
CAT-5 Jitter and Transmitter Mask Study

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This paper analyzes CAT-5 UTP cables, transmitters and receivers for the IEEE P1394b specification. The goal is to determine the correct rise and fall times (maximum and minimum values allowed), the maximum amount of peak to peak jitter the transmitter can be allowed to emit, and, given the above, determine what the transmitter output waveform mask should be to guarantee compliance with the standard and, hence, interoperability. This paper is strictly a theoretical work though we expect experimental results to agree with the model to a close degree.

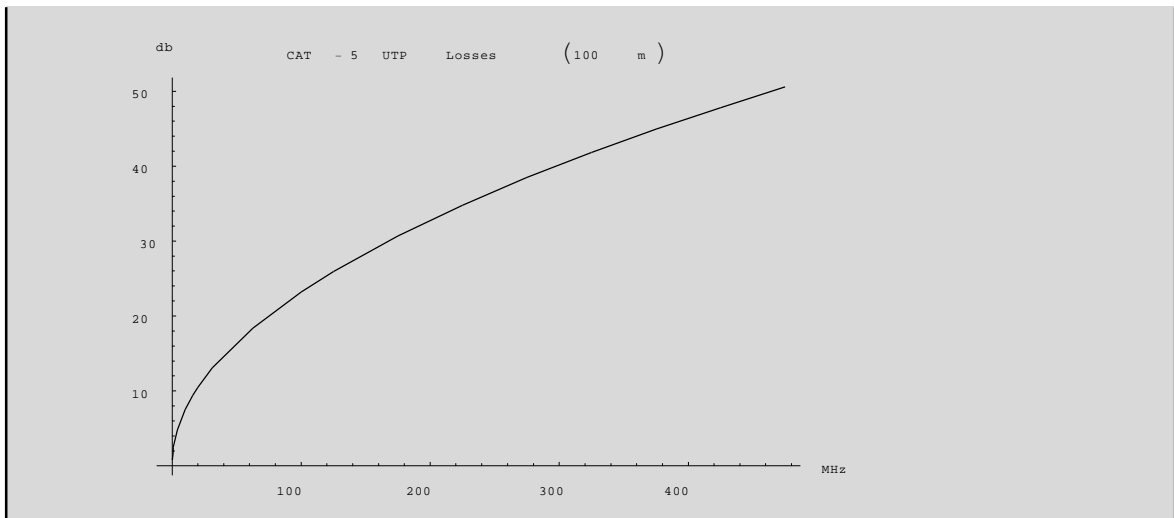
CAT-5 UTP Cable

■ Standards Specification

EIA/TIA 568 and DIS11801 standards specify the attenuation as a function of frequency for 100 meter CAT-5 UTP cable and connectors (the first column is frequency in MHz, the second column is cable loss in db):

0.064	0.8
0.256	1.1
0.512	1.5
0.772	1.8
1	2.5
4	4.8
10	7.5
16	9.4
20	10.5
31.25	13.1
62.5	18.4
100	23.2

We extend to frequencies higher than 100 MHz by use of the Sqrt relationship implicit in skin depth limited cables.



Cable Resistance Determination

Two conductor cables are described by the partial differential equations:

$$\partial_z v[z, t] == -r i[z, t] - l \partial_t i[z, t]$$

$$\partial_z i[z, t] == -g v[z, t] - c \partial_t v[z, t]$$

More generally we can make r frequency dependent. We neglect the g term assuming that there are no dielectric losses. Describing the v and i variables as complex phasors allows reduction in PDE order.

We need to get the cable's complex transfer function for 1-way energy flows:

$$E^{-z \sqrt{c \omega (-l r - l \omega)}}$$

Let's now get the attenuation factor:

$$\text{resistance(ohms/inch)} = -\frac{2 \sqrt{l} \log \text{Loss}}{\sqrt{c} z}$$

This equation determines the Ohms/inch from measured and pre-set cable parameters.

■ Cable Reactive Parameters

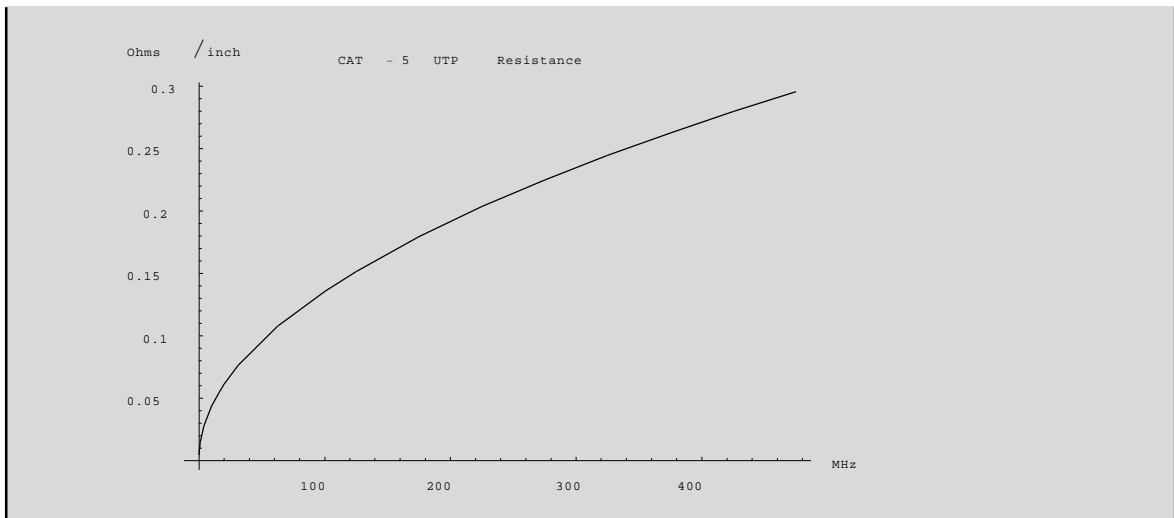
We model the frequency dependent resistance as an ideal skin depth effect (p.179, Clayton R. Paul, Analysis of Multiconductor Transmission Lines, Wiley, 1994):

$$r_{\text{internal}} = \begin{cases} r_{\text{dc}}(1 - i f / f_0), & f \leq f_0 \\ r_{\text{dc}} \sqrt{f / f_0} (1 - i), & f > f_0 \end{cases}$$

This expression accounts for the internal resistance and the internal inductance factors for lossy wires. We can generalize this expression by replacing the $\sqrt{f/f_0}$ term with a general exponent slightly above 0.5 to account for other system losses. Note: f_0 is generally about 1 MHz. Using the previous section's resistance determination we put the measured resistance times (1-i) into the cable equations to account for the internal resistance and inductance factors of the wires, thereby not needing the $\sqrt{f/f_0}$ factor.

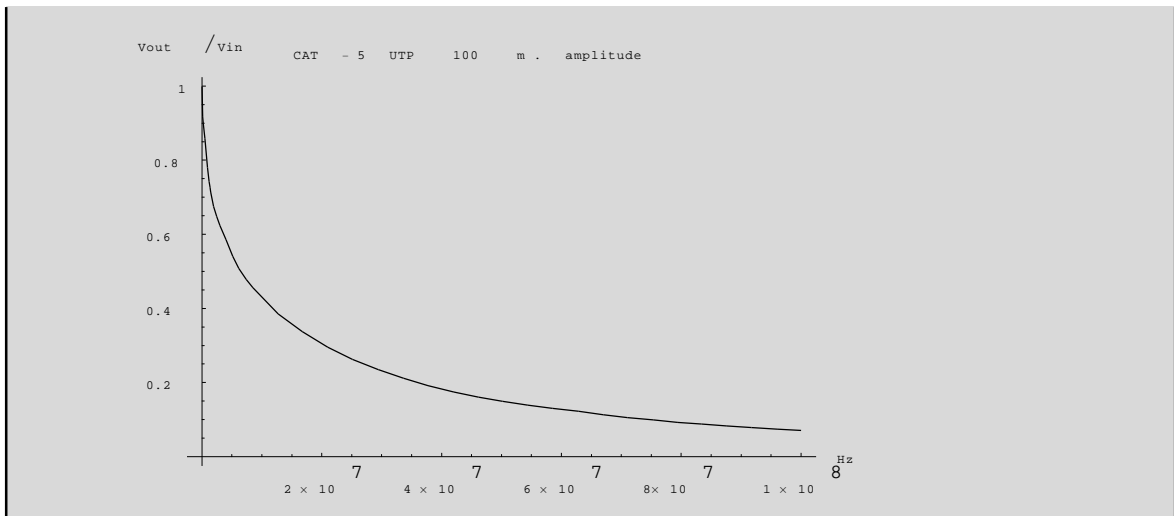
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(* ideal cable reactive parameter equations *)
e0inches = 2.249/10^13;
u0inches = 3.192/10^8;
cinches = 1.18*10^10;
awg[d_] := -10 - 20*Log[10, d];
diameter[awg_] := 10^(-((awg + 10)/20));
ztwist[d_, s_, er_] := 120/Sqrt[er]*Log[2*s/d];
ptwist[er_] := (84.72*Sqrt[er])/10^12;
ltwist[d_, s_, x_] := (x*10.16*Log[2*s/d])/10^9;
ctwist[d_, s_, er_, x_] := er*x*0.7065*1/(10^12*Log[2*s/d]);
```

```
(* CAT-5 UTP cable differential mode numbers *)
lMeter = 100;
length = lMeter*100/2.54; (* in inches *)
dia = N[diameter[28]]; (* we'll assume 28 gauge wire for now *)
er = 2.5; (* usual idealized assumption for now *)
propDelay = (85*Sqrt[er])/10^12;
roundTripTime = (propDelay*length);
sUTP = Solve[100 == ztwist[dia,s,er],s][[1,1,2]]; (*
  to get 100 Ohms impedance *)
(* per inch parameters *)
z0 = ztwist[dia, sUTP, er];
l0 = ltwist[dia, sUTP, 1.];
c0 = ctwist[dia, sUTP, er, 1.];
(* now get ohms/inch as a function of frequency for CAT-5 UTP: *)
rInch =
Map[{#[[1]],rExtract[10,c0,(-#[[2]]/20)*Log[10],length]}&,extendedCable
];
```



■ Lossy cable forward transfer function

This is for 1-way energy flows:



Receiver Optimal Equalization Filter

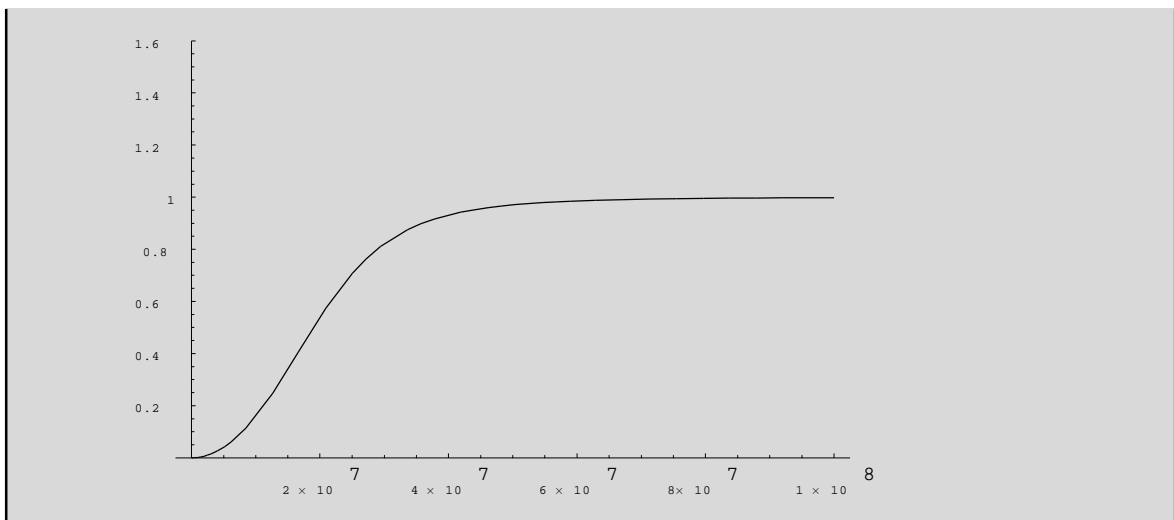
■ Amplitude Equalization

To compensate for the high frequency loss of the cable we use a high pass filter circuit. See p. 2-12 of Williams and Taylor.

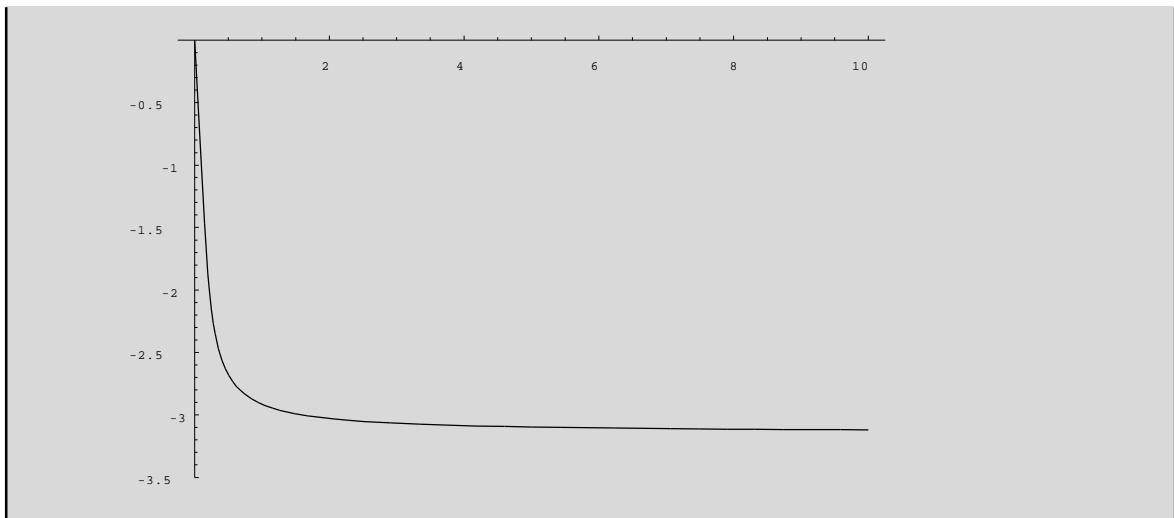
■ Filters

This filter has the expression below (cut is the high pass cutoff frequency):

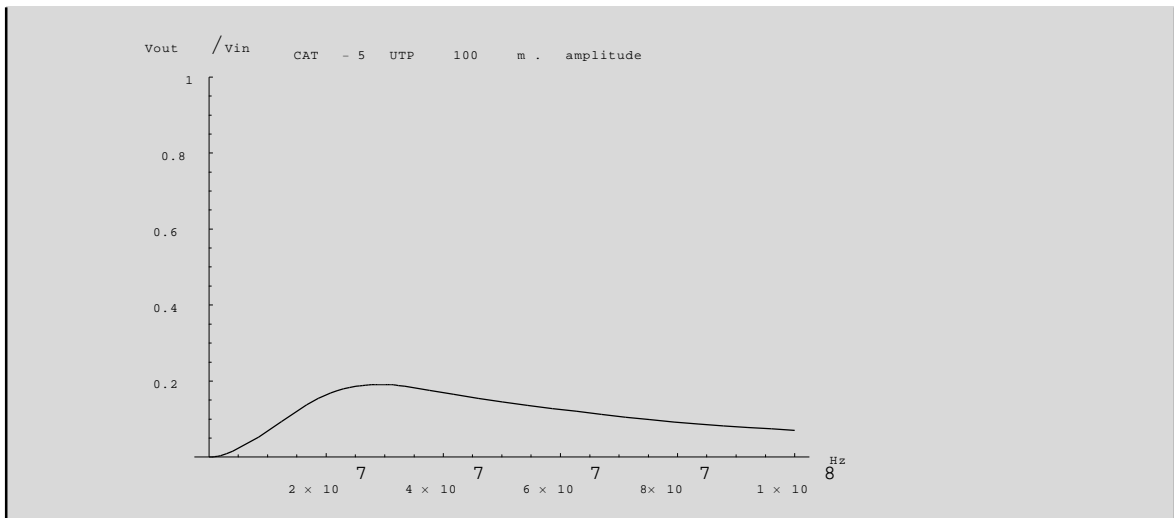
$$\frac{4 f^2 \pi^2}{\text{cut}^2 + 2 \pi \sqrt{2} \text{cut} f \pi - 4 f^2 \pi^2}$$



This high pass filter has the phase shift characteristic:



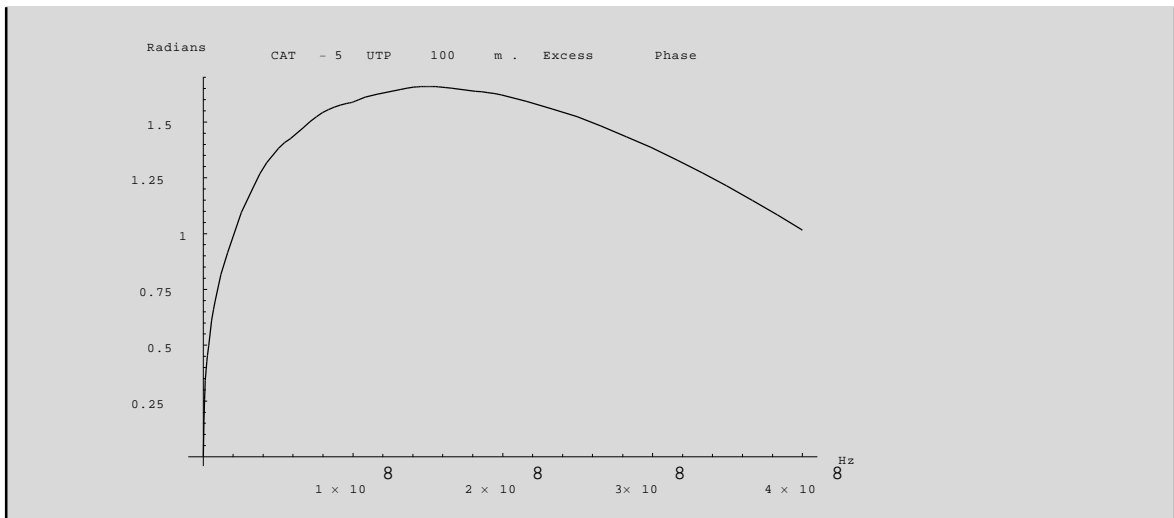
The combination of the 100 meters cable attenuation and the high pass filter is:



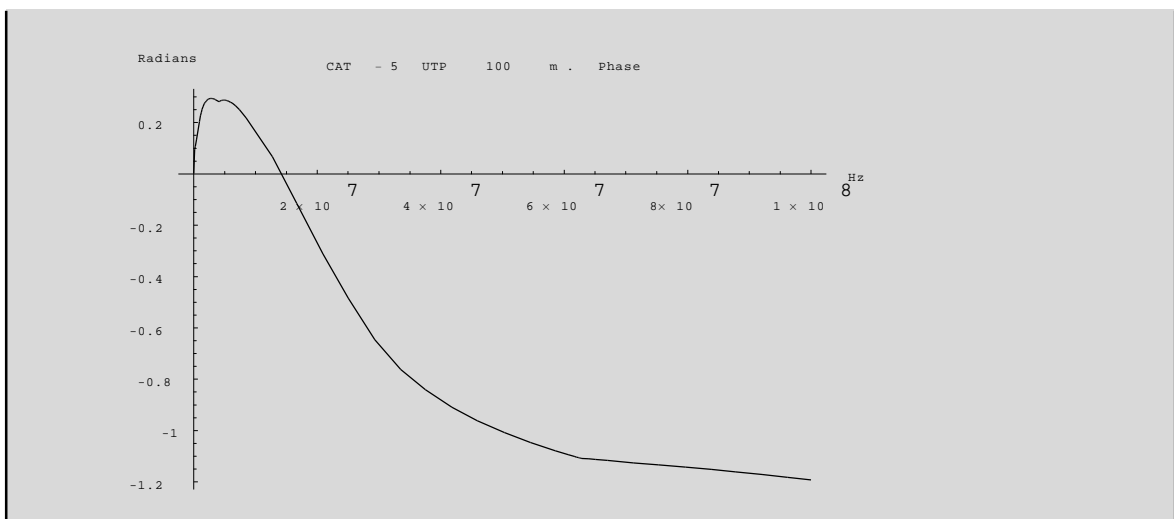
■ Phase Shift Analysis

Now let's get the excess phase shift of the cable:

The ideal phase comes from pure propagation delay. This is removed in the diagram below:



Let's now evaluate the high pass filter's phase effects combined with the cable phase shifts:



Clearly the amplitude correcting filter has a compensating phase effect on the skin depth limited 100 meter cable.

■ Bit Patterns

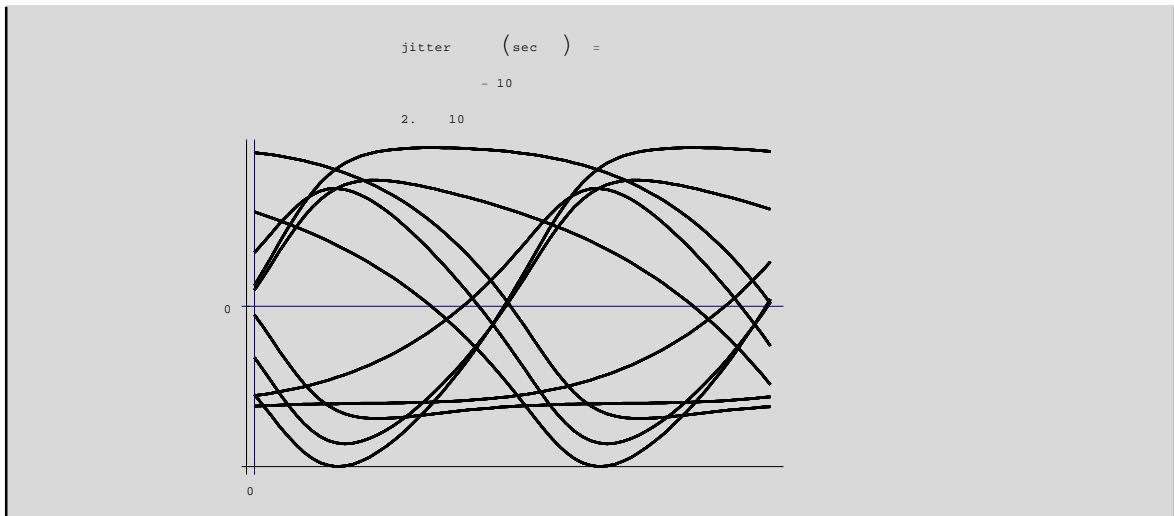
Using the above transfer functions we can simulate the effect on transmitting various bit patterns through three connectors + cable. We use the following bit pattern:

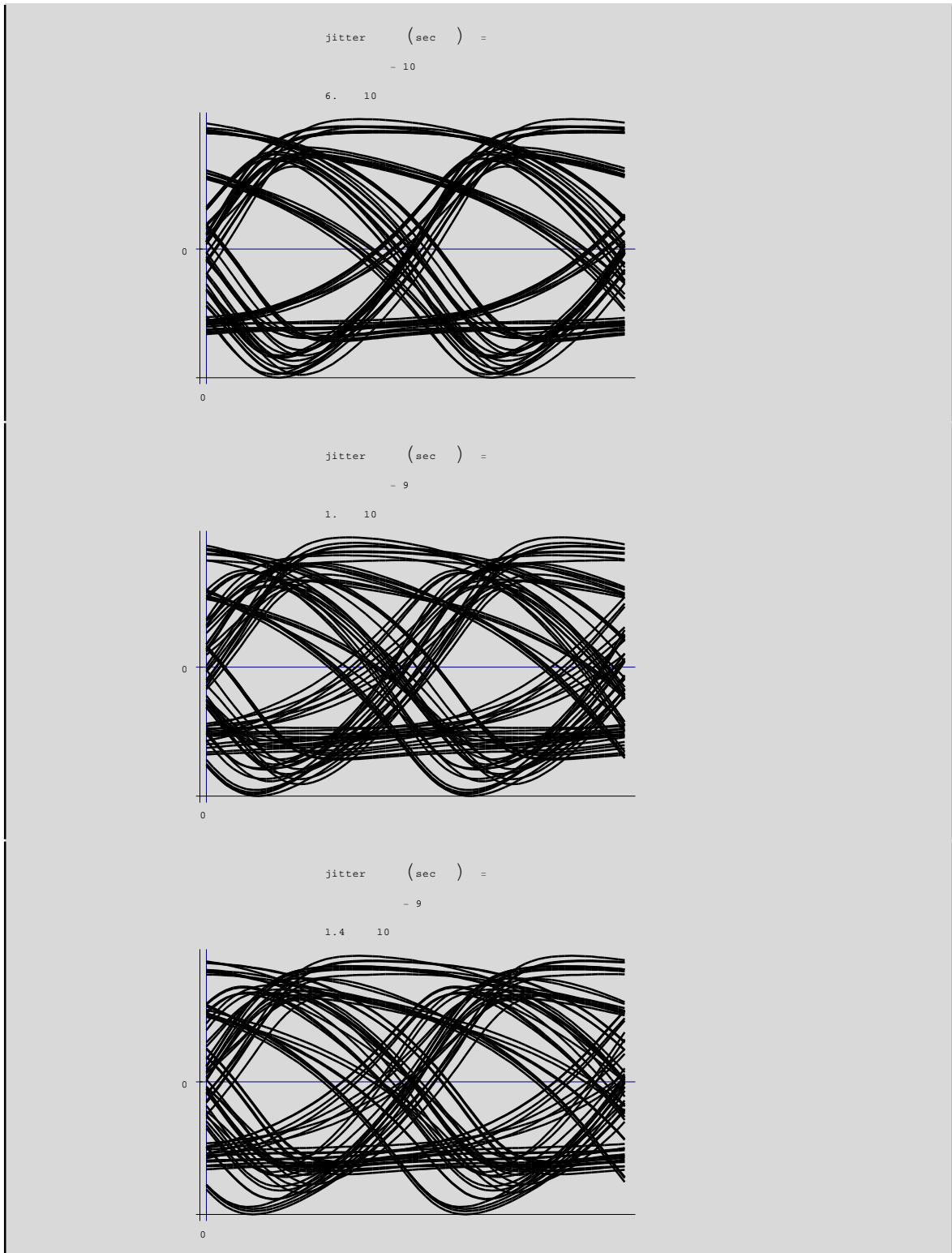
```
{1, 0, 0, 1, 1, 1, 0, 1, 0, 0, 1, 0, 0, 1, 1, 1, 0, 1, 0, 0, 1, 0, 0,
1, 1, 1, 0, 1, 0, 0, 1, 0, 0, 1, 1, 1, 0, 1, 0, 0, 1, 0, 0, 1, 1, 1,
0, 1, 0, 0, 1, 0, 0, 1, 1, 1, 0, 1, 0, 0, 1, 0, 0, 1, 1, 1, 0, 1, 0,
0, 1, 0, 0, 1, 1, 1, 0, 1, 0, 0}
```

For simulations we vary three parameters on the transmitter side. The transmitter's output voltage can vary between 0.525 volts differential and 0.475 volts differential. The maximum 80% - 20% rise/fall time is 3.336 ns, based upon the shape of the fundamental sine wave in a low pass filtered bit stream, i.e., we should at least preserve the first harmonic of the bit stream. The minimum rise/fall time is 0.5 ns, based upon input from the silicon vendors (who object to not going as fast as their silicon can go) and input from the connector vendors (who object to going too fast and hence causing reflections and radiation). The final parameter to be determined is the peak to peak jitter the transmitter is allowed to have.

■ Now simulate the receiver eye

We simulate the combination of the cable, the connectors, and the equalization filter under different amounts of jitter. The peak to peak jitter is used to shift the zero crossing time position of each ideal bit edge by -1, 0, or +1 times the jitter amount. The choice is made by means of a random number generator that generates -1, 0, or +1 with equal probabilities. The jittered bit stream is then filtered to have a rise/fall time equal to the average of the slowest and fastest r/f times the specification allows. The goal of this simulation is to determine at what transmitter jitter value the combination of transmitted jitter plus the cable's dispersion leads to a degraded receiver eye diagram.





This simulation sequence indicates that the peak to peak total jitter at the transmitter point should be bounded at 1.0 ns. For the minimum jitter we choose 0 ps.

Transmitter Mask Determination

The transmitter mask is determined by superimposing the max/min Trise and Tfall with Vmax and Vmin and JitterMax and JitterMin, i.e., we do the process corners. The CAT-5 UTP chapter of the IEEE P1394b specification characterizes the transmitted shape of the three 1's in the D0.0 symbol, this is the waveform we must bound by a mask:

