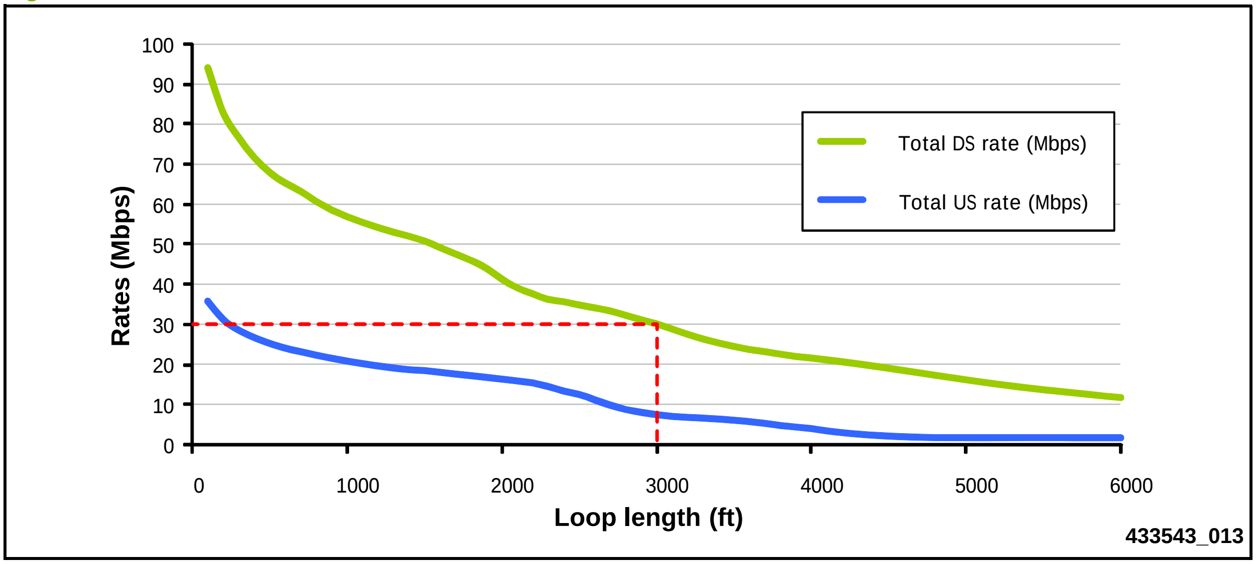


Table 7 calculates the total investment (in thousands of US dollars) for W-Telecom to upgrade their legacy ADSL customers to VDSL service based on typical equipment and installation costs.

NOTE:

For simplicity, the numbers cited in Table 7 assume a homogenous population density which yields a square relationship between loop length and cabinet density. However, in reality, this relationship is less than a true square dependence. Therefore, the numbers cited in Table 7 provide an upper limit for the investment in cabinet equipment.

Table 7 Estimated VDSL Deployment Upgrade Cost

	Low Estimate			High Estimate		
	Unit Cost	2010	2012	Unit Cost	2010	2012
Cabinets						
Number of COs/Cabinets in network		1,600	7,511		1,600	7,511
Service Radius (feet)		6,500	3,000		6,500	3,000
New cabinets installed			5,911			5,911
Cabinet equipment and installation (thousand USD)	$40.			$70.		
Investments in cabinets (thousand USD)			$236,444.			$413,778.
Equipment						
Cost per CPE	$30.			$145.		
Cost per CO Port	$45.			$76.		
Total CO + CPE cost	$75.			$221.		
Installation						
Hours	2.0			2.0		
Labor Rate	$25.			$65.		
Total Installation Cost	$50.			$130.		
Total Labor and DSL Ports	$125.			$351.		
Subscribers to Upgrade	1407			1407		
			$175,875.			$493,857.
Total cost of upgrade (USD)			$412,319.			$907,635.
Cost of upgrade per subscriber			$293.			$645.

VDSL Pair Bonding Upgrade Cost Analysis

As seen in Figure 17, 30/3 Mbps service is guaranteed for a maximum loop length of 5100 feet (1550 m) under the following conditions:

- 24 Self-Crosstalk disturbers;
- 26 AWG wire;
- UPBO is off.

Refer to Performance Gains with Bonding, for additional information.

NOTE:
It is assumed that double binder density for bonding is used since two wire-pairs are used per subscriber.

Figure 17 *Rate versus Reach for VDSL Pair Bonding; 24 Self-Crosstalk Disturbers; 26 AWG; UPBO Off*

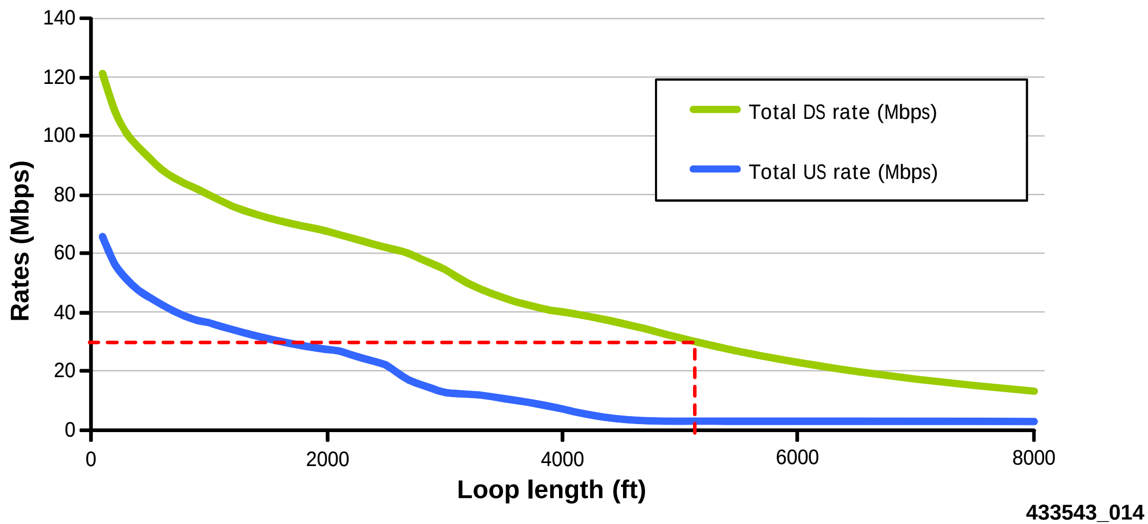


Table 8 calculates the total investment (in thousands of US dollars) for W-Telecom to upgrade their legacy ADSL customers to VDSL pair bonding service based on typical equipment and installation costs.

NOTE:
For simplicity, the numbers cited in Table 8 assume a homogenous population density which yields a square relationship between loop length and cabinet density. However, in reality, this relationship is less than a true square dependence. Therefore, the numbers cited in Table 8 provide an upper limit for the investment in cabinet equipment.

NOTE:
The number of new cabinets required is far fewer than that required for single-pair VDSL service due to the extended coverage radius for bonding mode (i.e., 5100 ft/ 1550 m)

Table 8 Estimated VDSL Pair Bonding Deployment Upgrade Cost

	Low Estimate			High Estimate		
	Unit Cost	2010	2012	Unit Cost	2010	2012
Cabinets						
Number of COs/Cabinets in existing network		1,600	2,599		1,600	2,599
Service Radius (feet)		6,500	5,100		6,500	5,100
New cabinets installed			999			999
Cabinet equipment and installation (thousand USD)	$40.			$70.		
Investments in cabinets (thousand USD)			$39,960.			$69,930.
Equipment						
Cost per CPE	$40.			$155.		
Cost per CO Port	$90.			$152.		
Total CO + CPE cost	$130.			$307.		
Installation						
Hours	2.0			2.0		
Labor Rate	$25.			$65.		
Total Installation Cost	$50.			130.$		
Total Labor and DSL Ports	$180.			$437.		
Subscribers to Upgrade	1407			1407		
			$253,260.			$614,859.
Total cost of upgrade (USD)			$293,220.			$684,789.
Cost of upgrade per subscriber			$208.			$487.

NOTE:

The average cost of VDSL pair bonding in deployments as of this writing is approximately $360.

Comparison

Advantages and disadvantages of each of the three deployment upgrade options considered by W-Telecom include:

- EPON
  - Advantages
    - Easily achieves bandwidths in excess of 30 Mbps;
    - Proven technology already deployed by the operator.
  - Disadvantages
    - Rising installation cost as the majority of new deployments shifts from pre-wired homes to green field.
- VDSL
  - Advantages
    - Lower cost solution than EPON
    - Proven technology already deployed by the operator
  - Disadvantages
    - Requires investment in new cabinets in order to install DSLAMs close enough to subscribers for an upgrade to VDSL rates
- VDSL pair bonding
  - Advantages
    - Doubles rates at any given loop length
    - Allows reach extension of ~2000 ft for typical VDSL rates
    - Innovative technology currently in field trials at multiple operators around the world

Figure 18 and Table 9 provide comparisons between the three upgrade options based upon the analyses performed in VDSL Upgrade Cost Analysis.

Figure 18 *Graphical Comparison of Investment per Subscriber for Three Upgrade Options*

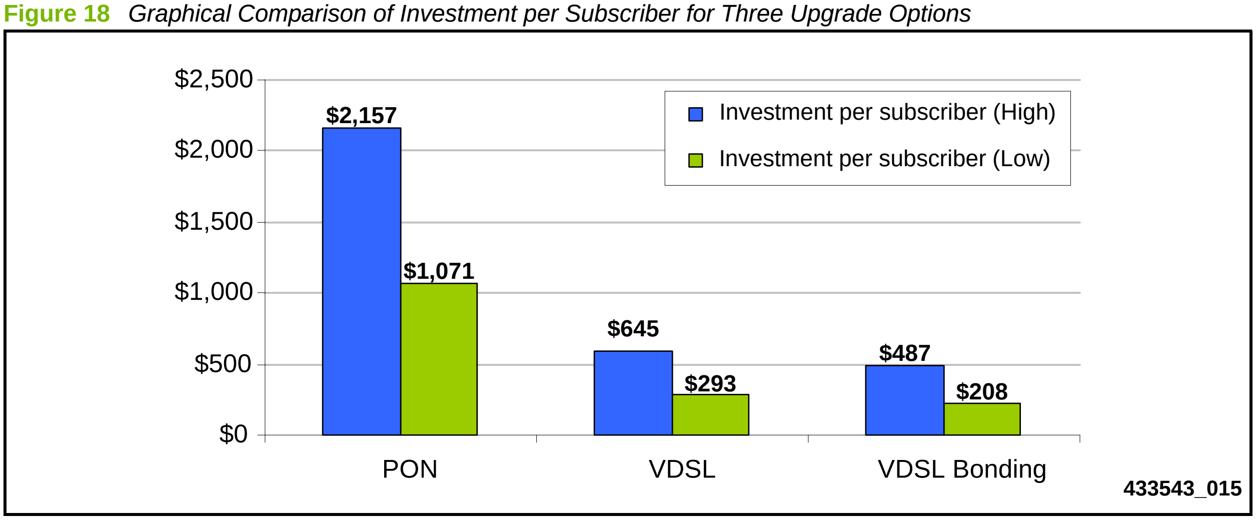


Table 9 High and Low Investment Comparisons of Three Deployment Upgrade Options

	PON	VDSL	VDSL Pair Bonding
Investment per subscriber (High)	$2,157.	$645.	$487.
Investment per subscriber (Low)	$1,071.	$293.	$208.
Total Investment (High)	$3,034,899.	$907,635.	$684,789.
Total Investment (Low)	$1,506,897.	$412,319.	$293,220.
Achievable Rates	30 Mbps	30 Mbps	30 Mbps
Additional Benefits	Possibility to increase rates beyond 30 Mbps with an upgrade of network access.	The majority of subscribers will benefit from higher rates due to a shorter average distance to the cabinet.	Most existing single pair VDSL users are eligible for a doubling of current rates. Increased stability compared with VDSL.

When comparing the costs associated with the three upgrade options side-by-side, two conclusions are immediately obvious:

- PON is an attractive option for a long-term service upgrade. However, the investment per subscriber remains extremely high.
- Despite the need for two VDSL ports, the increased service radius makes VDSL pair bonding the most economical alternative to upgrade legacy ADSL subscribers.

VDSL Pair Bonding Investment and Cash Flow Analysis

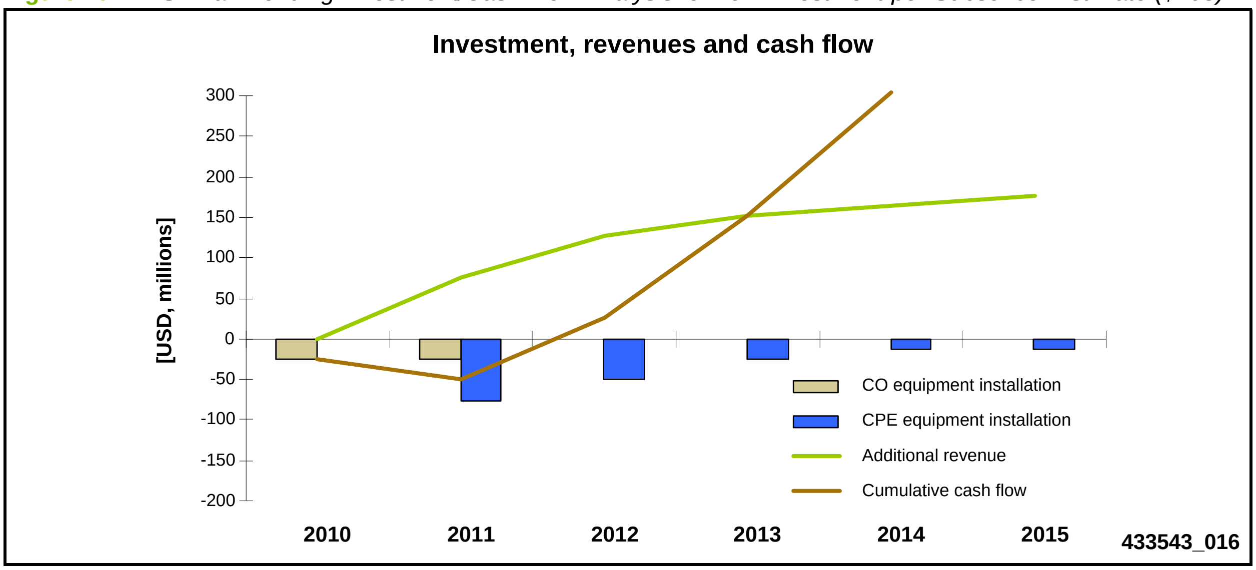
Based upon the results from the cost analyses for the three upgrade options, W-Telecom analyzed their potential investment versus cash flow for the high and low investment-per-subscriber values predicted for the VDSL pair bonding upgrade option.

Using an estimate of $208 investment per subscriber (i.e., the low estimate from Table 8), the VDSL pair bonding investment and cash flow analysis results in:

- An anticipated additional $15 of monthly revenue per subscriber[a];
- A net present value of the investment of $229 M (assumes 20% discount rate);
- An anticipated break-even point sometime during the second year following the initial investment as illustrated in Figure 19.

NOTE:
These results depend upon current economic conditions.

Figure 19 *VDSL Pair Bonding Investment/Cash Flow Analysis for Low Investment-per-Subscriber Estimate ($208)*



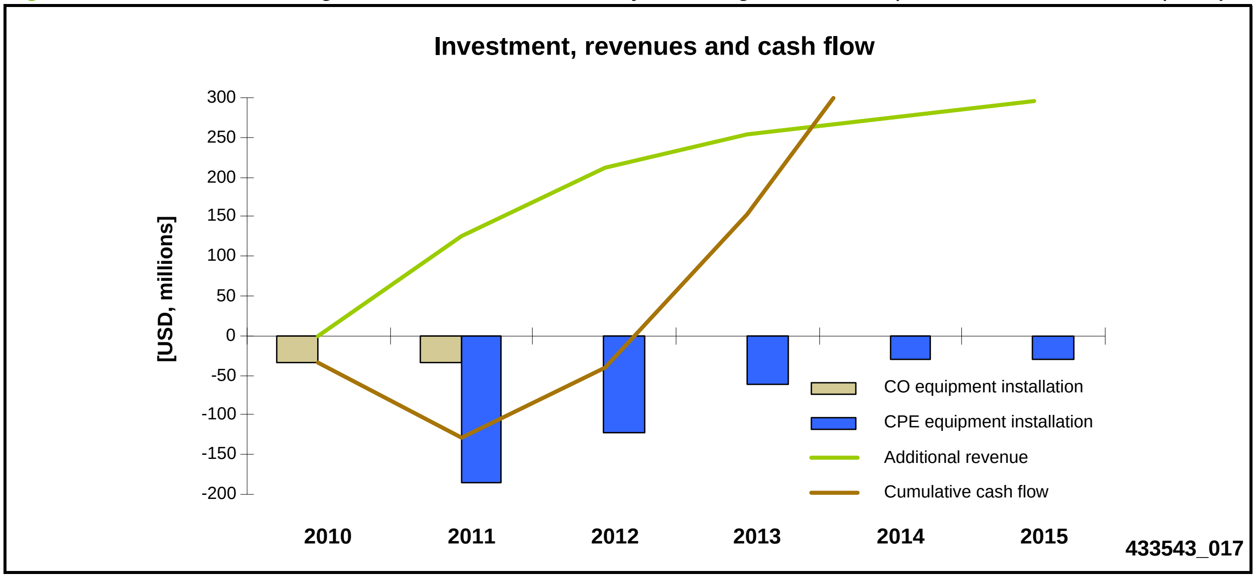
Similarly, using an estimate of $487 investment per subscriber (i.e., the high estimate from Table 8), the VDSL pair bonding investment and cash flow analysis results in:

- An additional $25 of monthly revenue per subscriber;
- A net present value of the investment of $284 M (assumes 20% discount rate);
- An anticipated break-even point sometime during the third year following the initial investment as illustrated in Figure 20.

NOTE:
These results depend upon current economic conditions.

a. This is an assumption made as part of the upgrade model used.

Figure 20 *VDSL Pair Bonding Investment/Cash Flow Analysis for High Investment-per-Subscriber Estimate ($487)*



In both the low- and high-estimate scenarios, the largest investment is in the CPE installation and equipment. This ensures that the new revenue curve closely follows the investment curve.

Case Study Findings

General findings of this case study include:

- Fiber remains three-to-four times more expensive than VDSL for service rates of approximately 30 Mbps.
- VDSL pair bonding offers significant advantages over VDSL and xPON, including:
  - Second line costs are more than offset by the savings realized due to the increased service radius of each cabinet/central office.
  - VDSL pair bonding is the most economical technology currently available when upgrading subscribers located outside of the single-pair VDSL service radius.
  - Improved quality of experience (QoE) resulting from the additional robustness provided by the second VDSL pair.
- There is a minimum lag between investment and tevenue curves resulting in a significantly reduced break-even point.
  - Investment costs are primarily driven by CPE upgrades and installation.
- Continuous technology innovations extend the capabilities of the existing infrastructure to enable advanced broadband services. For example:
  - VDSL pair bonding extends the attainable rate/reach using the existing wired infrastructure.
  - Vectored VDSL will enable further improvements by virtually eliminating crosstalk interference.
  - VDSL pair bonding combined with vectored VDSL will enable rates of 100 Mbps out to 3000 ft (900 m.)

Summary and Conclusion

When a second wire pair is available to an end-user, pair-bonded VDSL has been shown to be a viable solution for providing extended reach or higher bit rate over deployment of VDSL service on a single pair. Pair-bonded VDSL provides rate and reach gains over single pair VDSL systems with profiles 8, 12a, 17a, or 30a. Table 10 and Table 11 provide summaries of rate and reach gains for common service deployment scenarios. It should be noted that extended rate and reach results in greatly reduced capital expenditures thanks to a reduction in the number of cabinets required to service a given area.

Table 10 Summary of Bit Rate Improvements Using Pair-bonded Profile 12a

Distance	Profile 30a (Mbps)		Profile 17a (Mbps)		Profile 12a (Mbps)		Bonded Profile 12a (Mbps)	
	DS	US	DS	US	DS	US	DS	US
660 ft (200 m)	75	35	63	23	48	23	87	41
2000 ft (600 m)	41	16	40	16	37	16	68	27
2600 ft (800 m)	34	11	34	11	34	11	61	19
3900 ft (1200 m)	21	4	21	4	21	4	40	8

Table 11 Summary of Reach Improvements Using Pair-bonded Profile 12a

Deployment Scenario (Mbps)	Profile 30a		Profile 17a		Profile 12a		Bonded Profile 12a	
	DS	US	DS	US	DS	US	DS	US
100/50	230 ft (70 m)	200 ft (60 m)	-	-	-	-	360 ft (110 m)	330 ft (100 m)
70/30	820 ft (250 m)	820 ft (250 m)	425 ft (130 m)	260 ft (80 m)	-	-	1800 ft (550 m)	1600 ft (500 m)
50/10	1700 ft (520 m)	2700 ft (830 m)	1500 460 m	2700 ft (830 m)	425 ft (130 m)	2700 ft (830 m)	3200 ft (970 m)	3600 ft (1100 m)
25/2	3400 ft (1040 m)	4400 ft (1350 m)	3400 ft (1040 m)	4400 ft (1350 m)	3400 ft (1040 m)	4400 ft (1350 m)	5700 ft (1740 m)	> 5900 ft (1800 m)

The lower costs and advanced capabilities of hybrid copper/optical systems are allowing many major telecommunications providers to push forward with their multimedia network upgrade roll outs, despite reduced access to capital and slimmer profit margins. Many service providers once considered staunch proponents of FTTH architectures have reconsidered their commitment and are moving away from the FTTH option instead for the economic realities and price/performance advantages of VDSL.

Looking Ahead

Ikanos' bonding technology enables DSL service providers to overcome bandwidth limitations inherent to copper infrastructures. VDSL pair bonding from Ikanos increases the capacity of subscriber lines and enables service providers to dramatically increase throughput speeds and extend broadband services to more homes. Further advances in VDSL technology are on the horizon. Vectored VDSL is expected to enable fiber-class performance allowing service providers to deliver advanced multimedia services at a fraction of the cost of other technologies such as cable and FTTH. Alone or combined, these technologies allow service providers to maximize their investment in copper infrastructure while efficiently deploying the bandwidth necessary to deliver advanced multimedia services to customers.

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Ikanos Communications, Inc. (NASDAQ: IKAN) is a leading provider of advanced broadband semiconductor and software products for the digital home. The company's broadband DSL, communications processors and other offerings power access infrastructure and customer premises equipment for many of the world's leading network equipment manufacturers and telecommunications service providers. For more information, visit **www.ikanos.com**.

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