Project: **T1E1.4: Spectrum Management II**

Title: **Channel Identification with Dynamic Spectrum Management (147R1)**

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Date: **November 5, 2001 (Greensboro, NC)**

Dist'n: **T1E1.4**

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A chronology of major steps for the smooth transition in spectrum management to allow some dynamic aspects is suggested. Material references on uses of channel identification information are also enumerated.

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Channel Identification Proposal (147R1)

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Abstract:

This document addresses channel-identification under the Dynamic Spectrum-Management (DSM) project of Spectrum Management [1]. Basic parameters that can be identified are enumerated along with some references to existing material on estimation of these parameters. Some of the methods here might form the basis for future informative text in DSM on how to estimate line and crosstalk spectra and transfer functions. It is suggested here also that specification of the accuracy of supplied channel information will be useful.

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1. Introduction:

This contribution generally provides information relevant to Section 5 of the DSM Document [1] on *channel/spectrum identification.* Channel-identification information can be of many productive uses, particularly improved reliability in DSL service provisioning, identification of existing or impending crosstalk problem situations, and improved data-rates and ranges for all asymmetric and symmetric services (see 99-089 [2] for example).

Channel signal and noise identification is fundamental to all modern DSLs, even if its implementation is tacit within other channel-related parameters (like equalizer coefficients). Accurate channel identification leads to an improvement in receiver performance, and when used also at the transmitter in the form of loading bit/energy distributions or precoders, can lead to further large gains in the 3 "r's of DSL: rate, range, and reliability. However, existing channel identification for a single point-to-point channel only begins the possible DSL system-level improvements. By sharing such information with network administration agents for better provisioning and maintenance of circuits, or perhaps even for various levels of coordination of DSL line spectra and/or signals, yet larger improvements are possible [2]. This paper outlines the various types of channel identification, and their uses and potential uses, while providing reference to existing materials on the subject as well as encouraging further work and study.

Future spectrum-management text under the category of dynamic spectrum management may desire to maintain the practice of informative text on methods of channel identification to help normalize understanding and procedure in this area of greatest potential DSL improvement, even though such procedure is discretionary and some methods may be proprietary to equipment vendor and/or service provider. Often enumeration of an acceptable procedure is highly desirable, especially if specification of accuracy is somewhat subjective. It is hoped that this paper may help uncover just how much specification in a spectrum-management standard is desirable.

Section 2 attempts to identify some basic multiple-input multiple-output (MIMO) channel characterizations that may be of use in DSM. Section 3 then proceeds to identify some potential benefits of identifying

channels as suggested for DSM study in Section 2, while Section 4 suggests steps that would migrate from the present SM to use of DSM.

2. Channel Identification Parameterization

Channel identification predicates advances in spectrum management: Mutual aversion of unacceptable crosstalk disturbance in DSL through spectrum management depends on the knowledge of the interfering signals' spectra. Better knowledge enables better spectrum management. While such argument is easily accepted, the methods, essential parameters, and ultimate limits require considerable diligence to comprehend a complete DSM program.

2.1 Channel Identification Nomenclature

Channel quantities fall into 3 categories:

1. line responses
2. noises
3. source information, power and clocks

2.1.1 Line Responses

The line response can be characterized by a transfer function associated with a channel. The existing spectrum management standard provides a procedure for characterizing any twisted-pair transmission line using 2-port network theory (and enumerates a number of parameters for US 26 and 24 gauge twisted pair calculations). In actual practice, the receiver identifies the channel response directly or indirectly. Identification procedures vary, but ultimately the most complete line response identification would be the **matrix channel transfer function**

$$\mathbf{H(f)} = \left[H_{ij}(f)\right]_{i=1,\ldots,L\ j=1,\ldots,L}$$

where $H_{ij}(f)$ is the insertion-loss transfer function from line j to line *i.* i is a row index, while j is a column index. The insertion loss is measured by taking the ratio of voltage of a source across the receiver load impedance with the line present to the voltage measured at that same point with no line present and the source directly connected. L is clearly the number of lines in the binder/cable being measured and the transfer functions $H_{ii}(f)\big|_{i=1,\ldots,L}$ are the transfer functions previously considered for DSL when each line is considered independent of the others. When $i \neq j$, $H_{ij}(f)$ measures the gain/phase of the FEXT from line j to line i. Figure 1 illustrates the various transfer functions.

A continuous transform $\mathbf{H}(f)$ is indicated here to avoid the issues associated with possibly asynchronous clocking of DSL circuits. Many of the transfer functions between lines maybe zero or practically negligible, but there are a few dominant crosstalkers into each line (and which is dominant may depend strongly on frequency). For best ultimate performance of DSL, the entire matrix of channel transfer functions need be known. Methods for determining $\boldsymbol{H}(f)$ appear in [3], [19]. There are of course two transfer functions for downstream and upstream, however basic reciprocity in electromagnetic theory forces these two functions to essentially be the same – mathematically

$$H_{ij}(f) = H^{*}_{ji}(f) \quad \text{Reciprocity.}$$

For line signals traveling in opposite directions, NEXT coupling is also potentially of interest even for frequency-division multiplexed systems (as in DSL). In this case, the insertion loss transfer function from line j in one direction to line i at the same side of the binder is $G_{ij}(f)$. The $L \times L$ matrix is $\mathbf{G}(f)$ and

$G_{ii}(f)$ measures echo on line i. In Figure 1, a different font is used to represent the different NEXT couplings at different ends of the line.

Also of interest and easier to compute sometimes are the **channel magnitude profiles**

$$\left|H_{ij}(f)\right|^2_{i=1,\ldots,L\ j=1,\ldots,L} \quad \text{or} \quad \left|G_{ij}(f)\right|^2_{i=1,\ldots,L\ j=1,\ldots,L}.$$

Of great interest will be **a virtual binder group for line i,** which is that set couplings or pairs of lines J_i such that the maximum coupling from j into i exceeds a threshold $\max_f \left|H_{ij}(f)\right| > \sigma_i$ or $\max_f \left|G_{ji}(f)\right| > \sigma_i$. These are the only lines' crosstalk that will concern line i. The measurement of $\boldsymbol{H}(\boldsymbol{f})$ and determination of thresholds and procedures for locating virtual binder groups need discussion within DSM. The number of significant crosstalkers of a given type has been assumed through a model in previous spectrum management – clearly the virtual binder group and the matrix channel transfer function contain all the same information on an individual line basis, plus more information that is pertinent to each situation/DSL deployment.

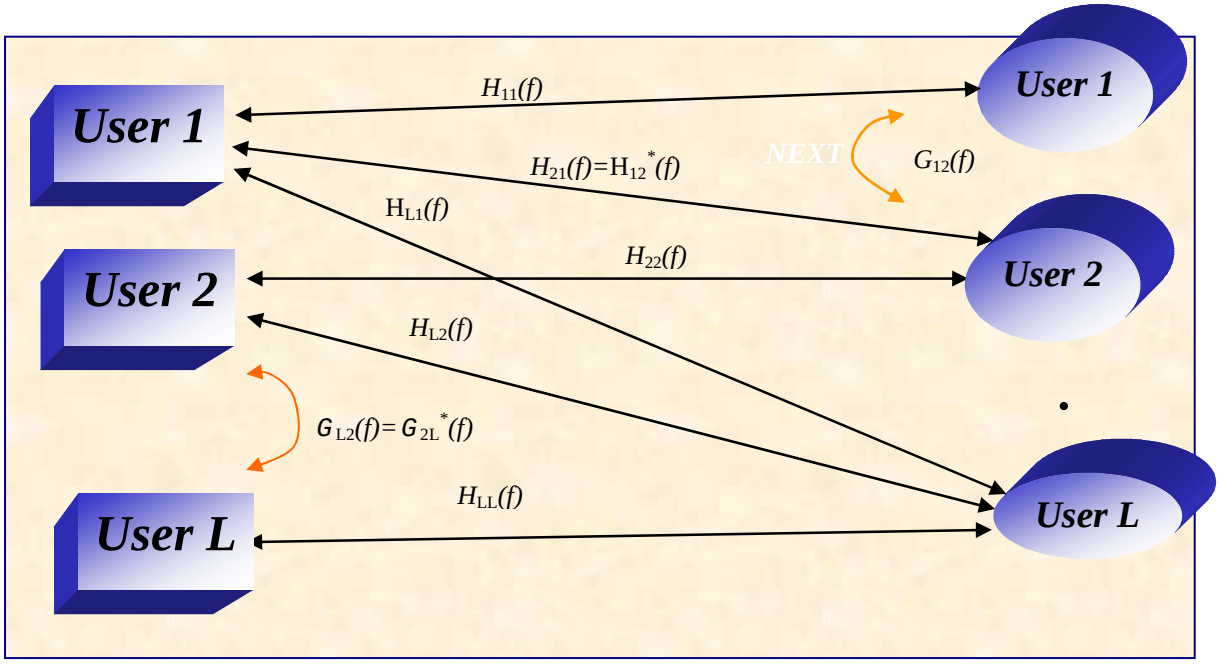


Figure 1 – Illustration of MIMO channel paths.

2.1.2 Noises

Noise sometimes includes crosstalk, and always did in earlier spectrum-management studies. Any crosstalking signal not in J_i is still a potential contributor to noise. Other noise sources are the inevitable thermal line and resistive termination noises and radio-frequency noises. Impulse noise is also of great concern, but not addressed in this particular paper.

Noise will be identified by a power spectrum $N(f)$. This residual noise has been modeled in spectrum management as Gaussian. Measurement of power spectrum will require specification of time intervals, averaged frequency bands, and required accuracies. Dynamic spectrum management will presume that the DSL modems measure this spectrum and report it, rather than assume it to be some fixed model.

The measurement procedure and accuracy for the noise power spectrum needs definition and specification. For example procedures, see [3] and [4]. Often, once a noise has been previously identified, it is relatively easy to detect subsequent recurrence [4]. DSM needs line-specific procedure for noise measurement, as opposed to current static spectrum management that uses worst-case noise models universally.

2.1.3 Source Information

The power level transmitted by any DSL line is known to that line only and cannot be measured on another line absolutely. There is always an ambiguity without specific knowledge of the transmit power spectrum of whether a signal measured at significant levels has absolute scaling determined by transmit power or by coupling between lines. The used power spectral density of the transmitter $P_i(f)$ can be reported by a modem.

Clocking information is important, however fortunately, signal processing methods exist at any point in a system to determine appropriate clock offset between any two signals in a virtual binder group. [3],[5].

2.2 MIMO FEXT Models

Dynamic Spectrum Management encompasses modeling of individual transfer functions. As a somewhat temporary assistance to such process for study, this subsection proposes a specific model for $\mathbf{H}(f)$:

T1.417 Spectrum Management [20] models FEXT power transfer of the $i \neq j$ terms as proportional to the line transfer function $|H_{ii}(f)|^2$, the square of frequency f^2, and the length of the line (in meters), d, which is explained on page 90 of [13]. This corresponds to a crosstalk-insertion loss transfer path of

$$H_{ij}(f) = h_{fext} \cdot H_{ii}(f) \cdot \left(\sqrt{-1} \cdot f\right) \cdot \sqrt{d} \qquad (2)$$

with a worst-case value of $h_{fext} = \sqrt{7.74 \times 10^{-21} \cdot (.3048 m / ft)} = 4.8 \times 10^{-11}$ for two adjacent category 3 telco-plant crosstalking lines. Equation (2) is for one crosstalking line – thus an extra multiplicative factor of $(L-1)^{.6}$ used in models that average several lines is not used in (2) because that factor is for more than just two adjacent crosstalking lines. The factor h_{fext} is reduced nominally by a factor of 10 (or 20 dB) for category-5 wiring with tighter twisting. However, quads in the telephone plant that instead sometimes twist all four lines in an ensemble, may have a higher value than the value above, as much as an increase by a factor of 20 dB. Thus, a range of h_{fext} may be given by

(category 5 independent twists) $4.8 \times 10^{-12} \le h_{fext} \le 4.8 \times 10^{-10}$ (category 3 ensemble-twisted quads).

This same FEXT model is often seen in a form that describes only energy transfer, in other words the squared magnitude of Equation (2). Here, the model is converted to voltage transfer because EFM studies may desire phase information also. My group at Stanford sometimes augments (2) with a linear phase term $e^{j2\pi f\tau}$ where τ is chosen to make the corresponding crosstalk impulse response causal. The matrix $\mathbf{H}$ can then be formed by finding the insertion-loss function for any twisted pair in the bundle and inserting this insertion loss along the diagonal terms of the matrix $\mathbf{H}$. The off diagonal terms are equal to Equation (2) with possibly randomly chosen phase offsets and/or linear phase. Some schemes that coordinate the lines may find the details of the off-diagonal terms increasing important.[1] In all cases, simple squaring of Equation (2) and treating the FEXT like Gaussian noise (which is what current transceiver designs and implementations do) leads to the lowest possible (i.e., uncoordinated) performance.

[1] When the off-diagonal terms are significantly smaller than the diagonal, the best coordinated schemes all converge to making the line appear as if there were no FEXT. While the details of the transfer function are then not of consequence to performance, the implementation still though depends on knowing the phase.

However, actual individual FEXT insertion losses do not follow such a smooth characteristic with frequency and indeed vary up and down with respect to the model in Equation (2), see Figure 2. The variations can vary with the individual pairs as in Figure 2.

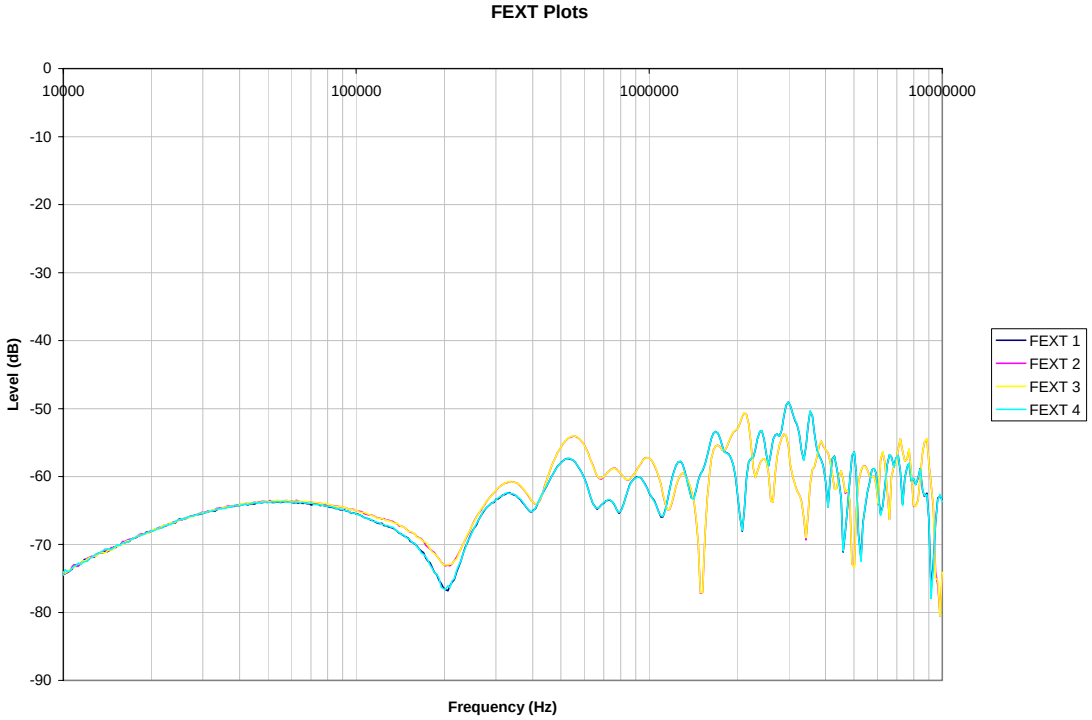


Figure 2 – 500 meter example FEXT insertion loss functions (courtesy, John Cook of BTexact)

The inaccuracy of the Equation (2) model is increasingly evident at higher frequencies. There is a raised sinusoidal appearance to the magnitude transfer. This plot is for two different coupling functions on a 500 meter .5 mm cable with 50 pairs. The cosine terms closely approximate the location of the dips and peaks in frequency seen in the measured FEXT insertion loss functions. Thus, the proposed model is

$$H_{ij}(f) = \begin{cases} H(f) & i = j \\ n_{lines} \cdot \sqrt{h_{fext} d} \cdot \left(\sqrt{-1} \cdot 2\pi f\right) \cdot \left[1 + 0.3 \cdot \cos\left(\frac{2\pi f d}{c_{line}}\right) - 0.3 \cdot \cos\left(\frac{4\pi f d}{c_{line}}\right)\right] \cdot H(f) \cdot e^{j\varphi} & i \neq j \end{cases}$$

where $H(f)$ is as above derived from standard transmission theory. c_{line} is the speed of light on the media (often just use 300 Mmeters/sec), and φ is a phase term (i.e., $\varphi = 2\pi f\tau + \phi_{mk}$ where τ makes response causal and ϕ_{mk} is chosen from uniform distribution on 2π independently for each pair of indices *m* and *k*). Normalizing each off-diagonal entry by the factor $n_{lines} = (K-1)^{.6/2} / \sqrt{(K-1)} = (K-1)^{-.02}$ on average can account for the fact that distant lines have less crosstalk than close lines within the bundle, and produces a slightly more accurate model when *K=25 or 50.*.

The following table suggests values for h_{fext} and n_{lines}:

	Category 5 Quad	Category 3	Telco Quads
h_{fext}	4.8×10^{-12}	4.8×10^{-11}	4.8×10^{-10}
n_{lines}	1	$49^{-0.2} = .459$	1

3. Uses and Potential Uses of Channel Identification Information

The are levels of use of channel identification information:

Provisioning will be defined to be the use of the information in Section 2.1 to predict reliable data rate and range for the DSL. Various levels of this information can either be assumed or determined via measurement and reporting. Measurement and reporting should lead to higher, more reliable data rates and ranges than presumption.

Fault prediction and isolation from the perspective of channel identification is the observation that a service may fail because of degrading line conditions in the virtual binder group. Isolation would determine which other lines precisely cause the greatest difficulty within the virtual binder. Both can be improved through measurement and reporting of accurate and detailed channel information.

Service Tiers – data rates and symmetries need not be fixed for all lines or even lines of the same DSL type. Prices for services that are at higher or lower rates may be set according to what is achievable and demanded at the price offered. Services may be guaranteed, offered at certain times of day, or as available. This area may likely determine the time intervals at which channel identification information is collected.

Transceiver optimization – crosstalk reduction methods such as multi-user detectors or cancellers [6]-[10] may require knowledge of the matrix channel transfer response. Such methods can lead to significant improvement. This area refers to the use of the information individually and in an uncoordinated manner on different lines.

Spectrum Balancing is an advanced form of frequency-dependent power management on different lines, see [2], [11],[17]. Spectrum balancing may be distributed or coordinated and makes use of the quantities $\left|H_{ij}(f)\right|$, $\left|G_{ij}(f)\right| N_i(f)$, and $P_i(f)$, $i = 1,...,K$, $j = 1,...,K$. Other pertinent references are [14] and [15].

Vectoring is a very advanced form of line coordination that occurs with packet unbundling [2], [12]. Vectoring makes use of the quantities $H_{ij}(f)$, $N_i(f)$, and $P_i(f)$. This may include MIMO echo cancellation (NEXT cancellation) at one or both ends of the transmission system.

4. Dynamic Spectrum Management Migration Chronology

An often posed question is "what is the series of steps that migrates from today's DSLs to those of the future." The particular technical concern is simply disruption of existing systems, or equivalently, the need to replace them. A migration chronology that endorsed such disruption would not be successful nor wise for the industry. Fortunately, there are cogent incremental steps that gradually improve DSL performance, ultimately leading to largest revenues, reliable data rates, and fiber, and which do not disrupt nor render obsolete existing DSLAMs.

Step 1 – current static management
Assess current dynamics of transmission systems with autonomous adaptive spectra

Step 2 – allow channel information to pass to admin site (see contribution 46, [18])
DSM procedures for info specification and passing
Better provisioning, problem isolation
Needs parameter specification

Accuracy specification, and perhaps recommended methods

Step 3 – some lines allow programmed spectra and spectrum balancing
Offer better rates and reliability
Increased symmetry allowed

Step 4 – some lines allowing vectoring
Yet higher data rates, reliability (better equip costs/aggregation

Final Step – all lines ultimately vectored
Tiny ONU's with extremely high symmetric data rates

5. Conclusion and Proposal

Normalized understanding of channel identification procedure across the DSL industry can lead to numerous improvements in range, rate, and reliability. This contribution identifies the gross intermediate steps to improve from present practice to future potential practice, as well as defining a number of parameters that likely need normalization via DSM. While no specific proposal is yet made in this contribution, it is hoped the parameters enumerated here as well as the steps will elicit comment from those with interest. This paper can form a template from which future contributions that do contain specific text proposals can successfully progress.

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