Project:	T1E1.4: HDSL2 Standard
Title:	**Optimal Transmit Spectra for HDSL2 under a Peak Frequency-Domain Power Constraint**
Authors:	Rohit Gaikwad and Richard Baraniuk Department of Electrical and Computer Engineering Rice University 6100 Main Street, Houston, TX 77005 RG – Tel: (713) 527–8750 x3786, Email: rohitg@rice.edu RB – Tel: (713) 285–5132, Email: richb@rice.edu Fax: (713) 524–5237
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Abstract

We present a technique for designing optimal transmit spectra for the HDSL2 service subject to a peak power constraint in the frequency domain. The peak power constraint might be imposed either due to engineering considerations or in order to optimize the transmission under a fixed transmit spectral mask (the OPTIS mask, for example). Using the channel and interference transfer functions, SNR estimates, and the peak constraint, we set up and solve an optimization problem to maximize the capacity. Sizable gains in performance margins (or bit rates) result. Furthermore, by design, the spectra are spectrally compatible with other services. While the technique is quite general — it does not depend on the exact choice of modulation scheme, for example — it is also extremely simple and of low computational complexity.

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1 Introduction

The T1E1.4 committee is charged with defining transmit spectra for HDSL2 service that both provide good performance margins and are spectrally compatible with existing services.

In an accompanying contribution [1] we presented a general framework for obtaining optimal transmit spectra. These spectra adapt to the noise and interference conditions on the channel in order to maximize the channel capacity under an average transmit power constraint. Sizable gains in performance margins (or bit rates) result [1]. Furthermore, the optimal spectra are, by design, spectrally compatible with neighboring services.

However, along with an *average* power constraint (as in [1]), in many cases it is important that the transmit spectra be limited by a *peak* frequency-domain power constraint. Peak constraints could be imposed for a number of reasons:

1. in an effort to maximize spectral compatibility with existing services,
2. in an effort to minimize power radiation into the atmosphere,
3. in order to optimize the transmission under an already standardized fixed transmit spectrum mask (the OPTIS mask [2] if standardized, for example).

In this contribution, we derive optimal transmit spectra suitable for these situations. We refer the reader to [1, 3] for more details.

2 Definitions and Notation

We will denote the upstream and downstream transmit frequency spectra by $S^u(f)$ and $S^d(f)$, respectively. An *EQPSD (EQual PSD)* signaling scheme in frequency band B is one for which $S^u(f) = S^d(f) \neq 0$ for all f in B (that is, both upstream and downstream transmissions occupy the band B in the same way). An *FDS (Frequency Division Signaling)* scheme in frequency band B is one for which $S^u(f) = 0$ when $S^d(f) \neq 0$ for all f in B and vice

versa (that is, both transmissions occupy orthogonal frequency bands within B.)

The term *self-interference* will describe self-NEXT and self-FEXT from neighboring HDSL2 lines (leakage from upstream into downstream transmissions and vice versa). *Different Service (DS) interference* will comprise interference from neighboring services other than HDSL2. Finally, we will use AGN to denote additive Gaussian noise.

3 Constrained Optimal Transmit Spectra

The optimization for HDSL2 transmit spectra in the presence of self-NEXT, self-FEXT, different service interferers, and AGN under an average power constraint is given in [1, 3]. A simple iterative algorithm yields the optimal solution. These optimal spectra utilize FDS to separate upstream and downstream transmissions in spectral regions facing high levels of self-interference. The shapes of the optimal spectra also vary widely depending on the interference type.

The addition of a peak power constraint to the above optimization merely limits the peak heights of the optimal spectra in certain spectral regions. The modified iterative algorithm for solution runs as follows [3]:

1. Estimate the switchover frequencies between EQPSD and FDS signaling.
2. Perform optimal power distribution within the EQPSD and FDS regions using *constrained* water-filling.[1]
3. Loop between 1 and 2 until convergence is reached.
4. Determine the power sharing between upstream and downstream transmit spectra within the FDS region(s).

In addition, we have found a simple test condition that closely approximates the optimal switchover frequencies for Step 1 [3]. This approximation reduces the above algorithm to two noniterative, computationally simple steps.

[1] Constrained water-filling is similar to water-filling [4, 5], except that we limit the peak of the transmit power by the frequency-domain power constraint.

It is key to note that the optimal transmit spectra do not dictate any specific modulation scheme for HDSL2, but rather simply describe how a modulation scheme should optimally distribute its power over frequency. Thus, optimal transmit spectra can be used with a number of different modulation schemes, including but not limited to DMT, CAP, QAM, PAM, etc.

4 Examples and Performance Margins

4.1 Simulation Details

Bit rate fixed at 1.552 Mbps.
Total average input power (one-sided) in each direction $P_{\max} = 16.78$ dBm.
Different service interference models obtained from Annex B of T1.413-1995 ([6], the ADSL standard), with exceptions as in [7].
Self-NEXT interference modeled as a 2-piece Unger model (see [8]).
Margins are calculated according to [9].
OPTIS PSD masks from [2] used as peak frequency-domain power constraints.
OPTIS transmit spectra are obtained by tracking 1 dBm/Hz below the OPTIS PSD masks (see [2]).
OPTIS performance margin numbers are from [2] and spectral compatibility numbers are from [7].
AGN of -140 dBm/Hz added to the interference.

DMT modulation scheme:
Sampling frequency $f_s = 1000$ kHz.
Bin width $W = 2$ kHz.
Number of bins $K = 250$.
Start frequency = 1 kHz.
Bit error rate = 10^{-7}.
SNR gap = 9.8 dB.
No cyclic prefix. No limitation on maximum number of bits per tone.

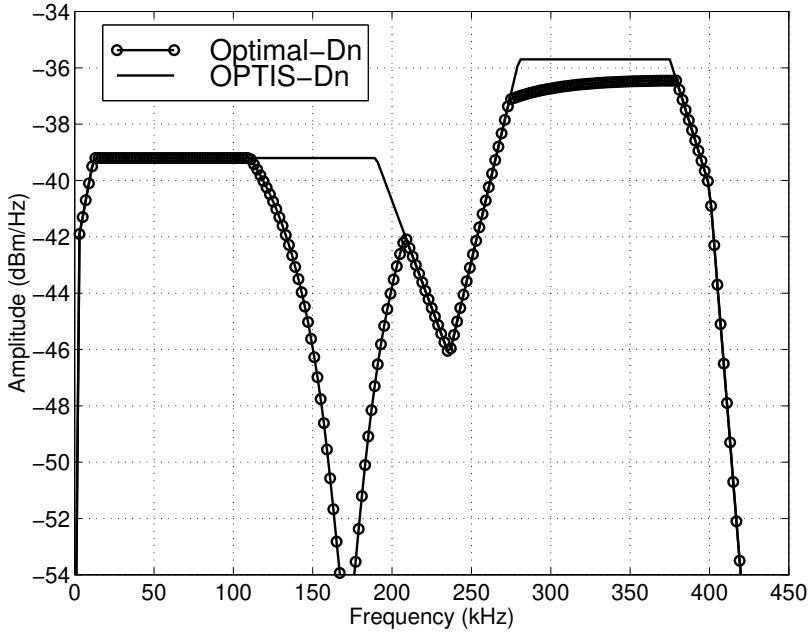

Figure 1: *Optimal downstream transmit spectrum of HDSL2 on CSA loop* 6 *under the OPTIS downstream constraining PSD mask with* 49 *HDSL different service NEXT interferers and AGN of* -140 *dBm/Hz. The '—' line denotes the constraining OPTIS PSD mask; the 'o—o' line denotes the constrained optimal transmit spectrum.*

4.2 Examples

In the following examples, we optimize the HDSL2 transmit spectra subject to the constraint that they be compatible with the OPTIS PSD masks [2].

Figure 1 shows the constrained optimal downstream transmit spectrum for HDSL2 under the OPTIS downstream mask constraint in the presence of different service NEXT interference from 49 HDSL interferers. Note the deep null in the optimal spectrum around 150 kHz in order to avoid HDSL. The optimal spectrum does not merely track the OPTIS PSD mask.

Figure 2 shows the constrained optimal upstream transmit spectrum for HDSL2 under the OPTIS upstream constraining PSD mask in the presence of NEXT interference from 25 T1 interferers. Note that the optimal spectrum avoids high-frequencies (to minimize T1 interference) as opposed to the

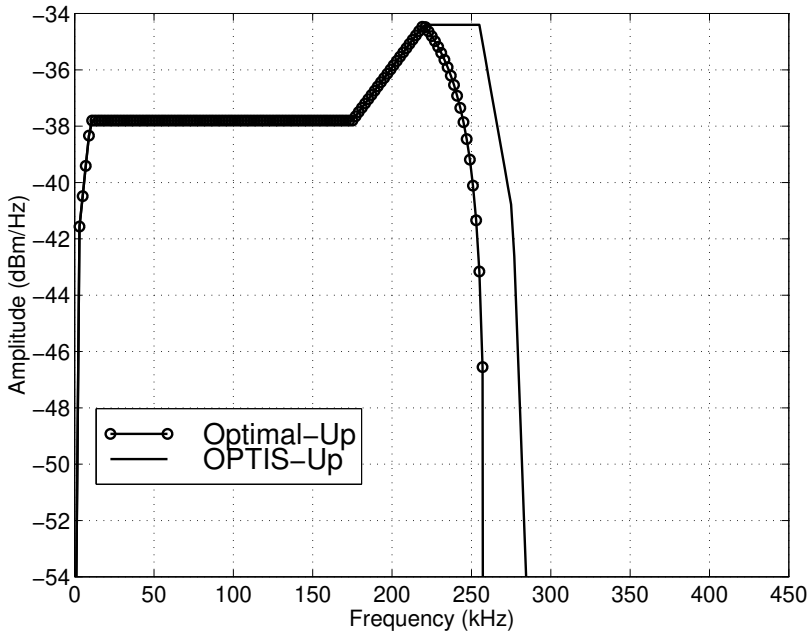

Figure 2: *Optimal upstream transmit spectrum for HDSL2 on CSA loop* 6 *under the OPTIS upstream constraining PSD mask with* 25 *T1 different service NEXT interferers and AGN of* -140 *dBm/Hz. The '—' line denotes the constraining OPTIS PSD mask; the 'o—o' line denotes the constrained optimal transmit spectrum.*

OPTIS PSD mask.

Figure 3 shows the constrained optimal upstream and downstream transmit spectra for HDSL2 under the OPTIS upstream and downstream constraining PSD masks in the presence of self-NEXT and self-FEXT from 39 HDSL2 interferers. Note that the optimal upstream and downstream transmit spectra use FDS in a large spectral region in order to avoid the high self-NEXT. In contrast, OPTIS transmit spectra have a large spectral overlap at lower frequencies (self-NEXT is sufficiently high here to warrant FDS), and this significantly reduces its performance margins.

In the case of bridged taps, the channel transfer function has nulls and varies with each loop. This strongly indicates the necessity of a transmit spectra that can adapt to the channel as well as interference conditions.

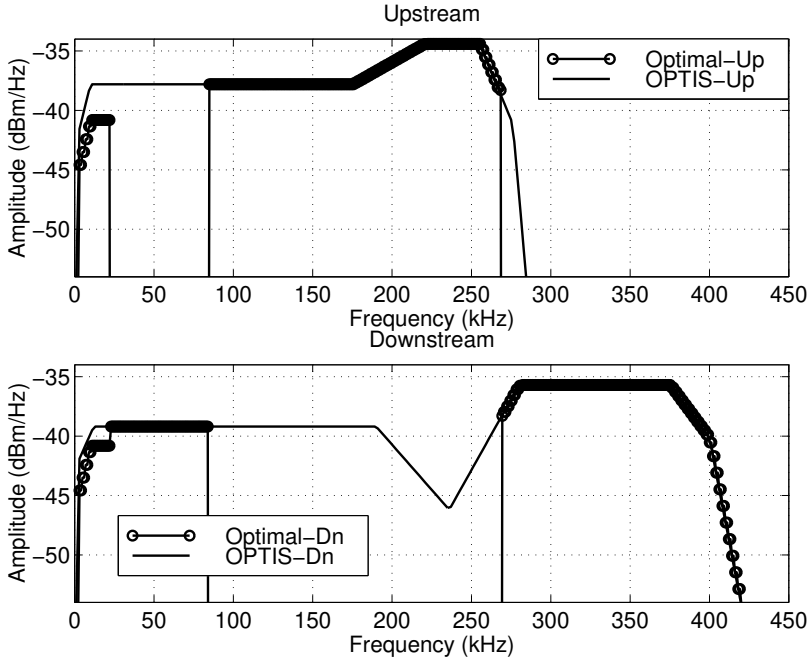

Figure 3: *Optimal upstream and downstream transmit spectra for HDSL2 (on CSA loop 6) under the OPTIS upstream and downstream constraining PSD masks with 39 HDSL2 self-NEXT and self-FEXT interferers and AGN of −140 dBm/Hz. The 'o—o' lines show the constrained optimal transmit spectra and the '—' lines show the constraining OPTIS PSD masks.*

4.3 Performance Margins

Table 1 compares the performance margins of the constrained optimal transmit spectra "under OPTIS" vs. the OPTIS transmit spectra [2] for CSA loop 6. For different service interferers (HDSL and T1), only the NEXT powers were considered, while for HDSL2 "self" comprises both self-NEXT and self-FEXT.

Key notes:

1. Constrained optimal transmit spectra vary significantly with interference type.

2. Constrained optimal transmit spectra do not follow the constraining

Table 1: *Uncoded performance margins (in dB) for CSA loop 6: OPTIS vs. Constrained Optimal "under OPTIS." OPTIS numbers were obtained from [2].*

		OPTIS		Optimal		Diff	
Crosstalk Src	xDSL service	Up	Dn	**Up**	**Dn**	**Up**	**Dn**
49 HDSL	HDSL2	2.7	12.2	3.7	13.8	1.0	**1.6**
25 T1	HDSL2	19.9	17.5	20.4	18.8	0.5	**1.3**
39 self	HDSL2	2.1	9.0	15.5	17.6	**13.4**	8.6
24 self+24 T1	HDSL2	4.3	1.7	4.5	4.7	0.2	**3.0**

Diff (Dn) = Difference in Downstream margins (Optimal − OPTIS)
Diff (Up) = Difference in Upstream margins (Optimal − OPTIS)

OPTIS PSD mask.

3. Optimal transmit spectra always outperform (have higher performance margins) than standard (non-adaptive) OPTIS spectra. Performance is significantly higher in cases of self-interference (HDSL2 self-NEXT and self-FEXT).

5 Spectral Compatibility

By design, the optimal transmit spectra achieve good spectral compatibility margins. Through water-filling, we distribute more HDSL2 power in regions of low interference and less HDSL2 power in regions of high interference. Thus, we avoid the transmission frequencies of neighboring lines and therefore simultaneously reduce the effect of HDSL2 transmissions on these neighboring lines.

To illustrate, consider the spectral compatibility between HDSL2 and HDSL. Table 2 lists the spectral compatibility margins of the optimal transmit spectra vs. those for OPTIS [7] on CSA loop 6. We compare the performance margins for HDSL in the presence of two types of interferers: other HDSL lines and HDSL2 lines. The column "OPTIS" lists the margins obtained using OPTIS transmit spectra for HDSL2 and the column "Optimal" lists the margins obtained using the constrained optimal transmit spectra for HDSL2 (different for each combination of interferers). We see that the

Table 2: *Spectral-compatibility margins (in dB) for CSA loop 6: OPTIS vs. Constrained Optimal "under OPTIS." OPTIS numbers were obtained from [7].*

			Optimal	
Crosstalk source	xDSL service	OPTIS	Up	Dn
49 HDSL	HDSL	7.86 (OPTIS and Optimal not involved)		
39 HDSL2	HDSL	7.84	**24.00**	**9.78**
49 HDSL2	HDSL	7.26	**23.01**	**10.22**

optimal spectra have better spectral compatibility margins with HDSL than OPTIS. A similar analysis could be carried out for T1 and ADSL services with similar results.

6 Summary of the Key Contributions

1. Constrained optimal transmit spectra can yield large gains in performance margins compared to fixed-mask schemes. We can trade these increased performance margins for increased bit rates or decreased average transmission power.

2. Optimal transmit spectra are inherently spectrally compatible with existing services, even when constrained by a peak power constraint.

3. Optimal spectra are not bound to any particular modulation scheme.

4. There exist near-optimal transmit spectra that are trivially complex to compute, even for complicated loops such as those with bridged taps.

5. No echo cancellation is required in bands employing FDS.

6. Transmit spectra can be adapted on-line to changes in line conditions (e.g., temperature variations, etc.).

7. This scheme requires knowledge of the characteristics of neighboring interfering services. These can either be estimated at start-up, or analyzed in a worst-case manner for a particular line under consideration.

This information could also be obtained from a central office database that specifies the type of services in each binder group in the telephone cable.

7 Recommendations

1. At the very least, adaptation under a fixed PSD mask should be allowed as an option in the HDSL2 standard.

2. Better, the Committee should entertain the idea of dynamic, rather than fixed transmit spectra (see [1]) for the HDSL2 standard.

3. If a single, fixed transmit spectrum mask is to be adopted by the Committee, optimal spectrum principles should be employed for its design based on worst-case signaling scenarios (see [1]).

   If adaptivity is employed "underneath" a fixed mask constraint (as in Section 4 above), then it is clear that even better results than "optimization under OPTIS" can be otained by choosing a better fixed mask than OPTIS.

4. The Committee should consider optimal spectra for the Spectral Compatibility Project.

References

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