A Temporary Model for EFM/MIMO cable characterization

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Abstract:
The multiple-input multiple-output (MIMO) characterization of a cable of twisted pairs merits attention and measurement for studies in ethernet in first mile (EFM) efforts. Quads or other groups of twisted pair within a cable may be combined for better transmission/duplexing: The interaction between lines within a subgroup or the entire cable can be exploited to improve performance and reduce transceiver complexity, motivating a model. This note suggests a temporary model for MIMO FEXT that can be used to evaluate/test EFM.

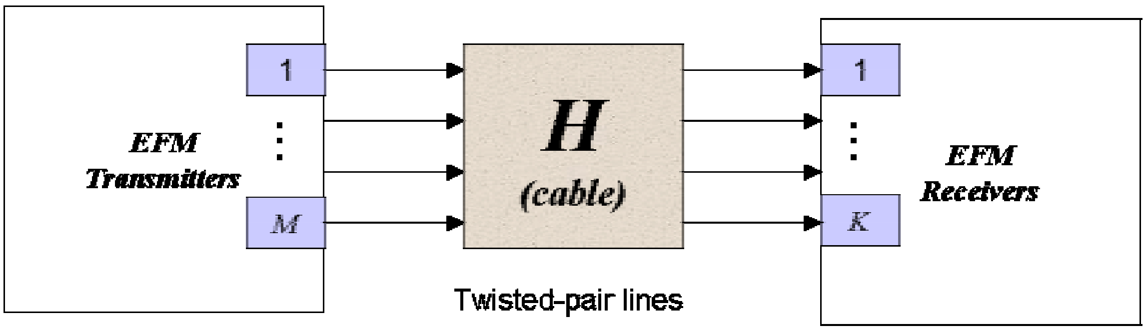

Figure 1 – Matrix Channel

The MIMO FEXT Channel: Figure 1 illustrates the matrix or MIMO FEXT twisted-pair channel. Each of the *M* inputs to this matrix channel may produce a component of the signal at each of the *K* outputs. Usually, *M=K*. For instance, a quad (4 twisted pairs tightly packed together) has *M=4* inputs and *M=4* outputs and a total of $16 = M \cdot K$ transfer functions of interest. These $M \cdot K$ transfer functions can be summarized in a $K \times M$ matrix $\mathbf{H}$. The $K \times 1$ vector of channel outputs $\mathbf{Y}$ is then related to the $M \times 1$ vector of channel inputs $\mathbf{X}$ by

$$\mathbf{Y} = \mathbf{HX} . \qquad (1)$$

Ultimately, the designer would desire the exact $\mathbf{H}$ for each binder of wires: Any FEXT information is contained within this matrix. Approximate models are of interest in evaluating the various EFM opportunities in terms of range, rates, service applications/market. In recognition that such transfer matrices either are not well known, this note suggests an $\mathbf{H}$ model for temporary use in EFM studies in the near-term. NEXT matrix models are of less MIMO interest since NEXT is either avoided by duplexing choice or by echo/NEXT cancellation between lines.

The km^{th} element of $\mathbf{H} = [H_{mk}(f)]_{k=1,\ldots,K \atop m=1,\ldots,M}$ is the transfer function from input *m* to output *k*. When *m=k*, then $H(f)$ is simply the transfer function of the m^{th} line, $H_{kk}(f)$ that can be determined from basic transmission line theory, given the length and RLCG parameters of the line [1]. Reference [1] also models FEXT power transfer of the off-diagonal terms as proportional to the line transfer function $|H_{kk}(f)|^2$, the square of frequency f^2, and the length of the line (in meters), d, which is explained on page 90 of [2]. This corresponds to a crosstalk-insertion loss transfer path of

$$H_{mk}(f) = h_{fext} \cdot H_{kk}(f) \cdot (jf) \cdot \sqrt{d} \qquad (2)$$

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 $(K-1)^{.6}$ 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

$$\text{(category 5 independent twists) } 4.8\times10^{-12} \le h_{fext} \le 4.8\times10^{-10} \text{ (category 3 ensemble-twisted quads).}$$

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.

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.

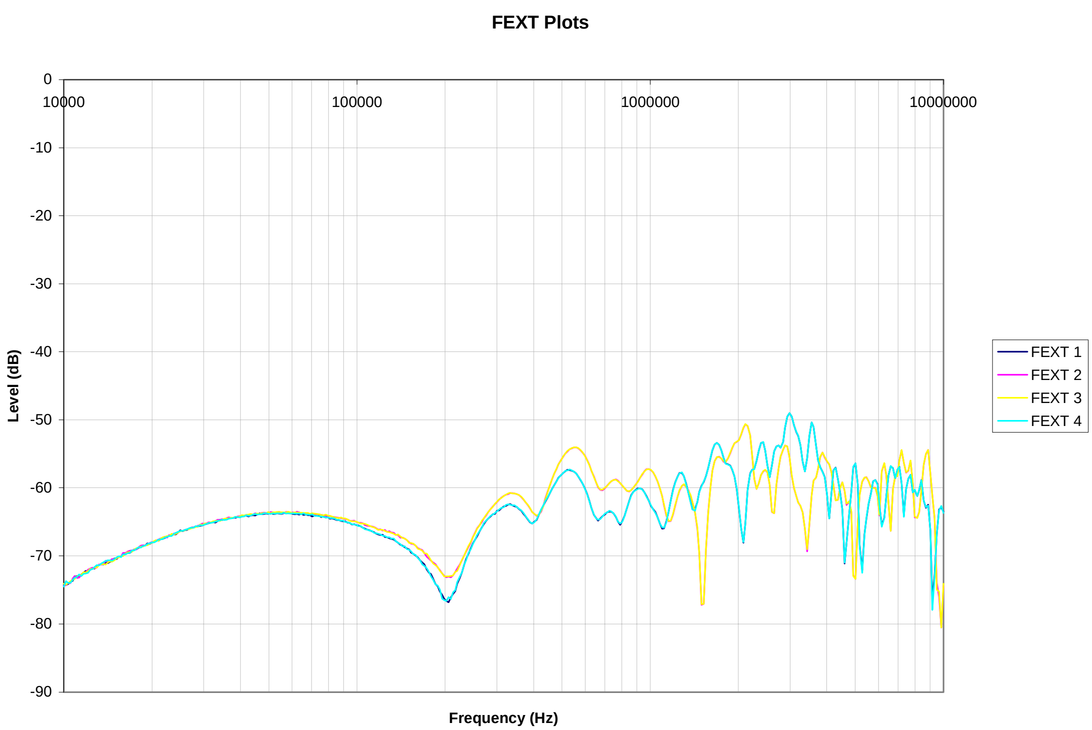

Figure 2 – 500 meter example FEXT insertion loss functions (courtesy, John Cook of BTexact)

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

[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.

$$H_{mk}(f)=\begin{cases} H(f) & m=k \\ n_{lines}\cdot\sqrt{h_{fext}d}\cdot(j2\pi f)\cdot\left[1+0.3\cdot\cos\left(\frac{2\pi fd}{c_{line}}\right)-0.3\cdot\cos\left(\frac{4\pi fd}{c_{line}}\right)\right]\cdot H(f)\cdot e^{j\varphi} & m\neq k \end{cases}$$

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

Summary:
This proposed MIMO FEXT model attempts to augment well-known existing models to include:

Quads: which may have better or worse coupling depending on the type of quad and associated independent (cat 5) or ensemble (cat3 telco quad) twisting;

Phase: phase coupling between lines that can be important for implementation of coordinated transmission schemes

Notches: the length-dependent frequency variation not included in earlier models, but which may become important in EFM studies.

References:

[1] Spectrum Management for Loop Transmission Systems, ANSI Standard T1.417-2001, New York, NY.
[2] T. Starr, J. Cioffi, and P. Silverman, Understanding DSL Technology, Prentice-Hall:1999.