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May 3, 2010

Via Email
David H. Su, NIST PAP15 Chair (david.su@nist.gov)
Rik Drummond, SGTCC Chair (rikd@drummondgroup.com)
Dean Prochaska, SGTCC Vice Chair (dean.prochaska@nist.gov)
Ron Ambrosio, SGAC Chair (rfa@us.ibm.com)

Re: Protection of DSL

Dear Messrs Su, Drummond, Prochaska, and Ambrosio:

The Alliance for Telecommunications Industry Solutions (ATIS) Copper/Optical Access, Synchronization and Transport (COAST) Network Access Interfaces (NAI) subcommittee is responsible for United States industry standards for DSL technology and also reviews United States input to the ITU-T regarding DSL and home networking standards.

ADSL, ADSL2plus, and VDSL2 transmission via telephone lines provide broadband service to approximately 40 million customers in the United States. The number of customers served by DSL technology is growing and the bit-rate delivered to these customers is also increasing. We request NIST's assistance to ensure the developing Smart Grid technology be designed to avoid adverse impact to the existing, widely used DSL technology.

The frequency band and transmitted power of signals used for Smart Grid communications to and from the home should be specified to minimize interference into ADSL (ITU-T G.992.1), ADSL2 (ITU-T G.993.2), ADSL2plus (ITU-T G.992.5), and VDSL2 (ITU-T G.993.2) due to electromagnetic emissions from power lines.

The most commonly used ADSL, ADSL2, and ADSL2plus frequency bands for ADSL are:
upstream: 25.875 kHz to 138 kHz (for all ADSL)
downstream: 138 kHz to 1.1 MHz (for G.992.1 and G.992.3)
downstream: 138 kHz to 2.2 MHz (for G.992.5)

The frequency bands specified in ITU-T Recommendation G.993.2 (VDSL2) are:
optional upstream band: 25.875 kHz to 138 kHz
downstream 1: 138 kHz to 3.75 MHz
upstream 1: 3.75 MHz to 5.2 MHz

downstream 2: 5.2 MHz to 8.5 MHz
upstream 2: 8.5 MHz to 12 MHz
downstream 3: 12 MHz to 23 MHz
upstream 3: 23 MHz to 30 MHz

Please note that the VDSL2 standard specifies several profiles which define different maximum frequencies: 8.5 MHz, 12 MHz, 17 MHz, and 30 MHz. Thus, not all VDSL2 implementations utilize the full 30 MHz spectrum.

As shown in Figure 10 of the attached document, the coupling between telephone and power drop wires decreases with frequency, particularly at frequencies below 2 MHz. Please note that the referenced paper only reports on measurements take at the drop wire. We do not have measured data on the coupling for inside wiring (power to telephone), but in general we expect the coupling to decrease with decreasing frequency.

Please let us know if you have any questions or comments. We look forward to working with you on this issue.

Sincerely,

John McDonough
ATIS COAST Chairman

Attached: ATIS NIPP-NAI-2007-058

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NIPP-NAI-2007-058

Network Interface, Power, and Protection (NIPP)
Network Access Interfaces (NAI) Subcommittee
Minneapolis, MN - May 14 -17, 2007

CONTRIBUTION

TITLE:	**Revised analysis of BPL interference into VDSL2**
SOURCE:	**AT&T** **Tom Starr** **ts1452@att.com** **+1-847-248-5467**

ABSTRACT

This paper, written by Dr. Ken Kerpez, provides revisions to the analysis of BPL interference into VDSL2 originally reported in NIPP-NAI-2006-158 to correct errors made for the impact to upstream VDSL2 performance. While the revised analysis still shows a serious potential reduction to downstream VDSL2 performance, the impact to upstream VDSL2 performance is less than previously reported. This is for information only.

Broadband Powerline (BPL) Interference into VDSL2 on Drop Wires

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1 Reason for Revision

The original version of this contribution, R0, failed to account for a likely consideration. Interference from BPL at the customer-end of a VDSL2 loop will probably be attenuated by the VDSL2 loop before impinging the upstream VDSL2 receiver. As seen in Figure 1, it is also possible that a bridged tap (an untermimated stub on the phone line, which is common) would couple BPL interference into the line near the CO, then the BPL interference would not be attenuated so then the results for the impact of BPL on upstream VDSL2 in the original version would apply. However, this is unlikely, so the contribution was revised.

In this revision it is assumed that interference from BPL on a drop line at the customer-end of a VDSL2 loop is attenuated by the VDSL2 loop before impinging on the upstream VDSL2 receiver. This results in BPL causing a small performance degradation to upstream VDSL2, the worst degradation was 1.4% of the upstream bit rate of VDSL2 profiles 8a and 12a. This was on the shortest loop (1 kft) examined.

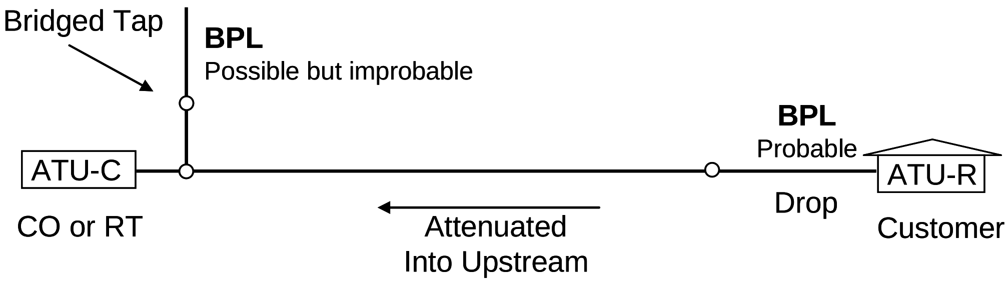

Figure 1. Reason for this revision.

While it was discovered that the impairment to VDSL2 upstream is relatively small, the impact to downstream remains a serious concern since the VDSL2 downstream bit-rates may be reduced up to 25% as the result of BPL emissions.

Impact on downstream VDSL2 is the same as previously, and so most overall conclusions are the same as in the original version since downstream is critical for IPTV service delivery.

2 Introduction

Broadband Power Line (BPL) communications systems transmit at frequencies (1.7 to 30 MHz) that overlap the passband frequencies of VDSL2 [1] (26 kHz up to 8 to 30 MHz). Electromagnetic leakage from BPL lines may be received on VDSL2 lines, and the potential for this to disrupt VDSL2 services is examined here. Radio emissions were measured from the BPL and VDSL2 drop lines used in this study, and BPL emissions were measured to be an average of 18 dB higher than VDSL2 emissions. This study shows that these BPL emissions decrease VDSL2 bit rates.

The coupling between BPL and VDSL2 drop wires were measured under typical scenarios with aerial drop wires. Couplings between a number of different lengths, types of drop wire, and termination impedances were measured and used here. Then, the measured couplings were input to well-developed and accurate models of VDSL2 performance to precisely determine the impact of BPL on VDSL2 [2][3]. A number of parameters were varied to see if the impact of BPL on VDSL2 can be mitigated.

It is shown here that downstream bit rates of VDSL2 are lowered 14% on average, and 25% maximum, from BPL interference on drop lines, a large decrease considering that a 100% decrease would equal zero bit rate. About a 35 Mbps downstream line rate is desired for new FTTN deployments for IPTV service, for this rate BPL was found to lower the average VDSL2 range by about ¾ kft, decreasing from about 3¼ kft to about 2½ kft, which would increase the necessary number of fiber-fed serving areas by roughly 70%.

Flat BPL transmit levels of -80 dBm/Hz or lower appear to be sufficient to avoid impacting VDSL2. Or, using frequencies no lower than about 8 MHz for BPL appears to be sufficient to avoid impacting VDSL2. A high-level presentation of results is given in Section 7, and many detailed results are presented in Sections 5 and 6.

Nearby homes that subscribe to VDSL would be disrupted about the same amount by a neighbor's BPL system that shares power connections at a power transformer as they would if they had their own BPL connection, since attenuation across a powerline drop wire is negligible.

Only the drop wires are considered here and not in-home wiring. Measurements and results are typical and not worst case; in particular average measured couplings are used and not a worst-case model. The baseline VDSL2 performance was calculated with crosstalk that is a little worse than average; as described in Section 4.2.

Section 3 of this report describes the measurement set-up, wiring, and geometry in detail. Section 4 describes the transmission systems and parameters of BPL and VDSL2 used in this study. Section 5.1 presents the radiated emissions measurement results for BPL and VDSL2. Section 5.2 presents the measured electromagnetic coupling from BPL to VDSL2 lines. Section 5.3 shows the bit rates of VDSL2 with BPL interference and compares these to VDSL2 bit rates with no such interference.

Section 6 presents various techniques that could stop BPL systems from impacting VDSL2: lowering the BPL transmit power, not transmitting any BPL signals at lower frequencies, balancing BPL lines, and identifying BPL interference from its signature. Some combination of these techniques may eventually become a workable solution.

While it was discovered that the impairment to VDSL2 upstream is relatively small, the impact to downstream remains a serious concern since the VDSL2 downstream bit-rates may be reduced up to 25% as the result of BPL emissions.

3 Measurement Set-Up for BPL and VDSL2

The power coupling between power line drop wires and phone line drop wires was measured. There was no coupling in the home or on the network side of the drop, only the drop wires had a long exposure length and were somewhat close together.

3.1 Measurement Apparatus

Wideband measurements of the power coupling from powerline drop wires into both flat and twisted telephone drop wires were made by Telcordia using different spacings, lengths, and typical types of drop wires. The measurements were representative of typical field conditions. The measurement set-up reflected the field practices, including grounding and terminations, which are recommended for the respective systems [4].

As shown in Figure 3, the drop wires were mounted aerially, with the powerline and telephone drops running roughly in parallel across the drop length. The lengths of the two drops were usually either 80 ft or 57 ft, although other lengths were measured. The measured drop wires hung well above the ground plane of the earth, with the powerline at least 12 ft above the ground. This exceeds more than the 10 ft National Electrical Safety Code (NESC) Rule 252 minimum height above the ground specified for aerial separations on telephone poles. The customer end of the powerline neutral support wire was grounded to a grounding rod and bonded to a water pipe at the building entrance and grounded to a grounding rod at the network pole end.

The minimum specification for distance between power and telephone drop wires is 12 inches (National Electric Code (NEC), Articles 230, 800, & 820; latest edition, National Electrical Safety Code (NESC), Section 23; latest edition) so the customer end was nominally at this separation, although a couple of larger separations were measured.

Prior to 1987, a clearance between power and communications wires greater than 40 inches had to be maintained at the pole. In 1987, an exception was added to NESC Rule 235 C2b(1)(a) to allow communications conductors to be as close as 30 inches at the pole and 12 inches at mid span (between two poles) to effectively grounded neutral conductors as long as they are electrically bonded together. Distances used in this study between telephone and power line drop wires at the pole were 40 or 48 inches.

The following drop wire types were measured:
For telephone/VDSL2: Two types of two-wire flat drop, and 2-pair twisted 24 gauge drop. Specifically:

Flat A - AT&T 1993 copper-clad steel flat drop wire, 22 AWG
Flat B - AT&T 1993 flat drop wire, integral fiberglass messengers 24 AWG
Twisted - General Cable Company ASW metallic support, 2 pair 22 AWG

For BPL: Different lengths of 2, 2 gauge aluminum conductors with 2 gauge neutral support wire This is commonly called 2 gauge triplex aluminum overhead service wire, and is typical for 100 Amp service on aerial lines.

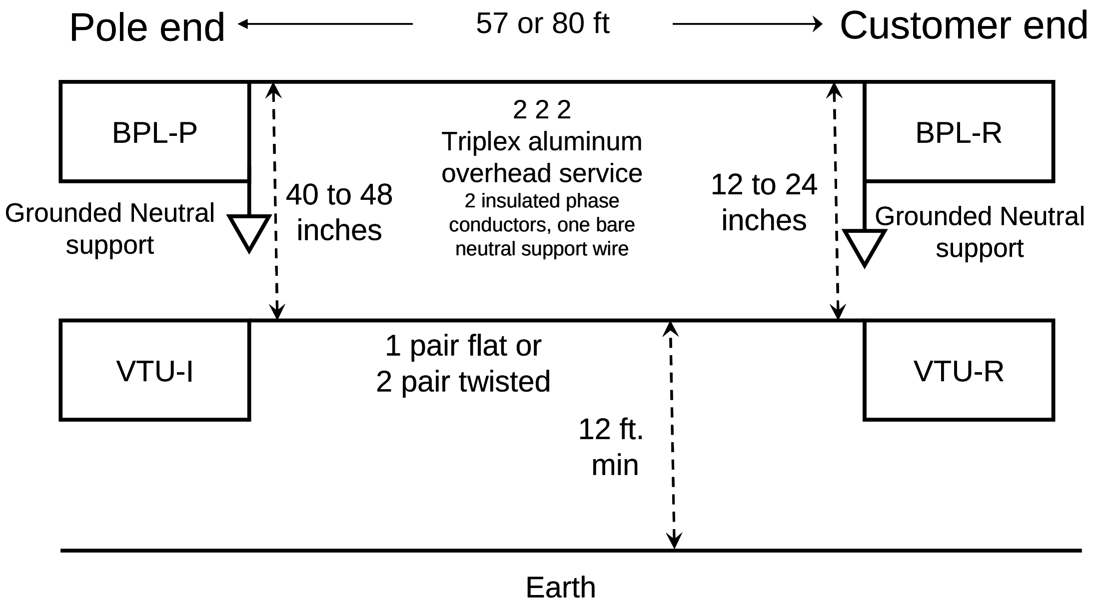

Figure 2. Physical Measurement set-up.

Measurements of coupling from BPL to VDSL2 drop wires were made with an HP8752C vector (magnitude and phase) network analyzer. Signals were injected into the power line through a balanced connection, i.e., an impedance-matching balun. The resulting signal received on the telephone wire was measured using a balanced connection, i.e., an impedance-matching balun. The loss of the connecting circuitry was calibrated out using the through response calibration procedure of the network analyzer. Each measurement recorded 1601 real and imaginary response points, evenly spaced from 300 kHz to 30 MHz. Coupling was well above the instrument's noise floor, except perhaps for some low frequencies of some measurements, below the 1.7 MHz minimum for BPL.

Telephone drop wire was either connected straight to a 100 Ohm measurement Balun, or connected through a splitter: here VDSL2 house wire consisted of a protector that had protection connected to ground connected to a VDSL splitter at the network interface (NI) which was terminated in 600 Ohm on the POTS side and 25 ft of Cat 5 cable to the 100 Ohm measurement Balun on the VDSL2 side. The network side of the VDSL2 drop terminated in 100 Ohms differential.

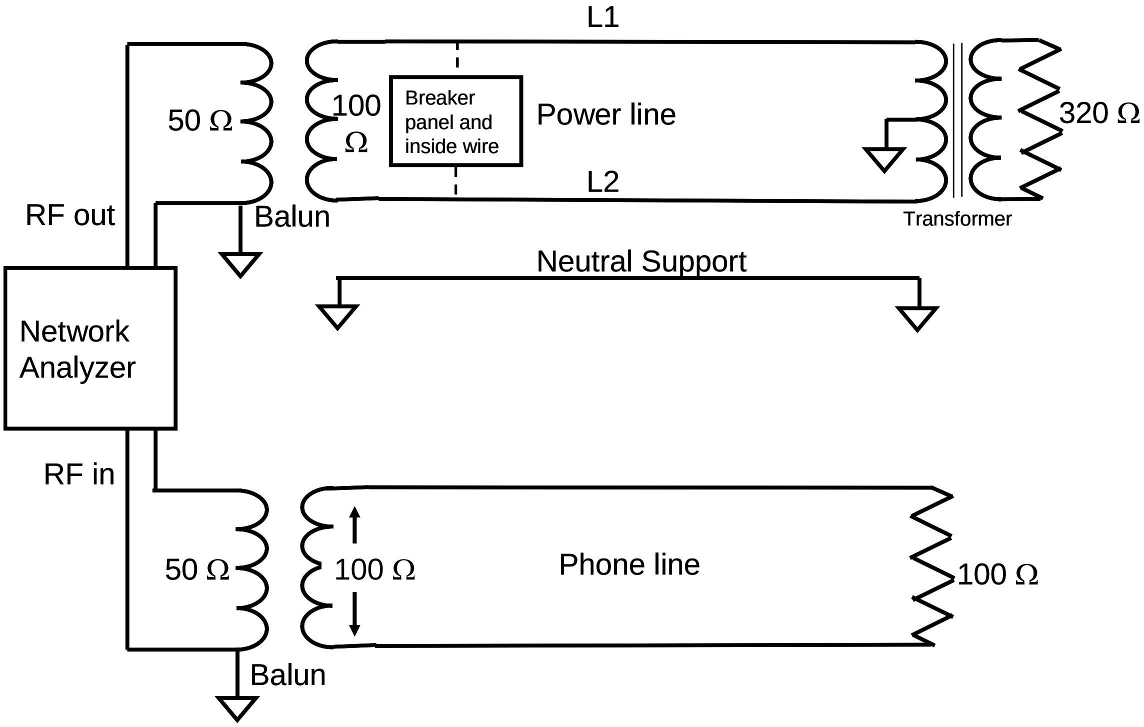

Figure 3. Electrical measurement set-up.

3.2 Impedances

The termination impedance is a primary determinant of the differential to common mode conversion. Termination impedances which are balanced on the differential and common modes will lead to lower radiation and coupling between lines than unbalanced impedances. Terminations on the VDSL2 phone drop wire ends will generally be balanced, except for perhaps very sight differences in wire length or in the impedance to ground at the network interface. All measured VDSL2 line terminations here were balanced. The VDSL2 system terminated in the standardized 100 Ohm purely resistive termination across the two wires.

Preliminary measurements showed that even slightly unbalancing the VDSL2 drop wire could cause a pronounced increase in power coupling from BPL, with roughly 20 dB increases. However, installation practices should balance the VDSL2 drops, and so they were always balanced in all reported measurements, other than perhaps some typical slight imperfections in the VDSL2 splitter and protector connections when terminating with the “house wire.”

The network side of the powerline drop may be reasonably well balanced simply due to symmetry, and such balance was used in measurements here. The network end of the powerline connected to a pair of transformers with windings for converting Medium Voltage at 4160 VAC into the two L1 and L2, 120V to Neutral, low Voltage legs typically used to serve homes in the USA [4]. The characteristic impedance of Medium Voltage aerial lines has been measured and modeled to be typically between 300 and 350 Ohms [7], and so terminations of 320 Ohms were used to approximate this on the network side of the transformers.

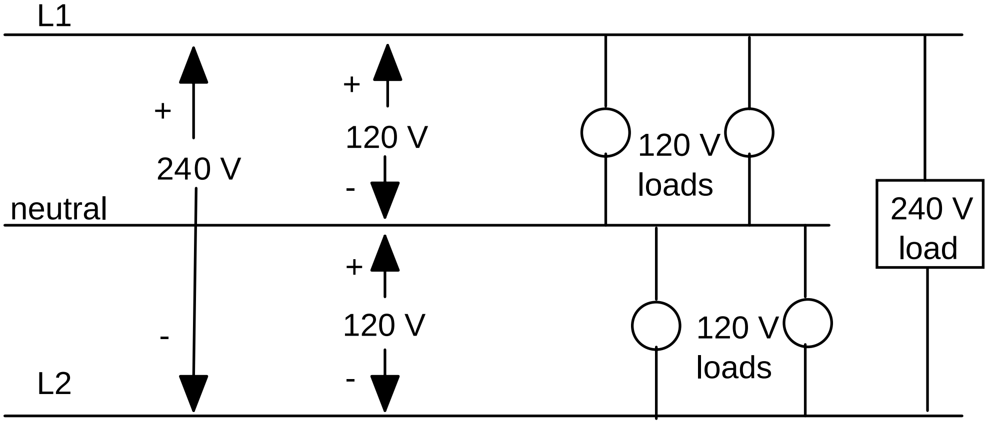

Figure 4. American 60 Hz, 240 VAC / 120 VAC residential electric power system.

The input impedance looking into a house, which becomes the termination impedance for the outdoor power line feed, is widely variable and dependent on many loads in the dwelling, as shown in Figure 4. Depending on the mode of transmission, the unbalanced termination from L1 to neutral or L2 to neutral can engender high common mode currents that cause emissions. In a recent study, power cable characteristic impedances were measured ranging from 73 to 140 Ohms differential and from 48 to 58 Ohms for pair-mode [5][6]. This variability increases substantially when attached loads are considered. Another paper found in-home termination impedances varying from 20 to 190 Ohms, and reported typical characteristic impedances of around 50 Ohms [8]. It is clearly possible for the L1 termination impedance to differ greatly from the L2 termination impedance. At MHz frequencies, 10 ohms on L1 or L2, and 150 Ohms on the other would not be uncommon.

Other studies have reported in-home powerline termination impedances as low as one Ohm at high frequencies with certain loads. MDUs have many taps into the power line feed so that, from the feed, the impedance looking into the home is very low. With buildings with many apartments the input impedance can be so low that it almost looks like a short. In these cases the powerline network may need conditioning, and then perhaps some impedance matching can be done.

Some measurements were performed to find characteristic impedance of the powerline drop wire used here. Differential TDR was used to evaluate the 2/2/2 aluminum service wire. TDR was used to directly measure the differential mode characteristic impedances, by comparing the voltages received along the line with known terminations and using reflection equations. There are several measurement configurations that can be performed with a three wire power service cable. While the L1-L2 response with Neutral open is readily interpreted as the differential mode characteristic impedance, the other results are affected by mode coupling. The differential or characteristic impedance was found equal to 82 Ohms. A detailed power cable model was explained in references [5][6], and for this model the pair resistance was found equal to 46 Ohms. The cable asymmetry, described by parameter ε, was estimated as $\varepsilon = 0.03$.

The BPL system was first terminated in a range of termination impedances to determine what best matches, subsequent measurements used the best matching impedance. It was found that in-home unbalanced terminations caused roughly 10 to 20 dB higher coupling than balanced terminations, often 10 dB or more. While changing the type of imbalance on the home end of the power line would alter the shape of the measured coupling somewhat, the magnitude generally didn’t vary much as long as it stayed imbalanced. Broadband powerline will probably transmit from one power phase conductor to neutral, which is already inherently unbalanced and which doesn’t generally worsen as terminations vary.

Some measurements had balanced powerline terminations for comparison, which engendered very low coupling. These are described further in Section 6.3. However, unbalancing by just substituting 20 Ohms to ground on one phase and 50 Ohms on the other phase at the home end was generally as bad as unbalanced transmission using the neutral.

For some measurements, the home end of the powerline drop connected to a circuit-breaker panel connected to some inside wiring, to reflect the desire to run BPL directly through to wall outlets in the home. The inside wire was three lengths of 12 gauge Romex, 200 ft, 150 ft, and 50 ft, connected to a few connected power converting transformers (“wall-warts”) and a surge suppressor. Other measurements had various controlled resistive impedances R_1 and R_2 from each of the two excited power wires to ground, representing typical in-home power line impedances and imbalances as described above. Some measurements simply left the terminations open for comparison.

4 VDSL2 Performance Simulations

The DSL community has accepted and standardized computer simulations for determining the performance of all DSL systems. These simulations have been proven to closely match lab performance, as was shown recently in the “VDSL Olympics” conducted by Telcordia and BT. Two most likely profiles of VDSL2 are simulated; profile 8a (8.5 MHz total bandwidth), and profile 12a (12 MHz total bandwidth). VDSL2 simulation parameters all follow standard practices, and these are presented in detail below.

4.1 General VDSL2 Simulation Parameters

Most details of the simulations of VDSL2 presented here can be found in the ANSI DSL Spectrum Management Standard, T1.417-2003 [2][3]. The simulation methodology, frequency bands, etc., are explained in detail in Section A.12 of T1.417-2003 [2]. Generally, the simulations model the discrete multitone modulation (DMT) of VDSL2 by assuming that each 4.3125 kHz wide sub-channel or tone has flat channel response and flat SNR across its narrow bandwidth. The simulations calculate the loop response and noise spectrum of each case. From this the received SNR of each tone is computed, and the capacity of that tone with that SNR is found assuming a 9.75 dB gap from the Shannon limit. Overall, the bit rate of each tone is computed at 12.35 dB below the Shannon limit, 12.35 dB = 9.75 - (5.0 dB effective coding gain) + (6.0 dB SNR margin) + (1.6 dB implementation loss). The bit rates of all upstream and downstream tones are separately summed, and are the presented line bit rates.

As specified in T1.417-2003, 6% of each side of each passband is allocated to guard space, and the passbands are the same as in T1.417. The VDSL2 system terminates in the standardized 100 Ohm purely resistive termination.

Simulations are modified from T1.417-2003 slightly to be a little more realistic, the only differences are imposition of min and max numbers of bits per Hz, and a slightly higher coding gain. Here, each tone carries a minimum of 1 bit per Hz, and a maximum of 15 bits per Hz, and all SNR margins are increased by 1.6 dB to account for implementation loss. Also, here coding gain is assumed to be 5.0 dB to model a concatenated trellis and Reed-Solomon code.

The VDSL2 transmit power spectral density is as defined in ITU-T G.993.2 Annex A (North American), plan 998. The optional upstream "U0" band is turned on and used from 26 to 138 kHz. Two VDSL2 profiles are simulated, 8a and 12a. These are expected to be the most common. Downstream VDSL2 transmits in two passbands, from 138 to 3533 kHz and from 5398 to 8302 kHz. Upstream VDSL2 transmits the U0 passband, and in the passband from 3837 kHz to 5113 kHz for both profiles 8a and 12a; and only profile 12a additionally transmits in the passband from 8710 kHz to 11790 kHz.

Table 1. VDSL2 profile parameters, extracted from ITU-T G.993.2 Table X-1

Frequency plan	Parameter	Parameter value for profile							
		8a	**8b**	**8c**	**8d**	**12a**	**12b**	**17a**	**30a**
All	Maximum aggregate downstream transmit power (dBm)	**+17.5**	+20.5	+11.5	+14.5	**+14.5**	+14.5	+14.5	+14.5
All	Maximum aggregate upstream transmit power (dBm)	**+14.5**	+14.5	+14.5	+14.5	**+14.5**	+14.5	+14.5	+14.5
All	Sub-channel spacing(s) (kHz)	**4.3125**	4.3125	4.3125	4.3125	**4.3125**	4.3125	4.3125	8.625
All	Minimum net aggregate data rate capability (Mbit/s)	**50 Mbit/s**	50 Mbit/s	50 Mbit/s	50 Mbit/s	**68 Mbit/s**	68 Mbit/s	100 Mbit/s	200 Mbit/s
998 (North America)	Index of highest supported downstream data-bearing sub-carrier (upper band edge frequency in MHz)	**1971 (8.5)**	1971 (8.5)	1971 (8.5)	1971 (8.5)	**1971 (8.5)**	1971 (8.5)	N/A	N/A
	Index of highest supported upstream data-bearing sub-carrier (upper band edge frequency in MHz)	**1205 (5.2)**	1205 (5.2)	1205 (5.2)	1205 (5.2)	**2782 (12)**	2782 (12)	N/A	N/A

The VDSL2 transmit power spectral density (PSD) is set to be 3.5 dB below the limit mask in ITU-T G.993.2 Annex A for operation over POTS. Upstream Mask Number 1, EU-32, with U0 up to 138 kHz is used. There is no upstream power back off since the remote transceivers are assumed to be collocated. Downstream PSDs are further limited to conform to the maximum aggregate transmit power as listed in Table 1. This is done by "clipping," if the downstream VDSL2 PSD were above a certain value at any frequency then it is lowered to that value. For Profile 8a, the PSD is clipped to be at most -47.6 dBm/Hz, and then has aggregate transmit power of 17.0 dBm. For Profile 12a, the PSD is clipped to be at most -54.0 dBm/Hz, and then has aggregate transmit power of 14.0 dBm.

VDSL2 HAM notches are turned on, within the following standard bands the VDSL2 transmit PSD is modified (if necessary) to be no higher than -80 dBm/Hz:
1.8 – 2.0 MHz
3.5 – 4.0 MHz
7.0 – 7.3 MHz
10.1 – 10.15 MHz
VDSL2 transmit PSDs are shown in Figure 5.

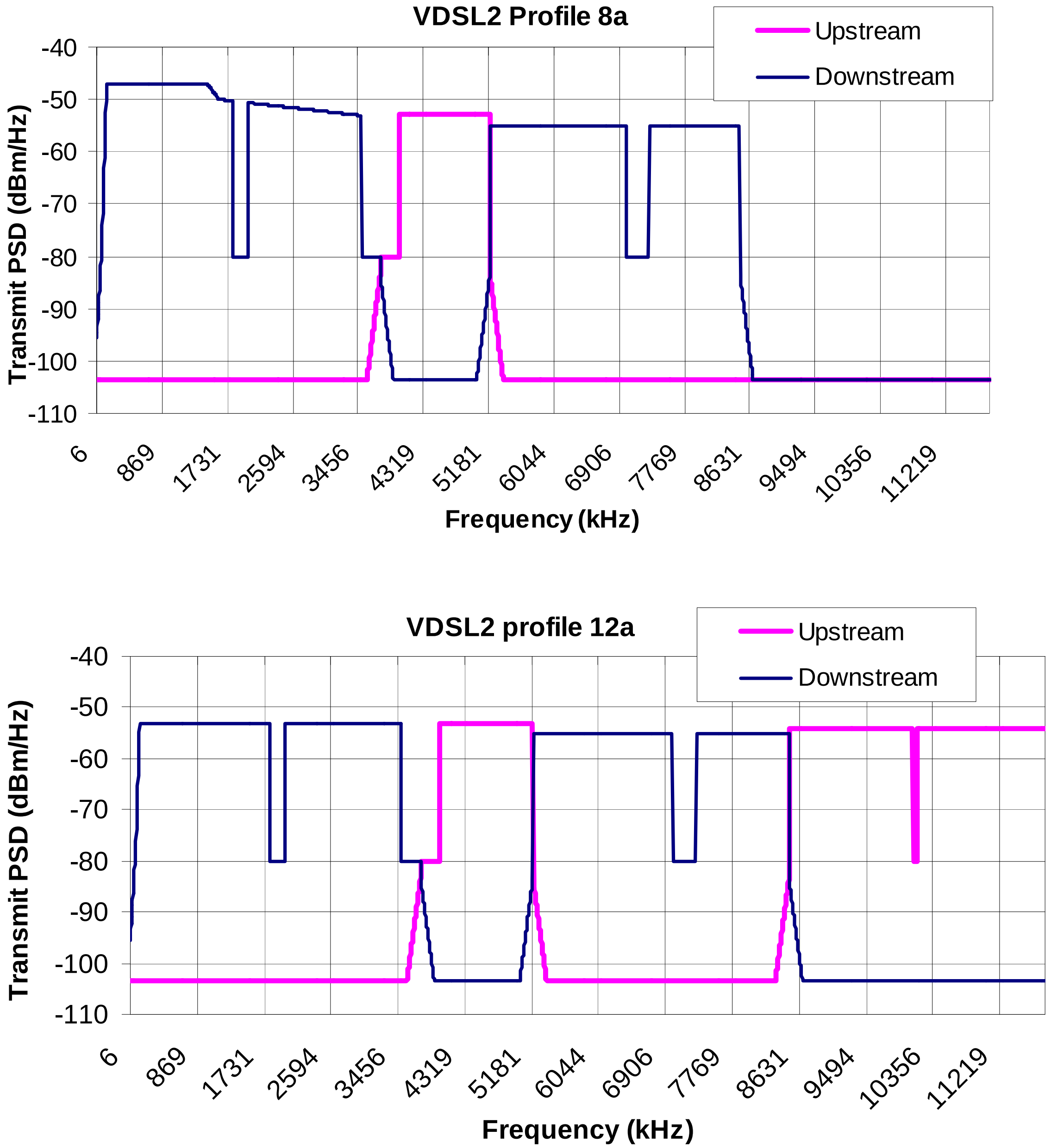

Figure 5. VDSL2 Transmit PSDs.

The tested VDSL2 loops were straight lengths of 26 American wire gauge (AWG) varying from 1 kilofeet (kft) to 6 kft. These loops are used as a typical industry practice, they have overall a give results similar to assuming thicker gauge wire with bridged taps and so are generally representative. All presented VDSL2 bit rates are gross line rates, actual data rates are somewhat lower than those presented.

4.2 Simulation Environment

All VDSL2 simulations have noise that includes -140 dBm/Hz AWGN plus the simulated crosstalk from two 99% worst-case VDSL2 self-crosstalk disturbers. The -140 dBm/Hz AWGN is a low level of background noise that is nearly always included in these studies, and is generally lower than the crosstalk. 2 sets of VDSL2 simulations were run to find the effects of having BPL present or not:

1. Two 99% worst-case VDSL2 self-crosstalk disturbers plus -140 dBm/Hz AWGN.
2. Noise from BPL plus two 99% worst-case VDSL2 self-crosstalk disturbers plus -140 dBm/Hz AWGN.

Assuming only two crosstalk disturbers may at first look like a low number. However, these are modeled as having the 99% worst-case crosstalk couplings [2]. This level of crosstalk can be seen to actually be somewhat worse than average.

Table 2 shows how the crosstalk coupling varies as that as the number of crosstalk disturbers varies [9]. Significant crosstalk occurs between pairs in the same cable binder, which typically has 25 pairs and so has at most 24 crosstalk disturbers. If 24 disturbers were modeled instead of 2, then Table 2 shows that crosstalk would increase by between 6.5 and 10.8 dB.

Table 2. Difference as the number of crosstalk disturbers is varied (dB) [9].

N = # disturbers	Difference in 99% worst-case crosstalk coupling = 6log10(N) (dB)	Difference in average crosstalk coupling = 10log10(N) (dB)
1	0	0
2	1.81	3.01
24	8.28	13.80

The difference between the 99% worst case crosstalk coupling and the average coupling has been measured for pair-to-pair (one crosstalk disturber) and for power sum (24 or 49 crosstalk disturbers) crosstalk [9] [11] [12]. The results are summarized in Table 3. There are no such published results for two crosstalkers, but the difference is almost certainly higher than the difference between 2 and 24 crosstalkers as described in the previous paragraph and Table 2. Moreover, it is almost certain that fewer than every pair in the cable binder are transmitting VDSL2.

Table 3. Difference, average to 99% worst case (dB) crosstalk coupling (dB).

	Pair-to-pair (One disturber)	Power sum (24 or 49 disturbers)
C. F. Valenti [9]	25.5	7.1
S. H. Lin [11]	23.1	5.9
H. W. Friesen [12]	21.5	5.7
Average [9] [11] [12]	23.4	6.3

The overall point of this subsection is that the crosstalk case used here can be seen to be somewhat worse than average. So, the baseline results here assume a noise level that is realistic and do not overly inflate VDSL2 performance.

4.3 Noise from BPL

The measurements of coupling between BPL power lines and VDSL2 telephone lines are presented as magnitude of the coupling in dB, with higher coupling indicating worse received noise. The noise PSD injected into a VDSL2 receiver equals the sum of the measured coupling, in dB, plus the BPL transmit PSD, in dB. The couplings were measured as described in Section 3, and BPL transmit PSDs are described here.

The FCC Report and Order on BPL [13] and FCC Part 15 [14] state that access BPL operations using overhead medium voltage power lines are prohibited in the frequency bands listed in Table 4. These frequency bands were notched in all studies reported here, transmit PSD within these bands is 20 dB below the nominal transmit PSD. Additionally, the BPL passband was restricted to at most 1.705 kHz to 30 MHz, to allow FCC part 15 to be satisfied by staying above AM radio frequencies and below 30 MHz.

Table 4. Excluded Frequency Bands

FREQUENCY BAND
2,850 – 3,025 kHz
3,400 – 3,500 kHz
4,650 – 4,700 kHz
5,450 – 5,680 kHz
6,525 – 6,685 kHz
8,815 – 8,965 kHz
10,005 – 10,100 kHz
11,275 – 11,400 kHz
13,260 – 13,360 kHz
17,900 – 17,970 kHz
21,924 – 22,000 kHz
74.8 – 75.2 MHz

Except for notches, the BPL transmit PSD was generally assumed flat. It’s been reported that a BPL transmit level of -60 dBm/Hz on medium Voltage lines can satisfy FCC part 15 [16]. BPL transmit PSD levels up to -50 dBm/Hz were reported by the National Association for Amateur Radio (ARRL). Considerable work on measuring BPL systems compliance with FCC part 15 has been performed by the NTIA [15]. A typical BPL transmit PSD used here is shown in Figure 6.

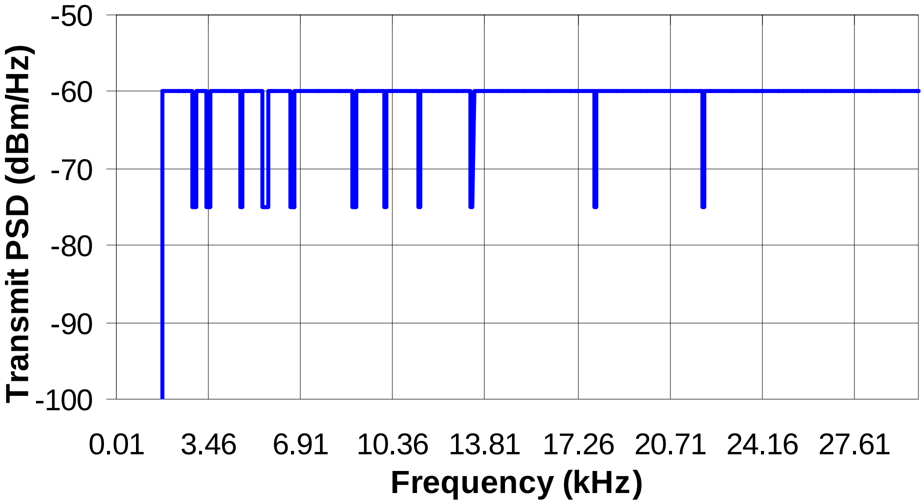

Figure 6. Typical BPL transmit PSD, flat -60 dBm/Hz with notches in the excluded frequency bands.

All studies here assume BPL transmits on powerline drop wires. There is negligible attenuation over these cable lengths, a 100 ft aerial drop wire was measured to only have 1 to 2 dB attenuation. All homes on the low Voltage side of the transformer share the same signal path. So, there would be about the same levels of BPL interference from neighboring homes that subscribe to BPL into VDSL2 as for someone who subscribed to both BPL and VDSL2.

5 Results

5.1 BPL Emissions Measurements

This section reports radiated emissions measurements. BPL transmit power and PSD levels are limited in the USA by FCC emissions limits; the FCC Report and Order on BPL [13] and the 2006 version of FCC Part 15 [14]. In the 1.7 to 30 MHz band the radiated emissions limit for BPL is 30 microVolt per meter, equal to 29.5 dB microVolt (dBuV) per meter.

The same wires and test rig used for measuring couplings in following sections were measured for radiated emissions. A white noise source was coupled to the line with a 100 Ohm balun, delivering a balanced connection on the line with flat -71.7 dBm/Hz transmit power. Most BPL scenarios transmit across one of the power phases, L1 or L2, to ground; and then the signal is unbalanced. Balanced transmission across L1 – L2 was also measured.

Recommended measurement practices were followed [13] [14]. The measurement apparatus was a Lindgren 6502 loop antenna with built in preamplifier connected to an HP E4401B ESA-E spectrum analyzer. All measurements were below 30 MHz, and so a 9 kHz resolution bandwidth was used. Measurements were power averaged over 20 traces, about ½ minute; these were found to be 6.5 dB below measurements made on Max hold for one minute, and about 3 dB below quasi-peak measurements.

Triplex aluminum 2 gauge overhead aerial power powerline drop wire 80 ft long was hung as described in Section 3. Measurements of emissions were taken 10 meters horizontal distance from the powerline drop. The measurement antenna was located at a height of 1 meter. The average height of the line was 4.36 m, which was 3.36 m above the antenna. The emissions measured from the phone-lines were near the noise floor at 10 meters, so these were instead measured at a horizontal distance of 3 meters. Slant range equaled 10.55 m at 10 m horizontal, and 4.5 m at 3 m horizontal. Assuming a mid-band frequency of about 12 MHz (the upper VDSL2 profile 12a band-edge), then as recommended the measurement locations were at distances of 0, ¼, ½, ¾, and 1 wavelength down the line, which in free-space is 0, 20, 40, 60, and 80 ft down the line.

The measurement location was a fairly low-noise suburban/rural area, and the measured noise floor was about -140 dBm/Hz with a few much higher spikes from radio transmitters. Two such radio spikes are often seen in the results at about 9.5 and 11.7 MHz and so these peaks should be discounted. The antenna was rotated to approximately maximize the measured emissions for each measurement.

Data was recorded in dBm per 9 kHz, then converted to dBuV using the values in Table 5. The BPL transmit PSD is assumed here to be flat -60 dBm/Hz from 1.7 to 30 MHz.

Table 5. Emissions measurements conversion and correction factors.

Transmit: -71.7 dBm/Hz to -60 dBm/Hz	
Add (dB)	11.7
Average to quasi-peak	
Add (dB)	3
Electric Antenna Factor (EAF)	
Add (dB) (Typical, varies with frequency)	10.5
Convert to dB microVolt (into 50 Ohms)	
Add (dB)	106.99
10 m to 30 m	
Subtract 40Log(30/10.55) (dB)	18.16
3 m to 30 m	
Subtract 40Log(30/4.5) (dB)	32.96
TOTAL (10 m) Add	**119.03**
TOTAL (3 m) Add	**104.23**

Similar to the coupling measurements reported in Section 5.2, emissions measurements were made with a variety of termination impedances, as shown in Table 6

Table 6. Powerline aerial drop emissions measurements. Measurements were made at 5 locations, locations 1, 2, 3, 4, and 5; at 0, 20, 40, 60, and 80 ft down the drop line

File Number	Location	Powerline conductors excited (L1, L2, N)	Network end termination	Home end termination
491	2	L1-N	Transformer	100 Ohm Balun only
492	2	L1-L2	Transformer	100 Ohm Balun only
493	2	L1-L2	Balanced, 50 Ohm to ground on both L1 and L2	100 Ohm Balun only
494	2	L1-L2	Balanced, 50 Ohm to ground on both L1 and L3	House wire
495	2	L1-L2	Transformer	House wire
496	2	L2-N	Transformer	House wire
498	2	L1-L2	60 Ohm to ground L1, 20 Ohm to ground L2	100 Ohm to ground L1, 20 Ohm to ground L2

499	2	L1-N	60 Ohm to ground L1, 20 Ohm to ground L2	100 Ohm to ground L1, 20 Ohm to ground L2
500	2	L1-N	20 Ohm to ground L1, 60 Ohm to ground L2	100 Ohm to ground L1, 20 Ohm to ground L2
504	2	L2-N	Transformer	100 Ohm Balun only
506	1	L2-N	Transformer	100 Ohm Balun only
508	1	L1-N	Transformer	100 Ohm Balun only
509	3	L1-N	Transformer	100 Ohm Balun only
510	3	L2-N	Transformer	100 Ohm Balun only
512	5	L2-N	Transformer	100 Ohm Balun only
513	5	L1-N	Transformer	100 Ohm Balun only
514	4	L1-N	Transformer	100 Ohm Balun only
515	4	L2-N	Transformer	100 Ohm Balun only
516	4	L2-N	20 Ohm to ground L1, 60 Ohm to ground L2	100 Ohm to ground L1, 20 Ohm to ground L2
517	4	L1-N	20 Ohm to ground L1, 60 Ohm to ground L2	100 Ohm to ground L1, 20 Ohm to ground L2
518	4	L1-L2	20 Ohm to ground L1, 60 Ohm to ground L2	100 Ohm to ground L1, 20 Ohm to ground L2
519	4	L1-L2	20 Ohm to ground L1, 60 Ohm to ground L2	100 Ohm Balun only

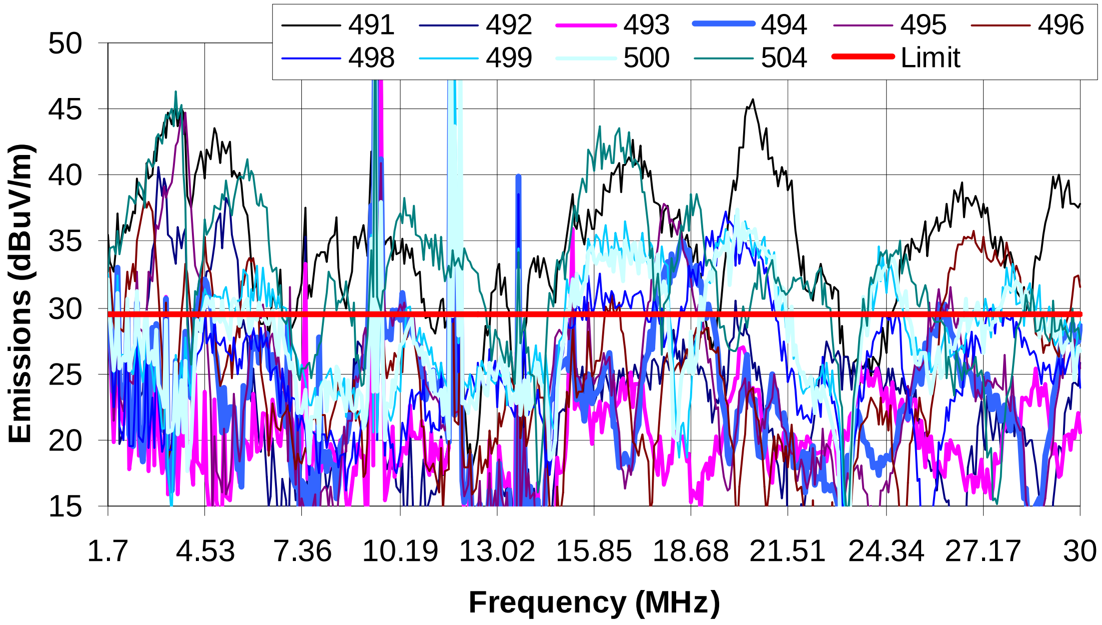

Figure 7. Powerline aerial drop emissions measured at location 2. BPL transmit spectrum is flat at -60 dBm/Hz. 9 kHz resolution bandwidth.

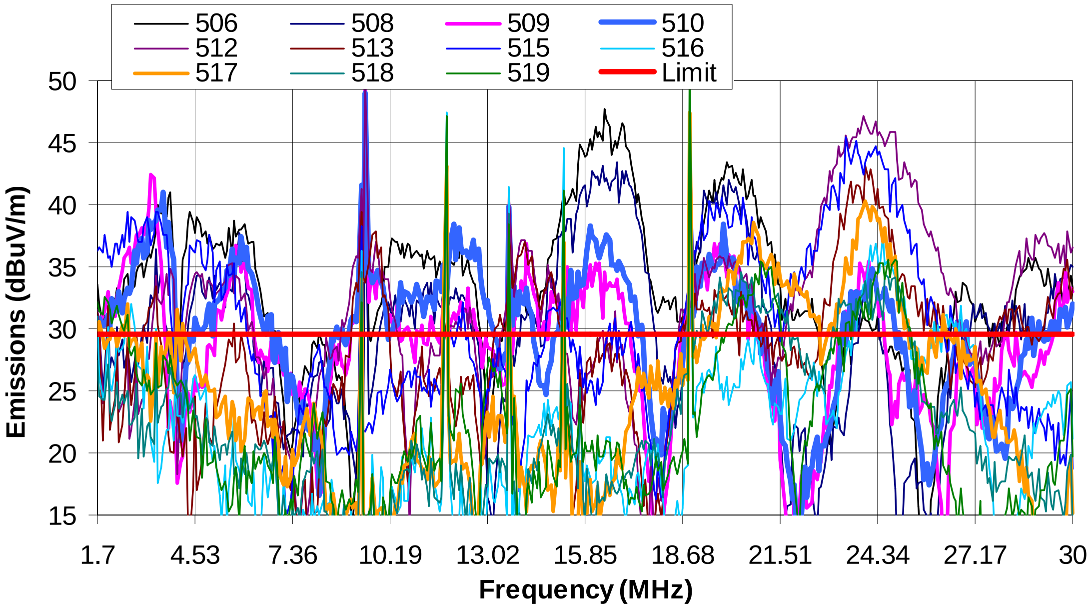

Figure 8. Radiated powerline aerial drop emissions measured at locations 1, 3, 4, and 5. BPL transmit spectrum is flat -60 dBm/Hz. 9 kHz resolution bandwidth.

Table 7. Phoneline aerial drop emissions measurements. Measurements were made on two types of untwisted (flat) telephone drop wire at 5 locations, locations 1, 2, 3, 4, and 5; at 0, 20, 40, 60, and 80 ft down the drop line.

Filename	Phone drop wire	Location
520	Flat A	4
521	Flat A	5
522	Flat A	3
523	Flat A	2
524	Flat A	1
525	Flat B	1
526	Flat B	2
527	Flat B	3
528	Flat B	4
529	Flat B	5

Figure 8 shows emissions measurements of VDSL2 on flat, untwisted aerial phone wire. Transmission is balanced and terminates in 100 Ohms. The transmit spectrum is the maximum of VDSL2 profiles 8a and 12a, upstream and downstream, as described in Section 4.1. This is pessimistic, on short loops upstream VDSL2 would back off the power and on long loops the downstream signal power on the drop line would be attenuated. Nonetheless, assuming this worst-case the measured peak was 26 dBuV, below the FCC limit of 29.5 dBuV.

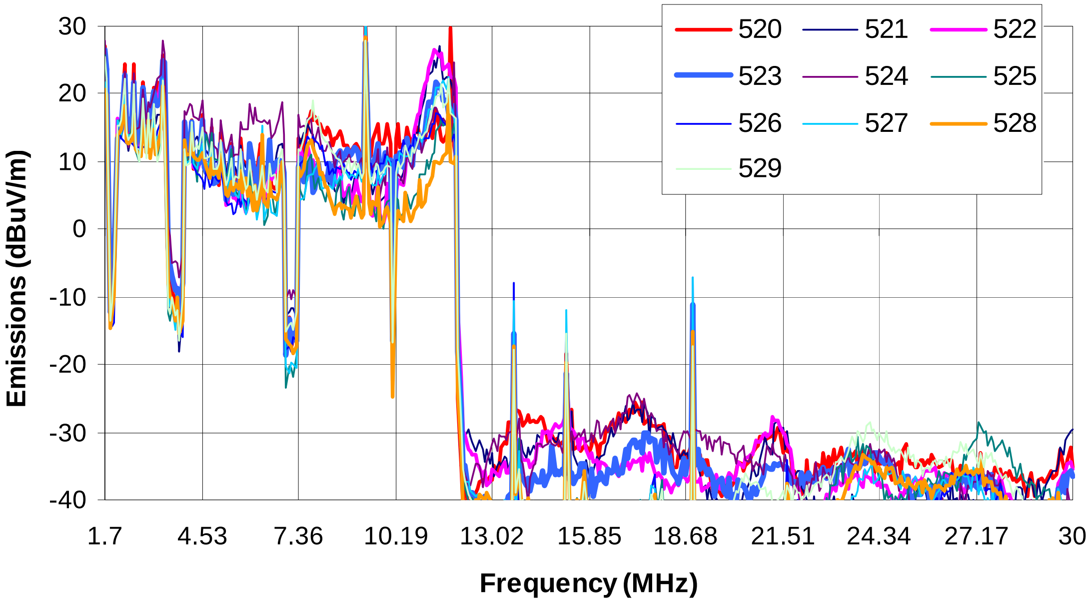

Figure 9. Radiated phoneline aerial drop emissions measurements. Transmit spectrum is the maximum of VDSL2 profiles 8a and 12a upstream and downstream. Balanced transmission, 100 Ohm termination. 9 kHz resolution bandwidth.

Assuming -60 dBm/Hz transmit power, measured BPL emissions on the aerial drop line were occasionally as high as 10 to 13 dB above the FCC limit of -29.5 dBuV [13] [14]. This is reasonably consistent with some previously reported measurements [15][16][17]. In-home or access link attenuation may lower the power on the drop line, and could allow emissions to be below the FCC limit. VDSL2 emissions are lower than BPL emissions primarily because the phoneline is balanced, while the powerline is unbalanced. Some measurements of emissions for balanced transmission on BPL were made, and were around the same levels as the phoneline emissions. However, balanced transmission on powerlines is generally impractical because connected loads have a wide range of termination impedances.

To make an overall comparison, all the emissions measurements reported here were averaged in dB from 1.7 to 12 MHz, the VDSL2 profile 12a band. Average BPL drop line emissions equaled 27 dBuV, and average VDSL2 drop line emissions equaled 9 dBuV. BPL emissions averaged 18 dB higher than VDSL2 emissions across this measurement set.

5.2 Measured Couplings from BPL into VDSL2 Drops

Two different drop lengths using different drop wire were measured as described in Section 3.

- 80 ft exposure length with 10 ft extra on the powerline (PL) and phoneline home end, and 20 ft extra on the pole or network end.
- 57 ft exposure length with 10 ft extra on the powerline (PL) and phoneline home end, and 25 ft extra on the pole or network end.

The BPL and phone wire ends beyond the drop exposure were widely separated physically. The twisted pair drop wire had a steel messenger that was grounded at both ends like the powerline neutral. Grounding rods were inserted into very wet earth with low resistance measured to ground at each end of the powerline. During the measurements, the weather was typically fair with temperatures around 70 degrees Fahrenheit, although one day was slightly damp (with little discernable effect). The measurement location was a low noise suburban/rural location, near Chester NJ.

Some overall findings were:

- The biggest effect on the coupling was caused by varying termination impedances on the powerline (VDSL2 terminations were always balanced.) Different imbalances cause different shapes in the coupling spectra.
- The amount of coupling does not always correlate directly with the balance of the termination impedances. Occasionally making the powerline less balanced in some way would counter-intuitively lower the coupling.
- Transmitting a balanced BPL signal across both of the power line hot phases (L1 and L2) with balanced powerline terminations on both ends of the powerline resulted in very low coupling, 20 dB or so below unbalanced. However, this is totally unrealistic since the home end is nearly certain to present different impedances to each phase. This is discussed in Section 6.3.
- Changing the distance between the drop wires (from 40 to 48 inches at the pole, or from 12 to 24 inches at the home end) had little effect.
- The measured twisted pair VDSL2 drop appeared to have only slightly less coupling than the flat drop wires.
- The peaks and valleys in the coupling spectrum do not seem to correlate well with exposure length or wire length. Their origin is a mystery, but may involve wire length, twist length, impedance resonances, etc. In free space, a quarter wavelength is at 4.3 MHz for 57 ft, and at 3.1 MHz for 80 ft.

Seventy coupling measurements were recorded, some just for calibration and scientific curiosity, etc. A representative set of 25 coupling measurements were gathered from these and used for further results. These are described in Table 8. It should be noted that these are typical couplings, not worst case.

Table 8. Description of 25 measured couplings.

File Number	Phone drop	Exposure length (ft)	Pole/home drop separation (inches)	Powerline conductors used (L1, L2, N)	Home phone line termination	PL network end	PL home end
4	Twisted	80	40 / 12	L1-N	Splitter to 100 Ohms	Transformer	House wire
7	Twisted	80	48 / 15	L1-N	Splitter to 100 Ohms	Transformer	House wire
9	Flat A	80	40 / 12	L1-N	Splitter to 100 Ohms	Transformer	House wire
11	Flat A	80	40 / 12	L1-N	Splitter to 100 Ohms	Transformer	Only 100 Ohm Balun
12	Flat A	80	40 / 12	L2-N	Splitter to 100 Ohms	Transformer	Only 100 Ohm Balun
15	Flat A	80	40 / 12	L1-N	Splitter to 100 Ohms	Open	Only 100 Ohm Balun
17	Flat A	80	40 / 12	L1-N	Splitter to 100 Ohms	Balanced, 50 ohm to Neutral on L1 and L2	Only 100 Ohm Balun
20	Flat A	80	40 / 12	L1-N	Splitter to 100 Ohms	Transformer	House wire

22	Flat A	80	40 / 12	L1-N	Only 100 Ohm Balun	Transformer	Only 100 Ohm Balun
24	Flat B	80	40 / 12	L1-L2	Only 100 Ohm Balun	Transformer	Only 100 Ohm Balun
25	Flat B	80	40 / 12	L1-N	Only 100 Ohm Balun	Transformer	Only 100 Ohm Balun
28	Flat B	80	40 / 12	L1-N	Only 100 Ohm Balun	Balanced, 50 Ohms to Neutral on L1 and L2	Only 100 Ohm Balun
33	Flat B	80	40 / 12	L1-N	Splitter to 100 Ohms	20 Ohm to Neutral on L1, 60 Ohm to Neutral on L2	Only 100 Ohm Balun
41	Flat A	57	40 / 12	L1-L2	Splitter to 100 Ohms	Transformer	House wire
42	Flat A	57	40 / 12	L1-N	Splitter to 100 Ohms	Transformer	House wire
45	Flat A	57	40 / 12	L2-N	Only 100 Ohm Balun	Balanced, 50 Ohms to Neutral on L1 and L2	House wire
48	Flat A	57	40 / 12	L1-N	Only 100 Ohm Balun	Balanced, 50 Ohms to Neutral on L1 and L2	20 Ohm to N on L2
52	Flat A	57	40 / 24	L1-N	Only 100 Ohm Balun	Transformer	House wire
56	Flat B	57	48 / 12	L2-N	Only 100 Ohm Balun	Transformer	House wire
58	Flat B	57	48 / 15	L1-N	Only 100 Ohm Balun	Transformer	Only 100 Ohm Balun
59	Flat B	57	48 / 15	L2-N	Only 100 Ohm Balun	Transformer	Only 100 Ohm Balun
60	Twisted	57	40 / 12	L1-N	Only 100 Ohm Balun	Transformer	House wire
63	Twisted	57	40 / 12	L2-N	Only 100 Ohm Balun	Transformer	Only 100 Ohm Balun
66	Twisted	57	40 / 12	L1-L2	Only 100 Ohm Balun	Balanced, 50 Ohms to Neutral on L1 and L2	Balun, with 20 Ohm to Ground on L1
67	Twisted	57	40 / 12	L1-N	Only 100 Ohm Balun	Balanced, 50 Ohms to Neutral on L1 and L2	Only 100 Ohm Balun

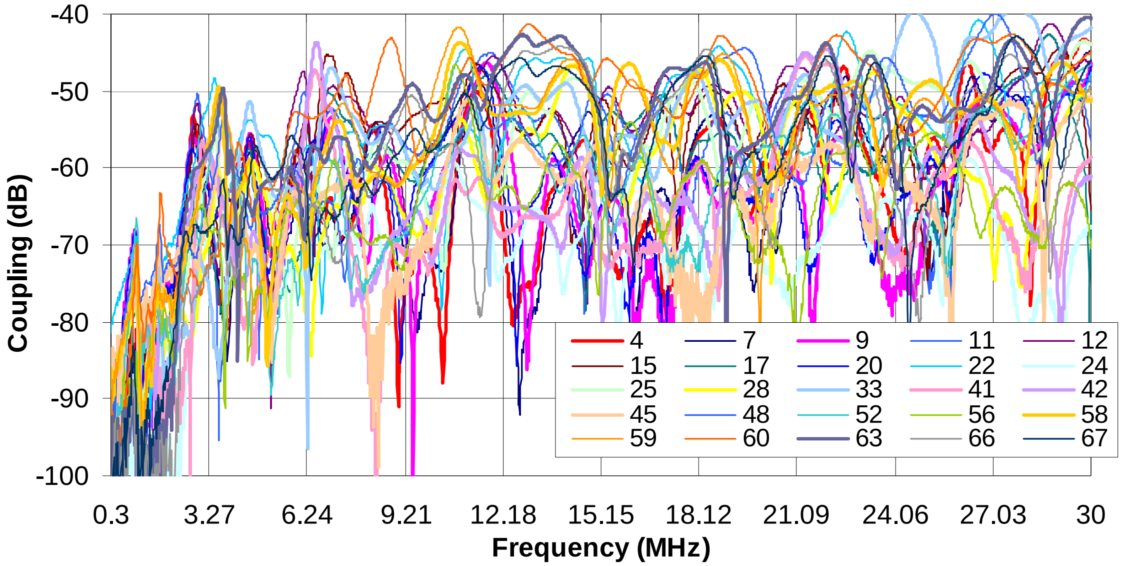

Figure 10. Twenty-five canonical coupling measurements, from 300 kHz to 30 MHz.

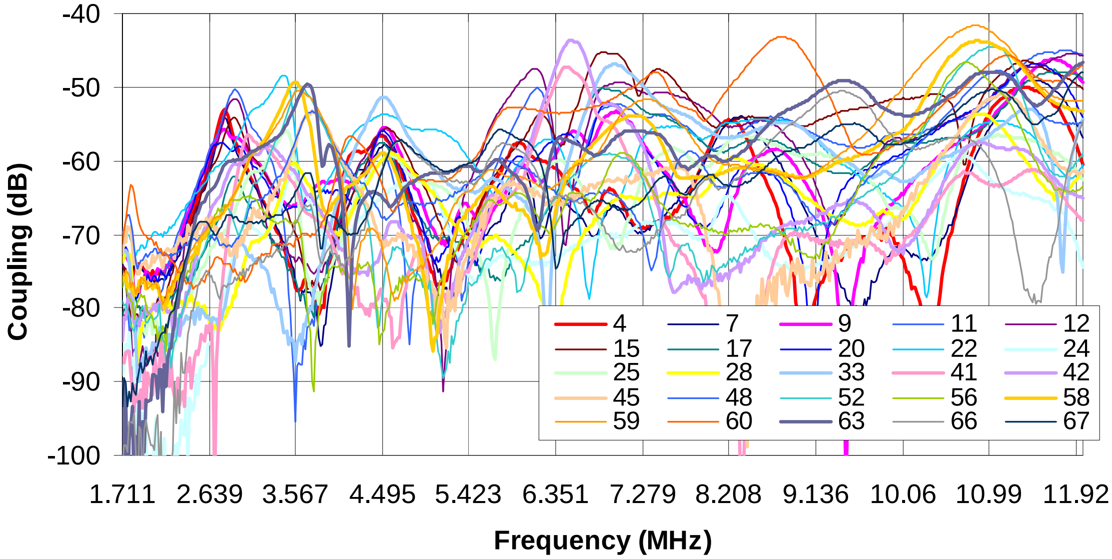

Figure 11. Twenty-five canonical coupling measurements, from 1.7 MHz to 12 MHz, frequencies where BPL can couple into VDSL2 profiles 8a or 12a.

5.3 VDSL2 Simulation Results

The impact on both upstream and downstream performance for VDSL2 was calculated via computer simulation as described in Section 4, with results presented here. It should be noted that these are typical couplings, not worst case. Results are shown in Figure 12 to Figure 15. These show the impact of each individual BPL to VDSL2 drop wire coupling scenario. The BPL transmit PSD is nominally -60 dBm/Hz flat, with all FCC excluded frequencies notched 20 dB down. These frequencies are distinct from the HAM band notches of VDSL2.

Results are shown for two groups of couplings: 80 ft. exposure and 57 ft exposure lengths. This is just to help the readability of the figures, there was not much difference between these groups.

Upstream BPL noise is attenuated by the VDSL2 loop before reaching the upstream VDSL2 receiver in the CO, and so the impact on upstream VDSL2 is small, resulting in the worst measurement here causing at most a 1.4% bit rate decrease to VDSL2 profiles 8a and 12a upstream bit rates. So, the impact of BPL on upstream VDSL2 is not displayed here.

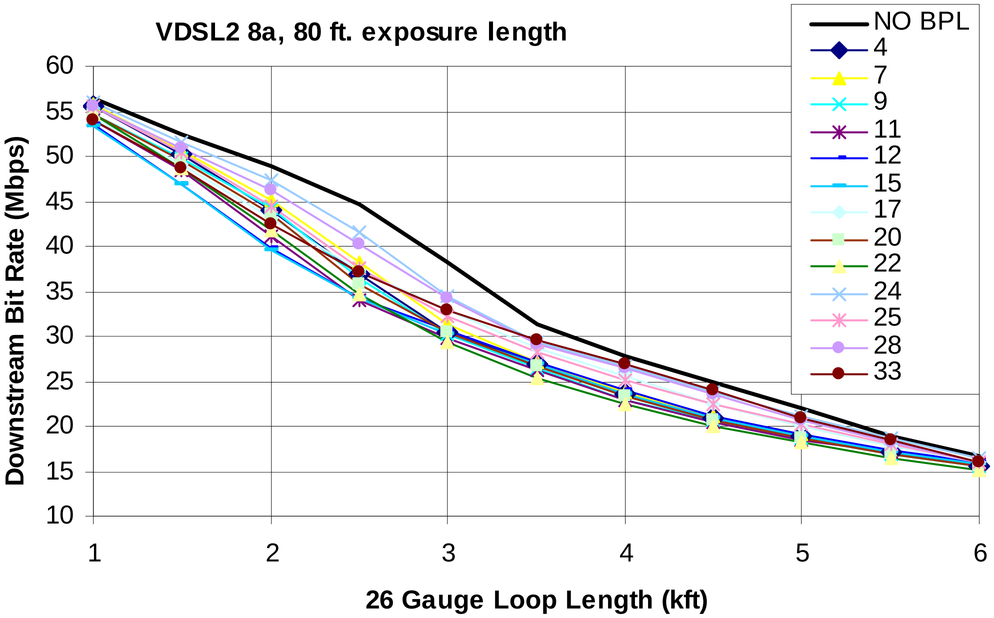

Figure 12. VDSL2 Profile 8a downstream bit rates, 80 ft exposure length, interference from -60 dBm/Hz BPL.

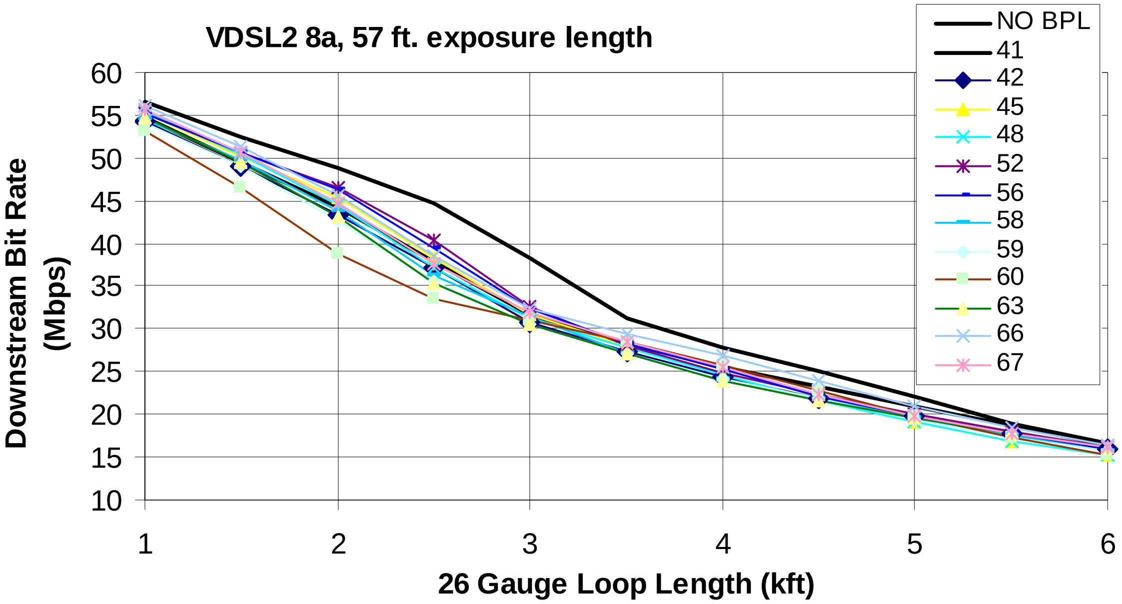

Figure 13. VDSL2 Profile 8a downstream bit rates, 57 ft exposure length, interference from -60 dBm/Hz BPL.

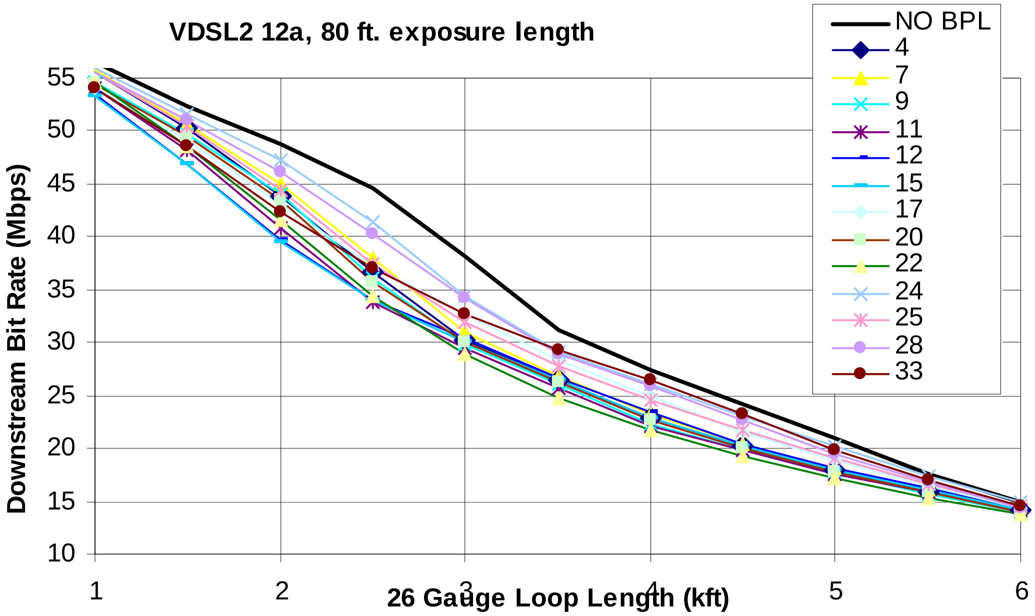

Figure 14. VDSL2 Profile 12a downstream bit rates, 80 ft exposure length, interference from -60 dBm/Hz BPL.

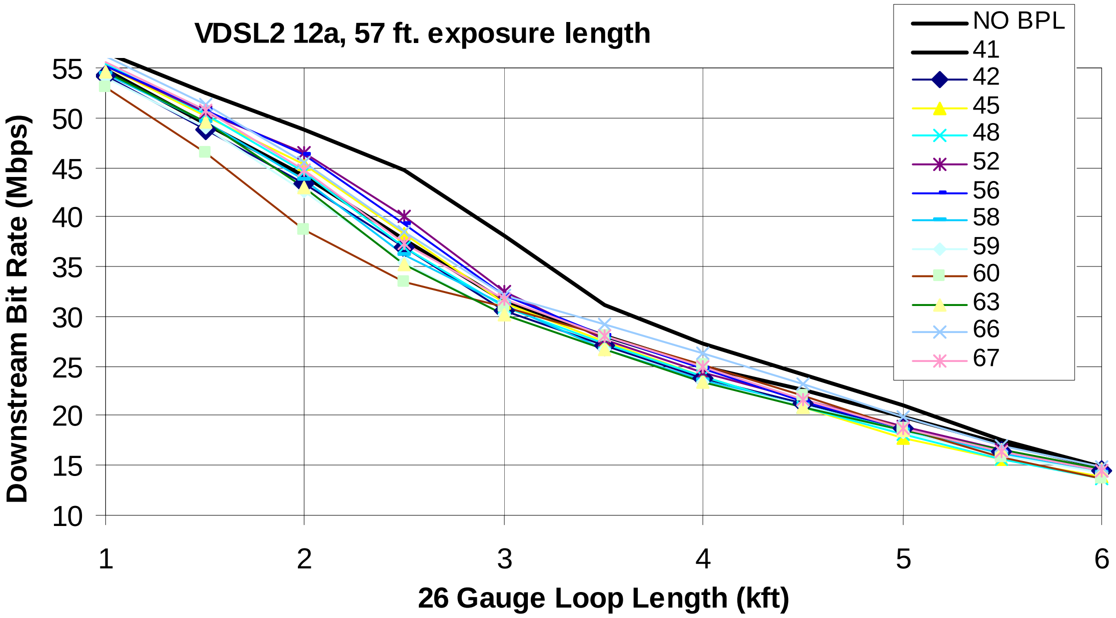

Figure 15. VDSL2 Profile 12a downstream bit rates, 57 ft exposure length, interference from -60 dBm/Hz BPL.

There are many results here, so a brief summary is presented. Operators are primarily interested in serving areas of 2 to 4 kft, so average differences over these lengths are shown in Table 9. The average decrease in bit rate was found across all couplings at each loop length, and then this was averaged across loop lengths from 2 to 4 kft.

Table 9. Average percent decrease in VDSL2 bit rates caused by BPL at -60 dBm/Hz.

Average percent decrease	VDSL2 Profile 8a	VDSL2 Profile 12a
Downstream	13.6	14.1

Table 9 presents *averages*, for the measurements here the *maximum* decrease in VDSL2 bit rates was 25% downstream (measured coupling 60, 2.5 kft VDSL2 loop).

5.4 Measurements of Live BPL and VDSL Lines

This section reports measurements of a live BPL line running next to a live VDSL line. These measurements were conducted in an indoor lab because it was impractical to move the DSLAM and copper loops outdoors. Two drop wires were hung, in about the middle of the lab, at a reasonable distance from metal boxes and equipment. The ambient noise was low, and only about -150 dBm/Hz or less coupled into the VDSL system with no BPL.

The 2/2/2 gauge triplex aluminum overhead power drop wire was hung above flat untwisted telephone drop wire type "flat B," as described in Section 3.1 except at a lower overall height. Separation between the drops was 40 inches at the "pole" end and 12 inches at the "home" end. The drop wires were 30 ft long, with 30 ft exposure length.

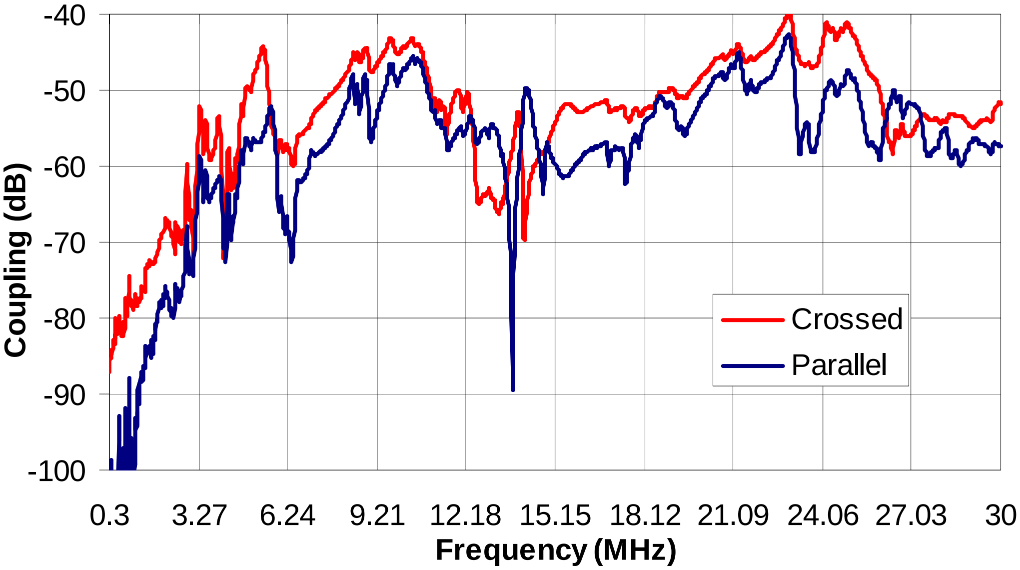

Figure 16. Couplings measured in the lab between 30 ft BPL and VDSL drop lines on the set-up that measured live VDSL traffic with live BPL interference.

With the drop wires roughly parallel, the same as the measurements reported in all other sections of this report, the measured coupling shown in the dark blue line in Figure 16 is somewhat lower than many measurements made outdoors on longer drop lines, probably because the drop wires length in the lab were only 30 ft long. So, as a stress test, the VDSL drop line was tightened so that it vertically crossed the sagging powerline drop near its middle. End points connections were unchanged. The powerline was only an inch or two away from the phone line at the two points where they crossed vertically, then sagged to about one-half foot below the phone line. This is not uncommonly seen in actual outside plant, since the powerline is heavy it sometimes sags down below the phone line. The measured "Crossed" coupling is the red line in Figure 16, and is higher than the parallel case, but roughly the same level as some other coupling measurements reported in Section 5.2.

The BPL system consisted of two broadband powerline adapters, with one connected to each end of the powerline drop, and to wall power. These adapters purportedly transmit line rates up to 200 Mbps, but only about 45 Mbps of throughput was actually experienced in this test set-up. The VDSL system used ITU-T G.993.1, "VDSL1," and not VDSL2, since VDSL2 equipment was not available at the time of measurement. The VDSL bandplan used is the same as VDSL2 profile 8a, and included the optional upstream low-frequency U0 band. The VDSL system was allowed to startup at max rate with 6 dB margin, and the resulting line bit rate is reported here. The maximum VDSL speed was 13.3 Mbps upstream and 56.9 Mbps downstream. There was a small variability in VDSL speeds under identical start-up conditions, less than about 1%. VDSL transmitted through the drop wire plus several lengths of 26 gauge, 12-pair, Brand Rex telephone distribution copper cable.

VDSL bit rates were recorded with several VDSL loops as shown in Table 10, which also shows the percent decrease in bit rate caused by running the BPL system across the powerline drop.

Table 10 VDSL line speeds measured with and without actual BPL drop wire interference.

Drop wires	BPL ON/ OFF	VDSL 26 AWG loop length	Upstream VDSL (Mbps)	Downstream VDSL (Mbps)	Upstream % decrease	Downstream % decrease
Parallel	OFF	3200 ft & 3200 ft bridged tap	0.96	25.728		
Parallel	ON	3200 ft & 3200 ft bridged tap	0.96	24.704	0	**4**
Parallel	OFF	2400 ft	5.76	51.904		
Parallel	ON	2400 ft	5.376	50.56	**7**	**3**
Parallel	OFF	3200 ft	1.536	38.016		
Parallel	ON	3200 ft	1.536	36.928	0	**3**
Crossed	OFF	3200 ft	1.984	37.44		
Crossed	ON	3200 ft	1.728	34.24	**13**	**9**
Crossed	OFF	3200 ft (4X800' sections)	1.728	39.872		
Crossed	ON	3200 ft (4X800' sections)	1.472	31.36	**15**	**21**
Crossed	OFF	2400 ft (3X800' sections)	5.376	46.016		
Crossed	ON	2400 ft (3X800' sections)	5.184	39.232	**4**	**15**

BPL was show to decrease downstream VDSL speeds by 10% to 20% in many cases in Table 10, similar to results in Section 5.3. Upstream VDSL was also affected. The VDSL system here used VDSL1, future VDSL2 systems are likely to have generally better performance and lower noise floors, and so would experience greater impact from BPL.

6 Mitigation of Impact on VDSL2

Three methods of mitigating the impact of BPL on VDSL2 are examined here: lowering the BPL power, only using higher frequencies for BPL, and balancing the in-home BPL impedances while using balanced transmission across the two power phases.

It may be most advantageous to combine some of these techniques, or to use a more advanced BPL spectral shaping than is currently presented here.

6.1 Lower BPL Power

BPL Transmit PSD levels were varied to find a level low enough to avoid impacting VDSL2. Results shown here are average VDSL2 bit rates, averaged over all 25 canonical measured BPL couplings. BPL transmit PSD has all required excluded frequency bands notched to 20 dB below the flat PSD level. Results in Figure 17 and Figure 18 show that flat BPL transmit levels of -80 dBm/Hz or lower appear to be sufficient to avoid impacting VDSL2.

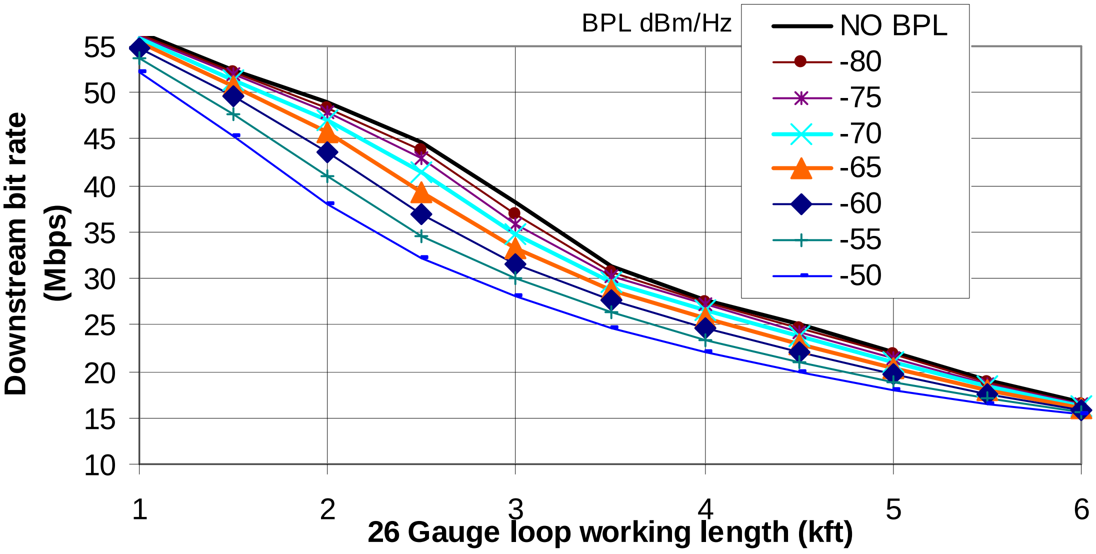

Figure 17. VDSL2 Profile 8a downstream bit rates averaged over the 25 canonical measured couplings, with flat BPL transmit PSD varying from -50 dBm/Hz to -80 dBm/Hz.

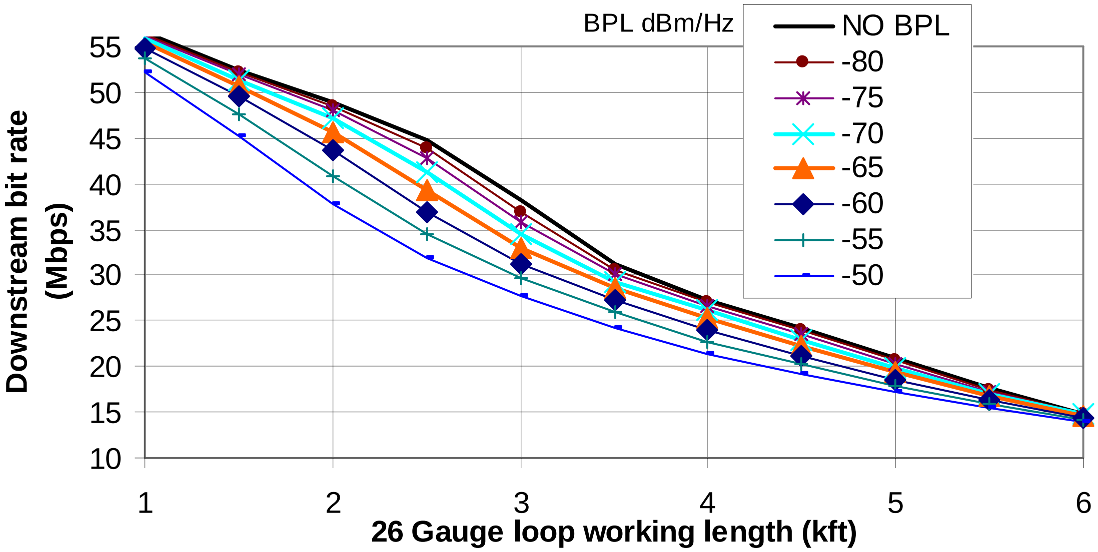

Figure 18. VDSL2 Profile 12a downstream bit rates averaged over the 25 canonical measured couplings, with flat BPL transmit PSD varying from -50 dBm/Hz to -80 dBm/Hz.

6.2 Use of Only High Frequencies for Access BPL

Additional tests varied the lower band-edge of the BPL PSD above 1.705 MHz, to 2 MHz and higher frequencies, reserving the lower frequencies for VDSL2. Results shown here are average VDSL2 bit rates, averaged over all 25 canonical measured BPL couplings. Results are shown in Figure 19 and Figure 20. There are discontinuities in these results because VDSL2 only uses certain bands for upstream or downstream. For example, upstream bands are from 26 to 138 kHz and from 3.75 to 5.2 MHz, with an additional upstream band from 8.5 to 12 MHz for profile 12a (not for 8a, which has highest a frequency of 8.5 MHz). Results for some BPL lower band-edges were omitted because they were redundant.

Overall, using frequencies no lower than about 8.5 MHz for BPL appears to be sufficient to avoid impacting VDSL2. If VDSL2 were only on loops longer than about 3½ kft, then limiting BPL to using frequencies no lower than about 3.75 MHz would avoid impact on VDSL2.

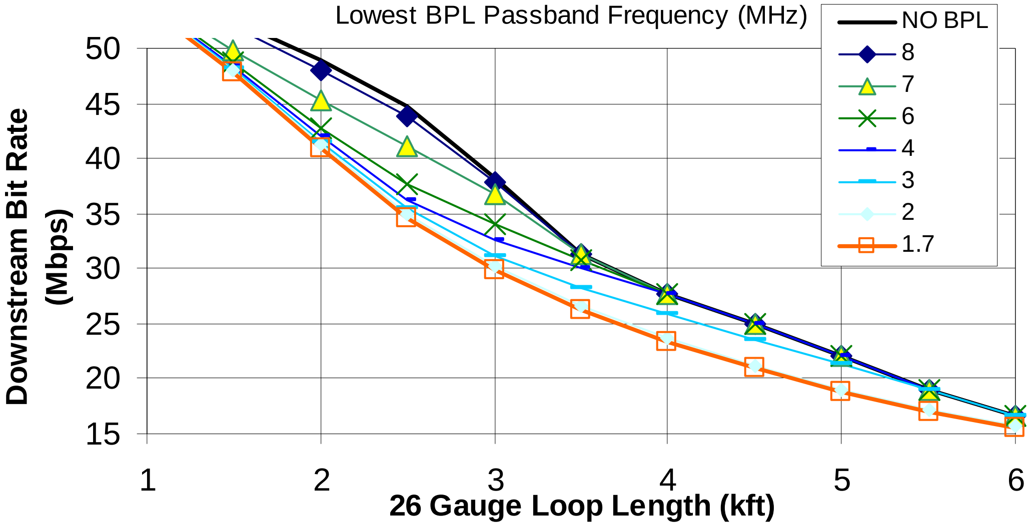

Figure 19. VDSL2 Profile 8a downstream bit rates averaged over the 25 canonical measured couplings, with lowest BPL band-edge varying from 1.7 MHz to 8 MHz.

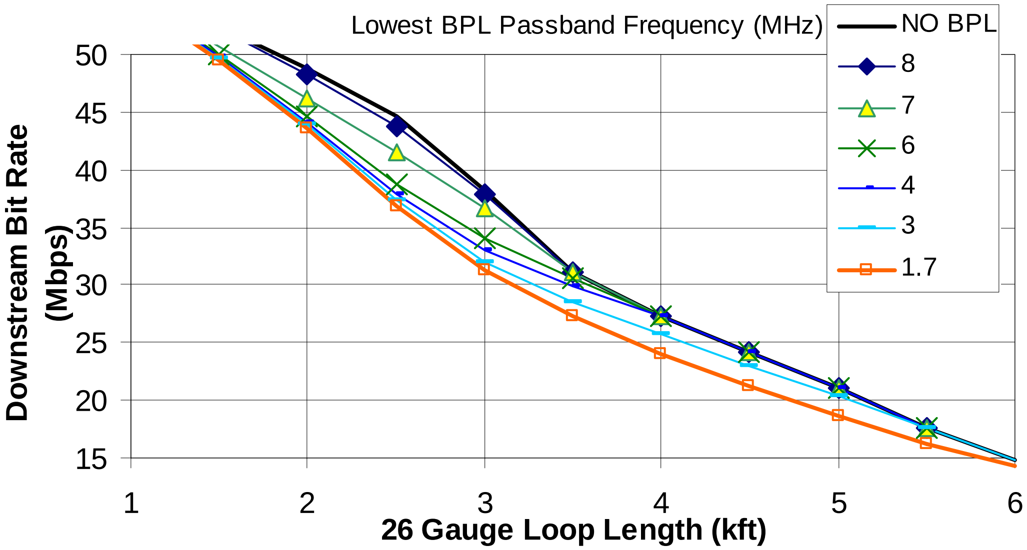

Figure 20. VDSL2 Profile 12a downstream bit rates averaged over the 25 canonical measured couplings, with lowest BPL band-edge varying from 1.7 MHz to 8 MHz.

6.3 Balanced Loads and Transmission

Some measurements were made with balanced powerline terminations, which engendered very low coupling from BPL into VDSL2. These terminated the network end of the power line in two 50 ohm loads to neutral, and transmitted a balanced signal from L1 to L1. This is only possible on 120/240 Volt circuits using three wires, since two wire power circuits would have one wire grounded and then be unbalanced. 100 Ohm measurement baluns were used. These measurements are described in Table 11 and shown in Figure 21.

Table 11. Balanced, and partially unbalanced, coupling measurements.

File Number	Phone drop	Exposure length (ft)	Pole/home drop separation (inches)	Powerline conductors used	Home phone line termination	PL network termination	PL home termination
16	Flat A	80	40 / 12	L1-L2	100 Ohm balun	50 Ohm to neutral, both L1 and L2	100 Ohm balun
27	Flat B	80	40 / 12	L1-L2	100 Ohm balun	50 Ohm to neutral, both L1 and L2	100 Ohm balun
46	Flat A	57	40 / 12	L1-L2	100 Ohm balun	50 Ohm to neutral, both L1 and L2	100 Ohm balun
65	Twisted	57	40 / 12	L1-L2	100 Ohm balun	50 Ohm to neutral, both L1 and L2	100 Ohm balun
18	Flat A	80	40 / 12	L1-L2	100 Ohm balun	20 Ohm to N L1, 50 Ohm to N L2	100 Ohm balun
31	Flat B	80	40 / 12	L1-L2	100 Ohm balun	20 Ohm to Neutral on L1, 60 Ohm to Neutral on L2	100 Ohm balun
47	Flat A	57	40 / 12	L1-L2	100 Ohm balun	50 Ohm to neutral, both L1 and L2	100 Ohm balun and 20 Ohm to neutral on L2
66	Twisted	57	40 / 12	L1-L2	100 Ohm balun	50 Ohm to neutral, both L1 and L2	100 ohm balun and 20 Ohm to neutral on L1

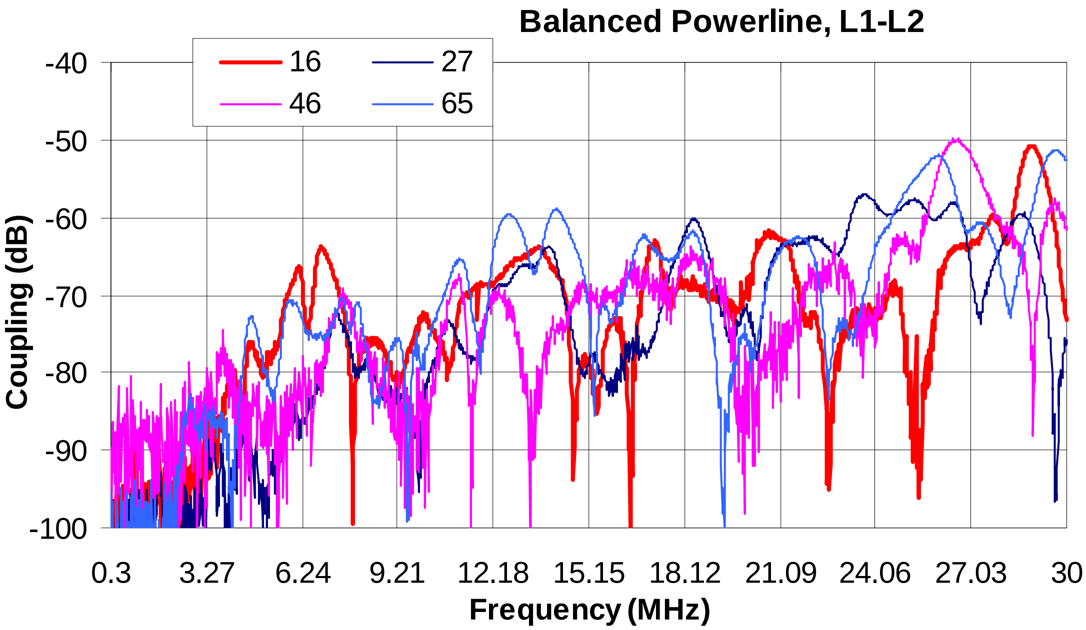

Figure 21. Coupling from BPL to VDSL2 drops with balanced powerline transmission and terminations.

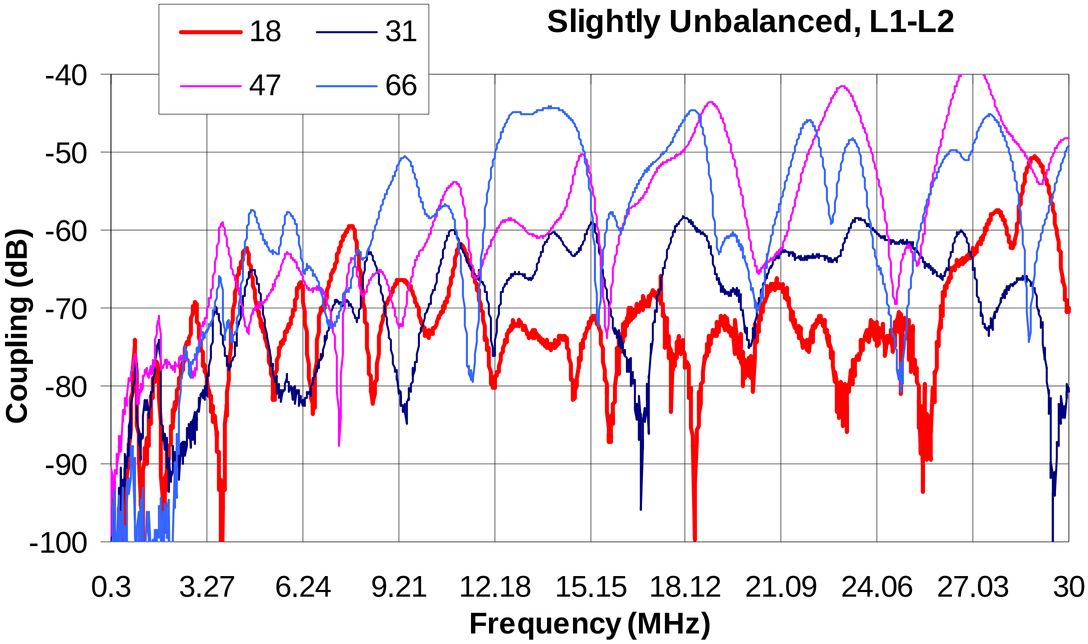

Figure 22. Coupling from BPL to VDSL2 drops with partially unbalanced powerline terminations.

Perfectly balanced transmission over powerlines is a nice goal since it would lower overall emissions and BPL impact on VDSL2 by as much as 30 dB. However, this is highly unrealistic since powerline loads in the home are uncontrolled at high frequencies and vary widely. Figure

22 shows that adding relatively small imbalances to the terminations is shown to cause coupling to increase nearly to the levels reported and used in the rest of this study.

6.4 BPL Signature

If the VDSL2 receivers could automatically identify that an interference condition was caused by BPL, then some type of cooperative remediation may be possible. VDSL2 should be capable of reporting the noise PSD it sees on a line. One way to recognize the BPL noise would be via identifying the excluded BPL frequency bands on medium voltage lines, as given in Table 4. These bands are distinct from the HAM bands that can be notched by VDSL2, given in Section 4.1, and so they may allow BPL noise to be identified distinctly from VDSL2 crosstalk noise. A plot of the received noise from BPL at -60 dBm/Hz and excluded frequency bands notched 20 dB down is shown in Figure 23. It appears that it may be possible to identify BPL interference by its noise PSD, although the accuracy of this identification is not known at this time. Additional mechanisms may be needed.

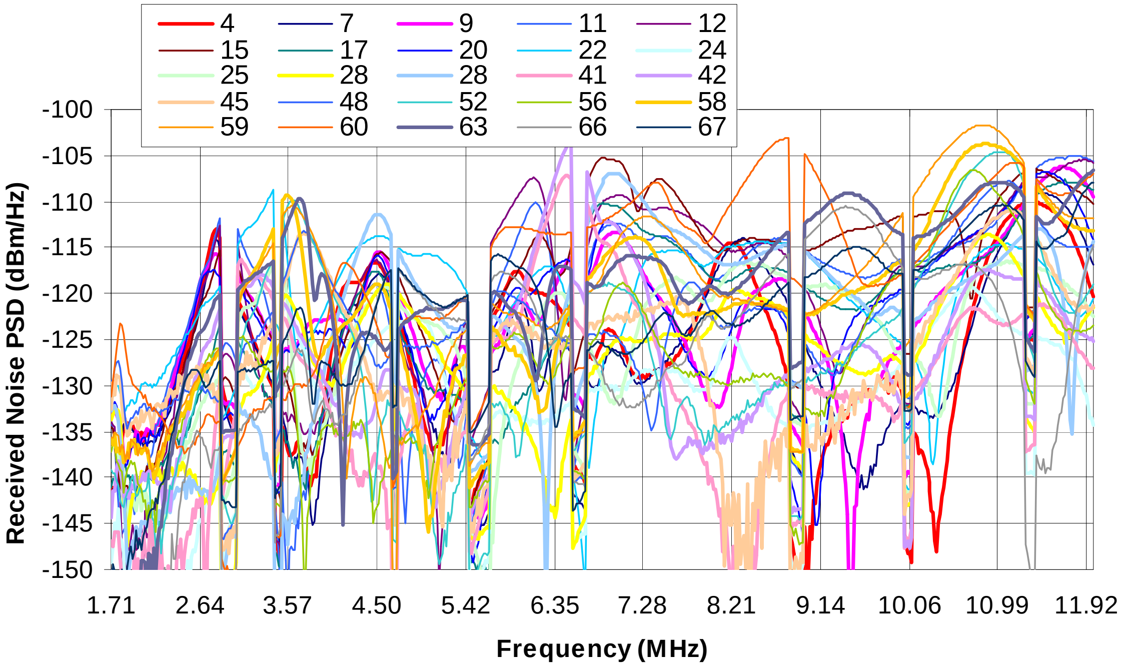

Figure 23. Received BPL noise "signature" over the 25 canonical measured couplings.

7 Discussion of Study Results

Measurements reported here found how much BPL power would couple into VDSL2 drop lines. All measurements followed standard wiring practices, and a number of conditions were examined to show a typical range of variability. Coupling was found to be substantial, with loss between about -40 db to about -80 dB in VDSL2 bands. This results in BPL induced noise on VDSL2 with levels up to about -100 dBm/Hz, well above typical crosstalk plus background noise levels experienced by VDSL2 which range between about -140 to -120 dBm/Hz.

Gross line bit rates of VDSL2 were determined and are presented here, these are a little higher than the payload data rate and scale proportionately. BPL systems were typically assumed to transmit -60 dBm/Hz down the drop lines. Detailed VDSL2 analyses found that BPL can corrupt VDSL2. Bit rates of VDSL2 are typically lowered by 10% to 20% by BPL interference. Taking an overall average on 2 to 4 kft long VDSL2 loops, BPL interference was found to decrease downstream VDSL2 bit rates by an average of 14%. About a 35 Mbps downstream line rate is desired for new FTTN deployments for IPTV service, for this rate BPL was found to lower the average VDSL2 range by about ¾ kft, decreasing from about 3¼ kft to about 2½ kft, which would increase the number of fiber-fed serving areas by roughly 70%, and therefore greatly complicate deployments. Moreover, this is based on typical results and not worst-case, measured couplings showed tens of dBs of variability, and worst-case impact would be considerably worse than the measurements presented here.

Emissions from BPL and VDSL2 drop lines were measured. Measured BPL emissions averaged 18 dB higher than measured VDSL2 emissions from 1.7 to 12 MHz. This showed that the BPL drop lines create much more emissions than VDSL2 lines, primarily because the VDSL2 line is balanced while the BPL line is unbalanced.

Measurements of a live BPL system generating interference on drop wires into a live VDSL1 system were made, and BPL decreased upstream and downstream VDSL1 speeds by 10% to 20% in many cases.

Several methods of mitigating the impact of BPL on VDSL2 were investigated. Lowering BPL power to BPL transmit PSD levels of -80 dBm/Hz or lower in the VDSL2 bands appears to be sufficient to avoid impacting VDSL2. Or, using frequencies no lower than about 8 MHz for BPL appears to be sufficient to avoid impacting VDSL2. If VDSL2 were only on loops longer than about 3½ kft, then limiting BPL to using frequencies no lower than about 3.75 MHz would avoid impact on VDSL2. A more advanced shaping of the BPL transmit spectrum may offer an overall better compromise and could be a palatable solution in the future.

Balanced BPL transmission over the two low-Voltage power phases, with balanced terminations and loads in the homes and power transformers, could theoretically be sufficient to avoid impacting VDSL2, although this is impractical.

It may be possible to identify BPL interference by its noise PSD as received by VDSL2, although the accuracy of this identification is not known at this time.

All studies here assume BPL transmits on powerline drop wires. There is only 1 to 2 dB attenuation over a typical length of drop wire, and all homes on the low Voltage side of the transformer share the same signal path. So, there would be about the same levels of BPL interference from neighboring homes that subscribe to BPL into VDSL2 as there is for a home that subscribed to both BPL and VDSL2.

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