Specifying a Channel Through Impulse Response

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July 9, 2004

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Current Practice

Current practice specifies channels in terms of S parameters.

- This is useful since S parameters are relatively easy to measure and can be proven to give a complete description on a linear channel.
- However, there are problems with S parameters, and I propose to get around the problems by using impulse response.

Overview

This presentation consists of:

1. Remarks on specifying a channel.
2. Problems with specifying S parameters.
3. Impulse response model for the thru channel.
4. Impulse response model for interference.
5. Review.

Remarks on Specifying a Channel

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Remarks on Specifying a Channel (cont.)

The description of a channel is a large array of numbers, in the frequency domain it could be magnitude and phase for N frequency values; or in the time domain, amplitude for 2*N time values.

The first problem in specifying channels is figuring out a way to reduce the vast Hilbert space to a manageable number of parameters which capture its useful characteristics.

Remarks on Specifying a Channel (cont.)

For defining a channel in terms of S parameters, usually the first step is to throw out phase and define a function of frequency which acts as a bound on magnitude. The function can be expressed easily in terms of a small number of parameters.

What I propose is to use a parametrically defined impulse response that will be fit to the measured channel impulse response in a LMS fashion. The allowable range of parameters and the LMS residue can then be specified.

Problems with Specifying a Channel

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Problems with Specifying S Parameters (cont.)

There are two fundamental issues with S parameters:

1. **They deal with the frequency domain while our signaling is time domain.**
2. **They use a logarithmic scale while real data is linear.**

Problems with Specifying S Parameters (cont.)

These issues cause three practical problems:

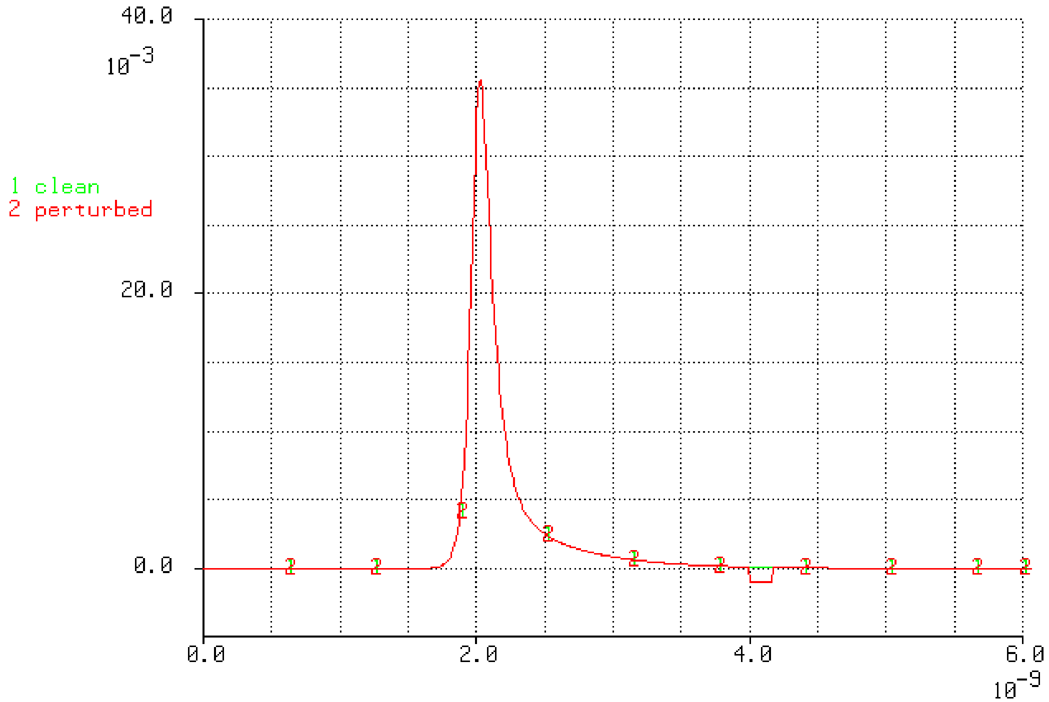
1. **Small perturbations in impulse response, of minor significance for system performance, can have dramatic effects on S21.**
2. **Deviations from phase linearity are very important, but good specification are hard to define.**
3. **The dB scale encourages specification of signals that are below the noise level.**

Impulse Response Small Perturbations

1. Small perturbations in impulse response, of minor significance for system performance, can have dramatic effects on S21.
2. Deviations from phase linearity are very important, but good specification are hard to define.
3. The dB scale encourages specification of signals that are below the noise level.

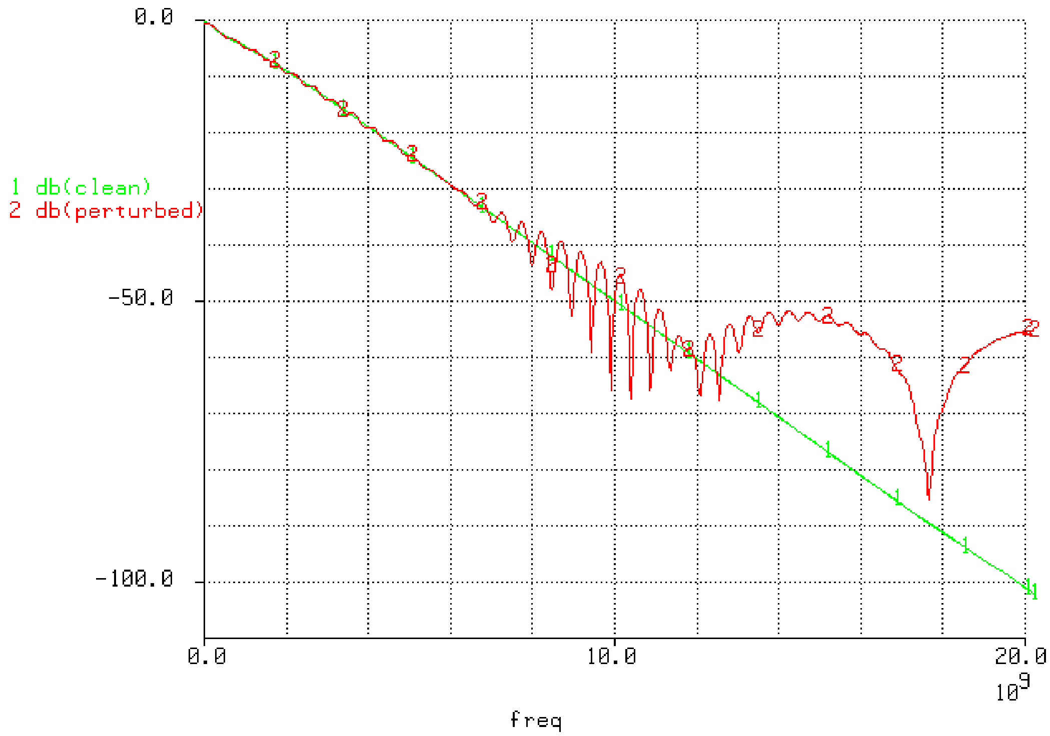
Impulse Response Small Perturbations (cont.)

This small perturbation in the impulse response...



...can have a dramatic change in the dB frequency domain representation.

Impulse Response Small Perturbations (cont.)



The green curve is very near the IEEE802.3ap guideline (at least below 15GHz), while the red curve is more than 10dB below.

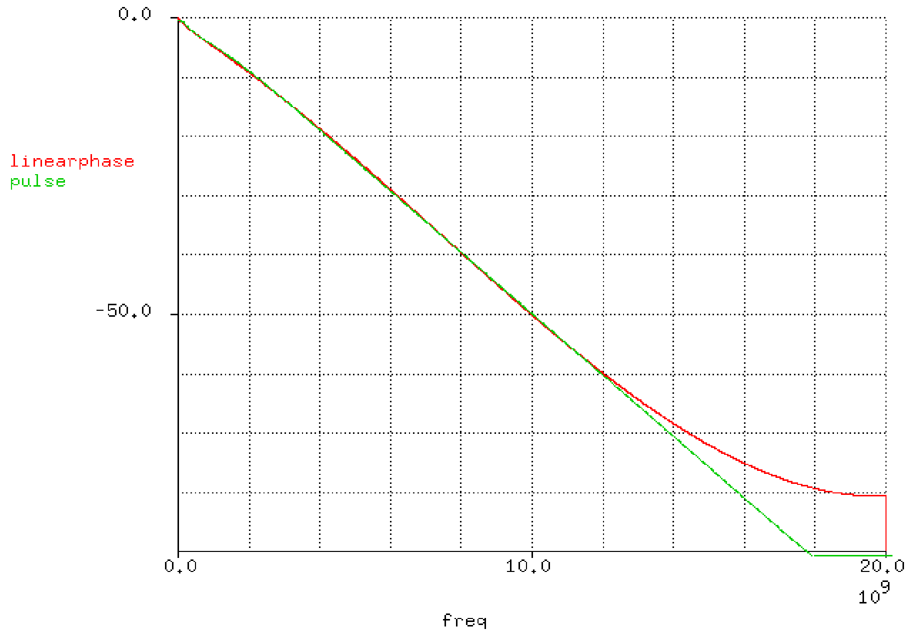
Impulse Response Small Perturbations (cont.)

While the glitch in the impulse response needs to be considered, making it equivalent in importance to a 30 percent change in attenuation at 10GHz, overstates its importance.

Deviations From Phase Linearity

1. Small perturbations in impulse response, of minor significance for system performance, can have dramatic effects on S21.
2. Deviations from phase linearity are very important, but good specification are hard to define.
3. The dB scale encourages specification of signals that are below the noise level.

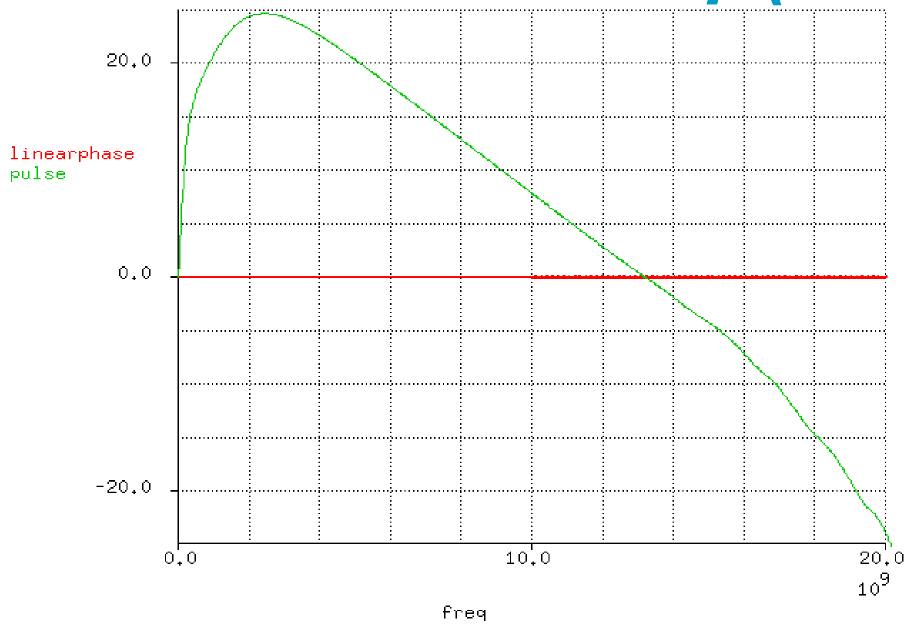
Deviations From Phase Linearity (con.t)



Here are two frequency domain transfer curves in dB.

The red curve is the ad-hoc channel committee's proposed amplitude limit with linear phase. The green curve is the Fourier transform of an impulse response defined by a parameterized pulse model, with parameters selected to fit the ad-hoc committee's curve, although it deviates below 60dB.

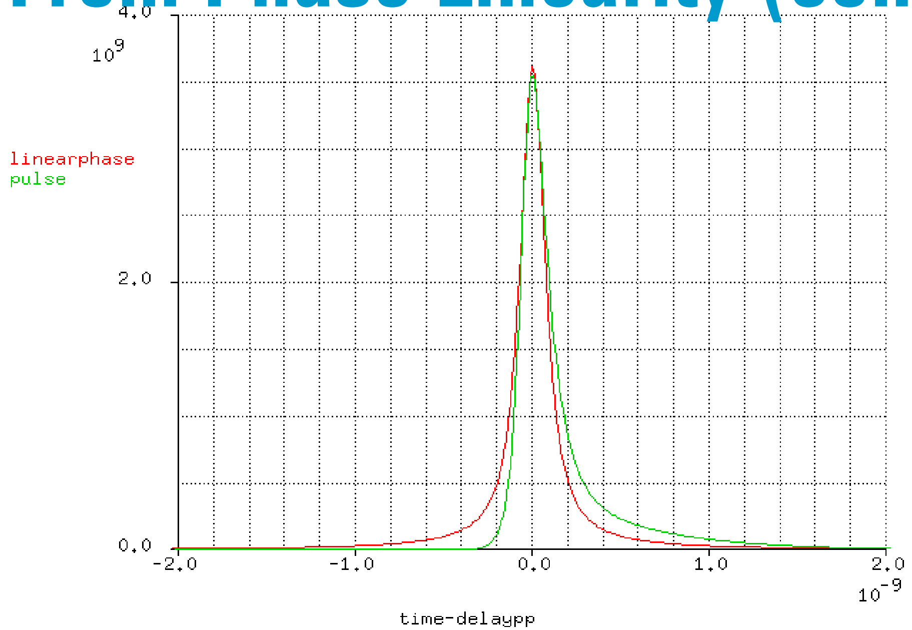
Deviations From Phase Linearity (con.t)



These are the phase characteristics of the two transfer curves with the average delay removed. Phase is shown in degrees.

Again, the red curve is the ad-hoc channel committee's proposed amplitude limit with linear phase. The green curve is the Fourier transform of an impulse response defined by a parameterized pulse model, with parameters selected to fit the ad-hoc committee's curve, although it deviates below 60dB.

Deviations From Phase Linearity (con.t)

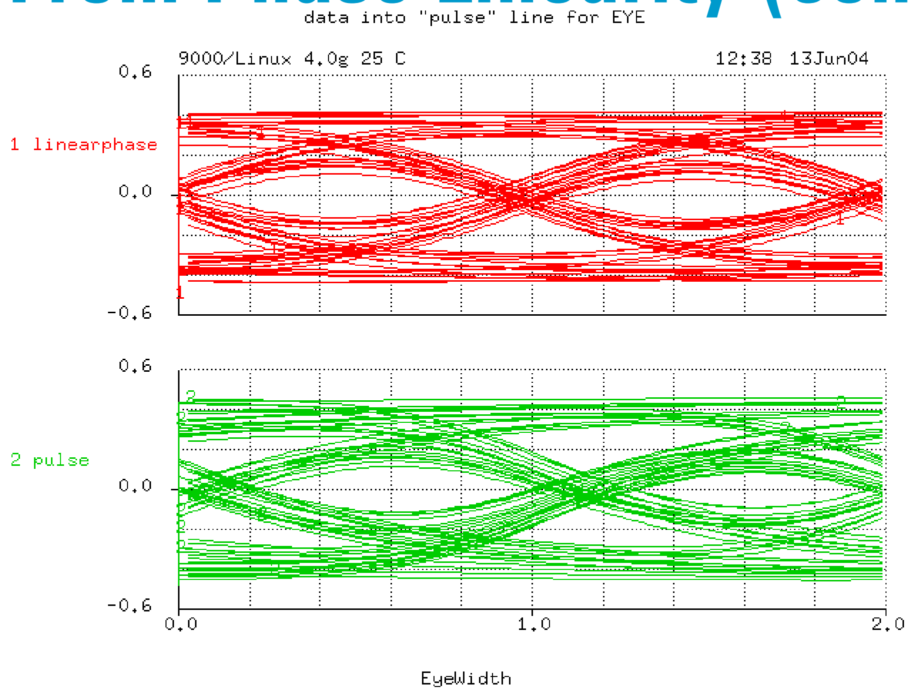


This shows the impulse responses of the two channels.

Both impulse responses are about the same width, but the "linerPhase" impulse response is symmetric while the "pulse" response rises quickly and falls much more slowly.

Again, the red curve is the ad-hoc channel committee's proposed amplitude limit with linear phase. The green curve is the Fourier transform of an impulse response defined by a parameterized pulse model, with parameters selected to fit the ad-hoc committee's curve, although it deviates below 60dB.

Deviations From Phase Linearity (con.t)



If a 127-bit PRBS pattern is sent through each channel at 5Gb/s, the EYE pattern at the receiver end is about the same for each of the two channels.

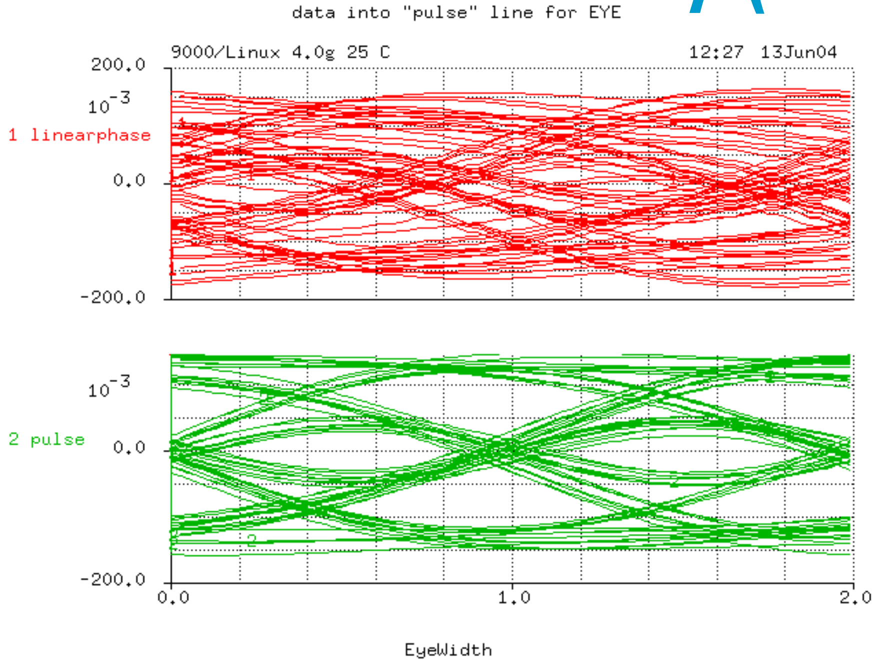
Again, the red curve is the ad-hoc channel committee's proposed amplitude limit with linear phase. The green curve is the Fourier transform of an impulse response defined by a parameterized pulse model, with parameters selected to fit the ad-hoc committee's curve, although it deviates below 60dB.

Deviations From Phase Linearity (con.t)

If the data rate is increased to 10Gb/s, neither channel will show an open EYE.

But if 10dB of transmitter post-cursor equalization is applied:

Deviations From Phase Linearity (con.t)



The asymmetric Tx equalization nicely opens the channel with a non-linear phase and an asymmetric impulse response, while the channel with linear phase and a symmetric impulse response is still closed.

DFE on the receiver side shows an even greater preference for the non-linear phase channel.

Again, the red curve is the ad-hoc channel committee's proposed amplitude limit with linear phase. The green curve is the Fourier transform of an impulse response defined by a parameterized pulse model, with parameters selected to fit the ad-hoc committee's curve, although it deviates below 60dB.

Deviations From Phase Linearity (con.t)

Phase characteristics are important, at least regarding how the channel responds to equalization.

Specifying phase is difficult. I am not sure it can be done in a satisfactory manner.

Signal Specification Below Noise Level

1. Small perturbations in impulse response, of minor significance for system performance, can have dramatic effects on S21.
2. Deviations from phase linearity are very important, but good specification are hard to define.
3. The dB scale encourages specification of signals that are below the noise level.

Signal Specification Below Noise Level (cont).

To find the S/N ratio of data at the end of a channel, first find the signal.

At the output of the transmitter, assume the amplitude is 1V p-p differential. Then the total RMS value of a square wave is 500 mV.

Signal Specification Below Noise Level (cont).

The Fourier components of this are:

1. first harmonic = 450mV RMS
2. second harmonic = 0mV RMS
3. Third harmonic = 150mV RMS
4. Fourth harmonic = 0mV RMS
5. Fifth harmonic = 90mV RMS

This assumes 0 rise and fall times. Actual harmonics fall off faster than indicated due to finite rise and fall times.

Signal Specification Below Noise Level (cont).

Above the data rate frequency, twice the highest square wave frequency, the third harmonic predominates. Call the transmitted amplitude 150mV.

Signal Specification Below Noise Level (cont).

Then find the noise. The thermal noise is:

VnoiseRMS = sqrt(4*k*T*B*R)

where:

k = Boltzman's Constant (1/381e-23J/K)

T = Temperature (I assume 85°C = 358K)

B = Bandwidth (I assume 20GHz)

R = Resistance (50Ω for a fully terminated 100Ω differential channel.)

Vnoise = 140.6u

Signal Specification Below Noise Level (cont).

For a non-attenuating channel, the S/R for the third harmonic is 60.6dB assuming the following:

- Rise and fall times of 0
- Receiver noise figure of 0dB

In reality, neither condition is met, so the S/N is less. This makes it pointless to specify SDD21 below –60dB.

Signal Specification Below Noise Level (cont).

This is actually easy to handle – just limit the range over which SDD21 is specified to the frequency range where it is above –60dB.

If it is specified down to lower levels, there is risk of rejecting otherwise acceptable channels because they have holes in their SDD21 characteristic at a frequency where even a compliant channel would transmit nothing of value.

thru Channel Impulse Response Model

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thru Channel Impulse Response Model

The problem with using impulse response modeling of the channel, is finding a useful parametrically defined impulse response function. I propose:

```
Pulse Amp/(exp(-to/tr)+1/(
        1*exp(-to/tf1) +
     ep2*exp(-to/tf2 +
     ep3*exp(-to/tf3
))
```

where:

to = time-delay

delay = effective channel delay (approximately)

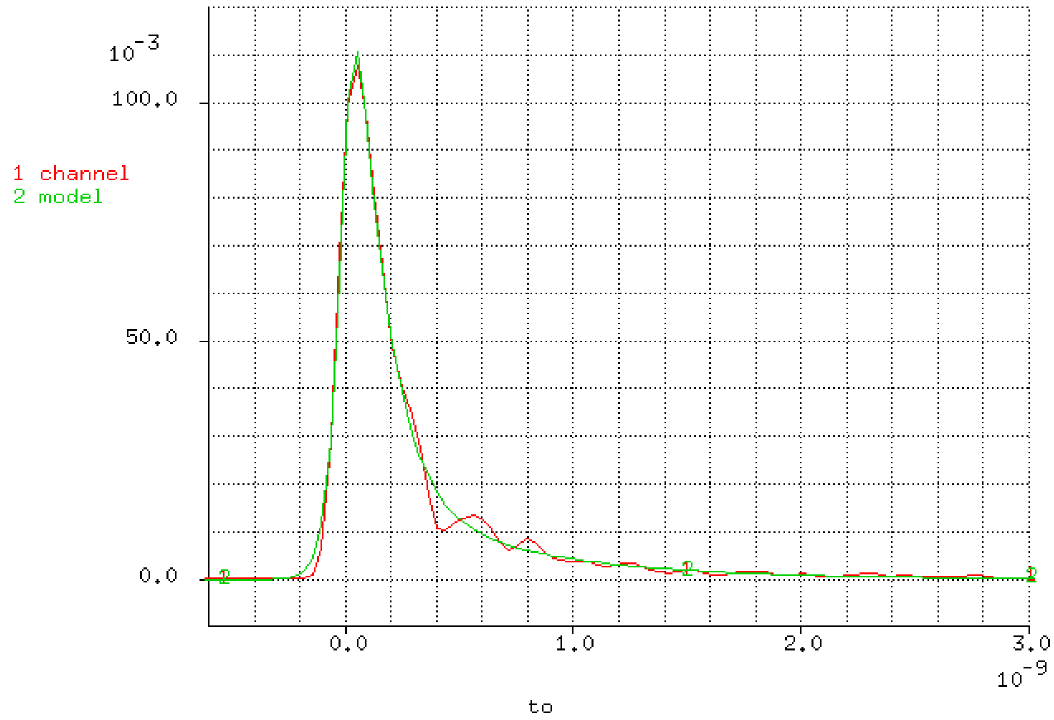
amp = chosen so ∫(pulse dt) = DC gain of channel

tr = rise time parameter

tf1, tf2, tf3 = fall time parameter (with tf1 < tf2 < tf3)

ep2, ep3 = fitting parameters (with ep3 < ep2)

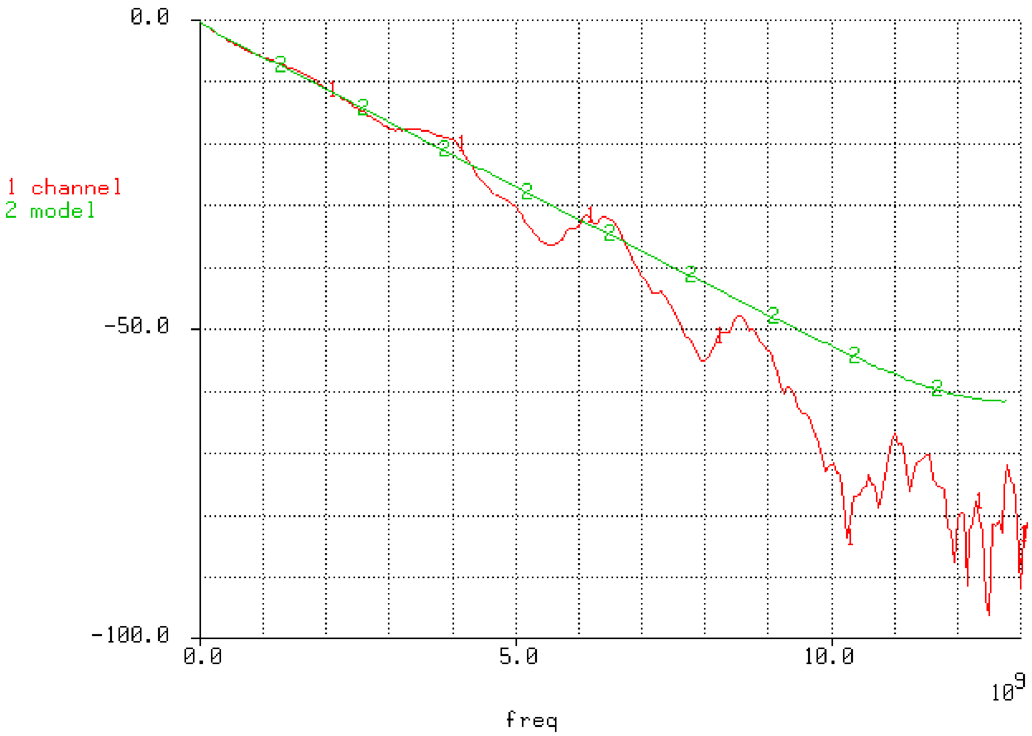
thru Channel Impulse Response Model (cont.)



Example of an impulse response model fit for "Channel A."

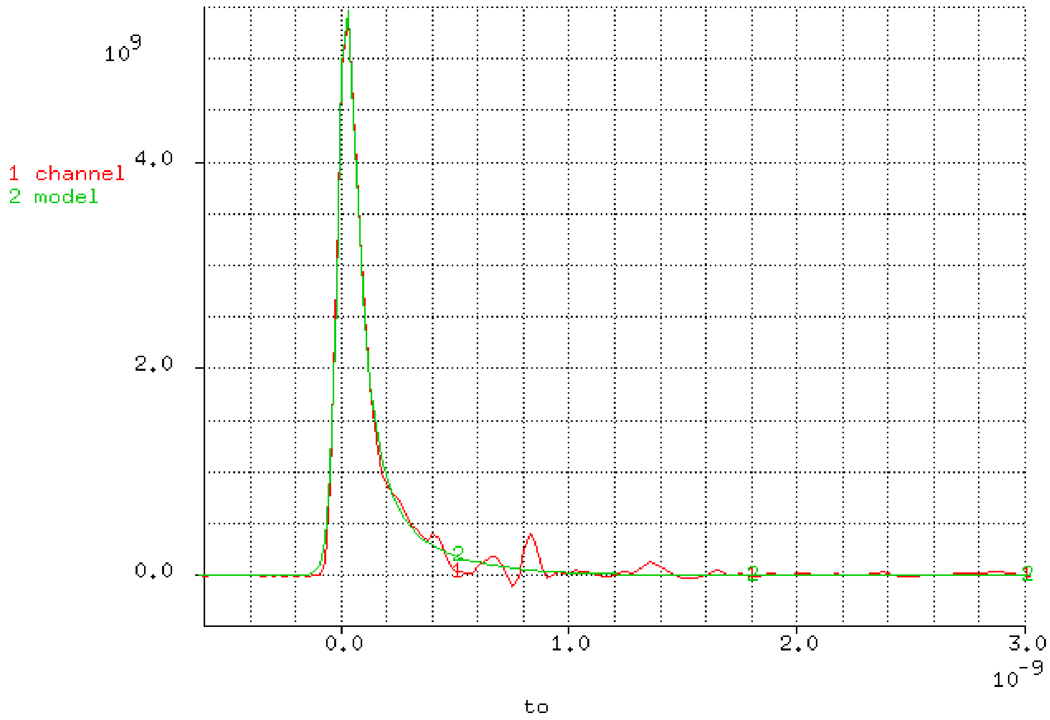
Note there is a fair amount of difference between the two in the form of fast ripple (more on this later).

thru Channel Impulse Response Model (cont.)



The same information in the frequency domain, amplitude only.

thru Channel Impulse Response Model (cont.)



Another example of an impulse response model using "Channel D."

Note there is a fair amount of difference between the two in the form of fast ripple (more on this later).

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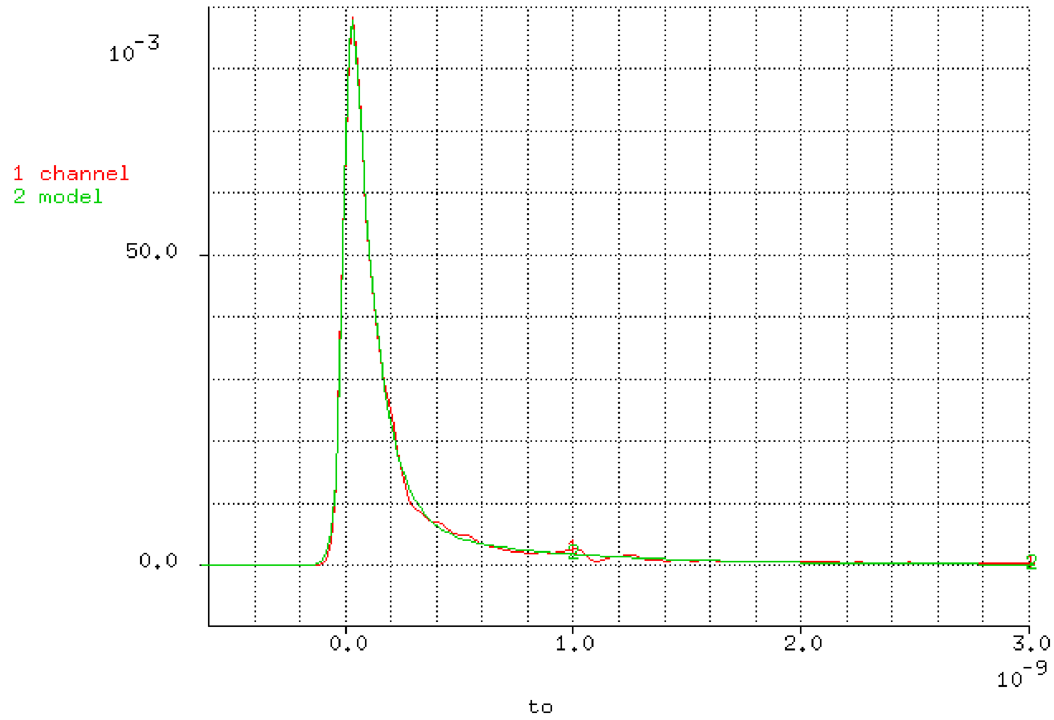
thru Channel Impulse Response Model (cont.)



Another example of an impulse response model using "Channel E."

Note there is still residue, but it is much smaller.

thru Channel Impulse Response Model (cont.)

Real channels can be fairly well fit by a function with 8 adjustable parameters. For specification purposes, they could be reduced to four:

1. **Delay, or channel latency. Either not specified or with a very loose specification.**
2. **DC gain (a minimum specification may be needed).**
3. **Rise time represented by parameter tr. This needs a specified maximum as it controls the hard to correct pre-cursor ISI.**
4. **Total width which can be represnted by:**
tt = tr + tf1 +ep2*tf2 + ep3*tf3
Maximum total width needs to be specified.

The residue is very important and should be treated as a form of interference (like FEXT and NEXT), which is discussed next.

Interference Impulse Response Model

1. Remarks on specifying a channel.
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4. **Impulse response model for interference.**
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Interference Impulse Response Model (cont.)

Specify interference in terms of the peak interference caused by a worst case interfering data pattern. Interference from several channels, including FEXT, NEXT, and self interference is added linearly to get total interference.

Self interference is defined as the difference between the actual channel impulse response and the modeled impulse response. Self interference may be reduced by removing those portions which can be corrected by a FIR receiver filter.

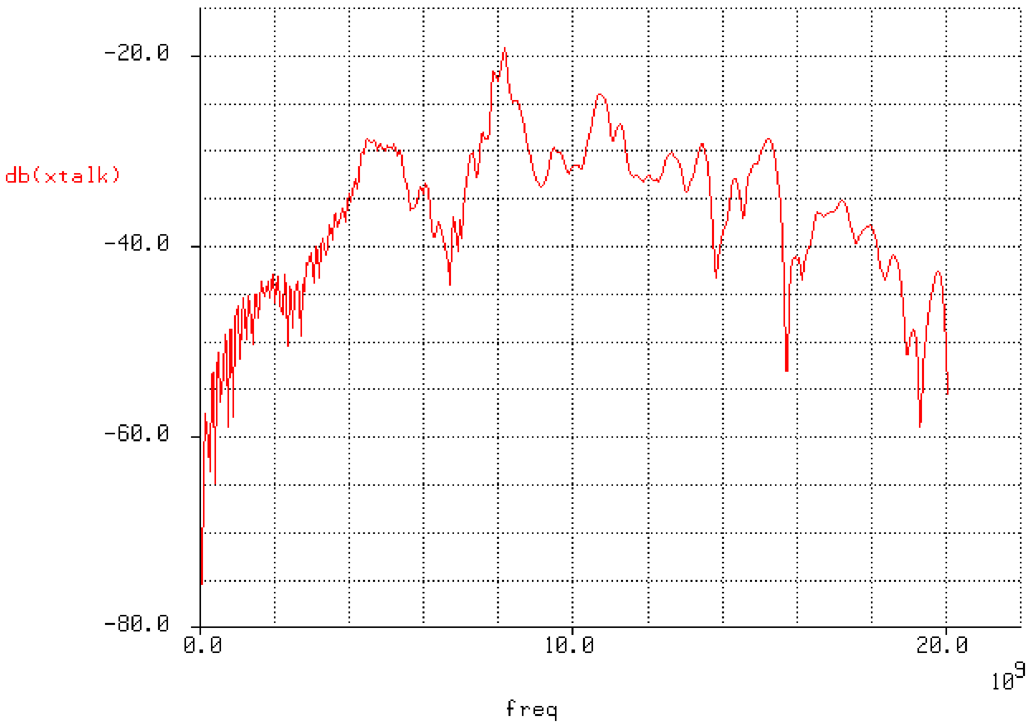
Interference Impulse Response Model (cont.)

To determine the peak interference caused by a worst case data pattern:

1. **Simulate the interference channel with an input of a unit pulse one baud period long. Include any IEE802.3ap specified filtering, including low pass at the Tx and Rx, and any specified equalization.**
2. **Sample the simulated signal at the receiver at the baud rate. Sum the** magnitude **of the samples.**
3. **Shift the all the sample points later by .1 baud period and re-sum. Repeat for all 10 possible shift values and find the largest sum. This is the peak interference. Actual peak interference has to be scaled by the transmitter output amplitude.**
4. **If for the worst case sample point, the signs of the samples are saved in an array, and the array is reversed in order, this gives the worst case data pattern for this interference channel.**

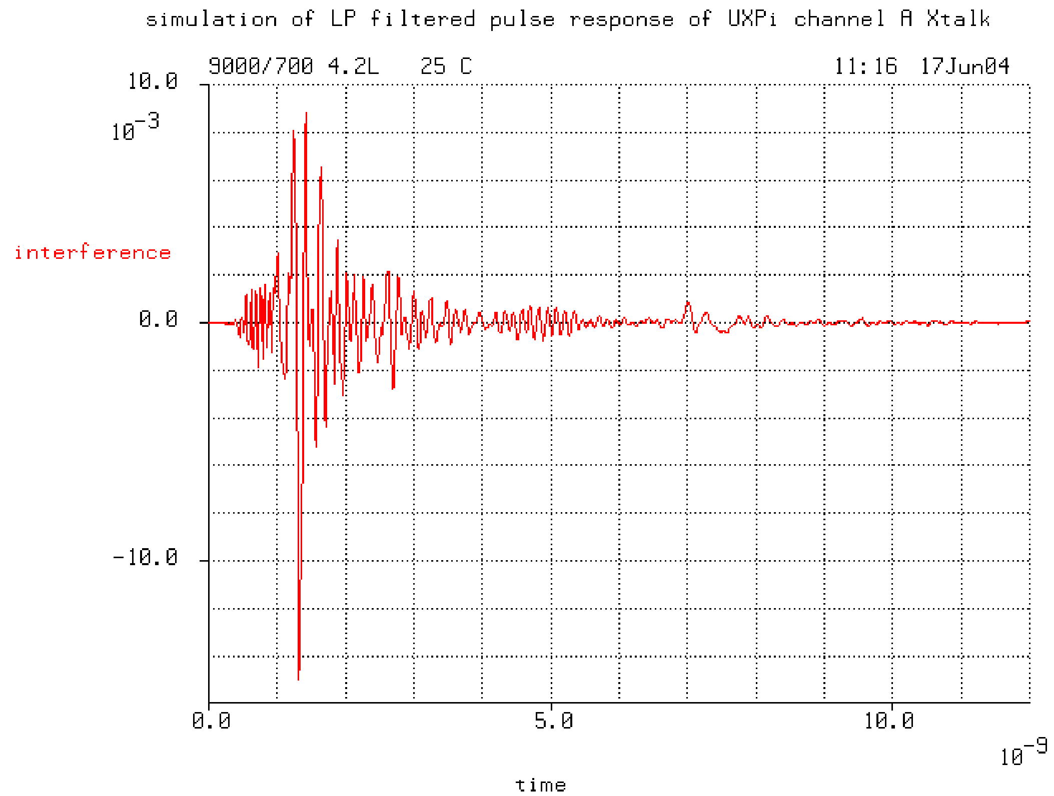
Interference Impulse Response Model (cont.)

For example:



This is the frequency domain version of the NEXT channel associated with Channel A.

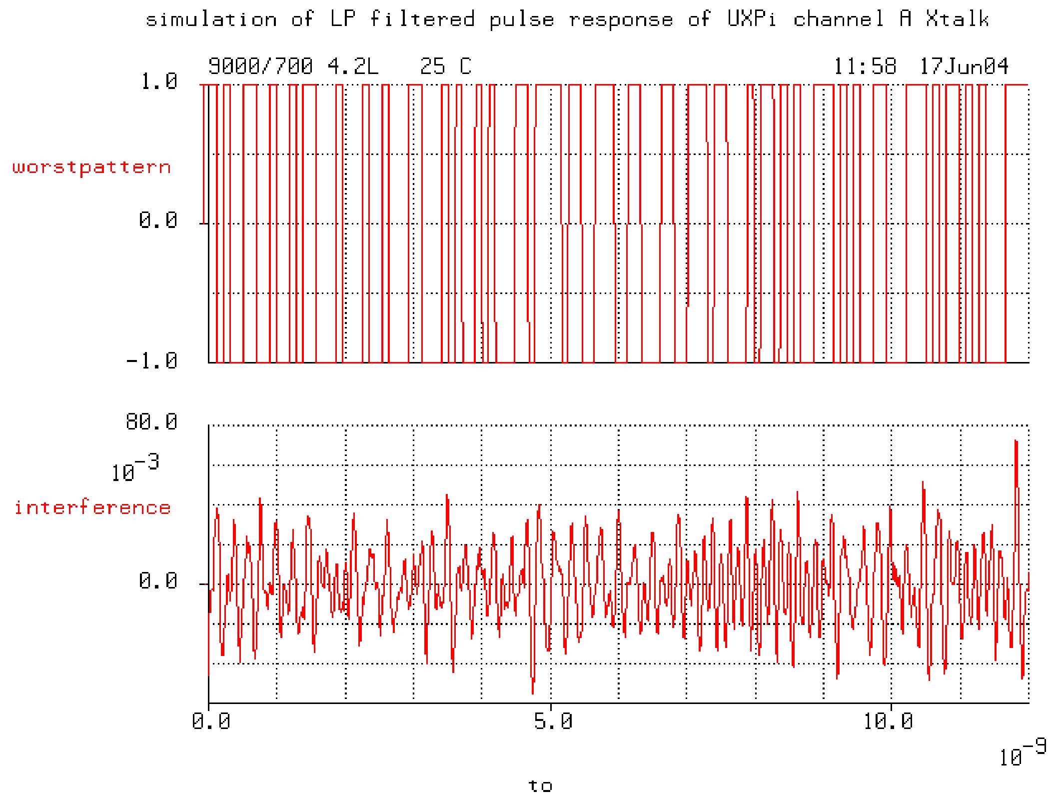
Interference Impulse Response Model (cont.)



This is the pulse response (not impulse) of the interference with some low pass filtering.

Summation on the pattern at a 10.3Gb/s rate gives a peak interference of 0.0700.

Interference Impulse Response Model (cont.)



Here is the worst case bit pattern that produces a peak interference of 70E-3 at the end of the pattern. In addition, it produces other interference at other times.

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Interference Impulse Response Model (cont.)

This allows one to specify the peak interference or to predict it for information in simulating the channels operation.

Review

1. Remarks on specifying a channel.
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Review

I have demonstrated:

1. There are problems with specifying channels in the frequency domain.
2. Real channels can be reasonably described in terms of a parametrically defined impulse response function, which uses a small number of parameters. The error in this model can best be treated as another interference signal.
3. That worst case peak interference can be calculated for interference paths. This worst case peak can be used for specifying interference.