Applicability of Coaxial Cables at Picosecond Range Timing

K. Kalliomaki [1], J. Mannermaa [2], and T. Mansten [1]
[1) MIKES, FI-02150, Espoo, Finland
[2) Nokia Corporation Technology Platform, FI-33100, Tre, Finland
kalevi.kalliomaki@mikes.fi.

Timing performances of conventional coaxial cables like RG 223 and RG 58 were studied. The effects of timing pulse shape, cable bandwidth, ambient fluctuations and physical stress were as input parameters. Pulse delays and shapes were studied using a time interval counter and a fast digital oscilloscope. Delay as a function of frequency was studied with resonance method and phase delay measurements. Effects of ambient factors and physical stress were studied at a frequency of 5 MHz using a phase comparator capable of resolving 10 fs.

The results revealed that conventional tick pulse is not anymore usable below 1 ns if the cable delay has to be well known. Environmental effects may change the cable delay up to 100 ps. Therefore, as a first approximation the pulse shape has to be changed to fit the properties like bandwidth and velocity dispersion of cables. Cos^2 pulse or RF-burst may help but finally one has to use optical cables.

1. INTRODUCTION

Time and Frequency Metrology has encountered new challenges because the inaccuracy level requirements approach picosecond range. Bandwidths of conventional coaxial timing cables are limited to 100 MHz…1 GHz range depending on their length, and quality and the rise times of the PPS ticks are typically about 10 ns. Steeper pulses produce too much pulse shape changes. Moreover, the propagation velocity in cables is not constant and it is influenced by changes in temperature, in air pressure, and physical stresses due to e.g. bending. MIKES and Nokia Corporation Technology Platform have studied the impact of these phenomena on the trigger level of timing pulse. Results of the studies concerning the effects of these phenomena on the trigger level were presented in the EFTF'05 [1].

Experimental measurements were carried out to study the performance of the theoretical models and to find out, in practice, the relative short term instability of the measured value.

According to the preliminary results, e.g. the influences of air pressure changes are observed at the relative level of -5 ppm/mbar, or worse.

As conclusions, the increasing accuracy requirements of the PPS ticks can only be satisfied by the meticulous design of timing pulse shape and quality of the transmission lines. Also air pressure will effect on performance of the systems.

II. MATERIALS

The coaxial cables to be studied were RG 223 and RG 58 with BNC-connectors in different lengths up to 100 m. Most of them were in fixed installations in Time & Frequency laboratory (NMI), only short cables up to 10 m were studied separately. The reference plane for delay measurements is defined to the outer end of the dielectric insulator inside the connector.

III. MEASUREMENT METHODS AND RESULTS

Useful equations [2]

If the frequency f is high (> 1 MHz)

$$t_p \approx \sqrt{l_\infty c}\,(1+\frac{r}{2\omega l})$$

$$t_g \approx \sqrt{l_\infty c}\,(1+\frac{r}{4\omega l})$$

where: t_p is phase delay [s/m]
t_g is group delay [s/m]
r is the cable resistance/m
c is the cable capacitance/m
l is the nominal cable inductance/m
l_∞ is the cable inductance/m at high frequency

Cable resonance method

We have earlier used with good results resonance measurements of open and short circuited cables. By measuring all resonant frequencies up to 100 MHz, we obtain both the cable delay at fixed frequencies and the delay dispersion (and attenuation, too). Because the resonances are quite sharp, the repeatability is quite good, 0,1...0,2 % rms. of the delay for a single point. By combining all the results, we can easily go down to 100 ps level using this very simple method. The necessary instrumentation is a crystal controlled signal generator and an oscilloscope. Because we need only one end of the cable, we can measure delays of already installed cables. See Fig. 1 for results.

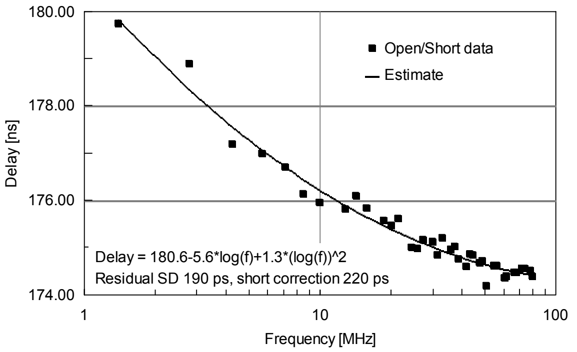

Fig. 1: Propagation delay dispersion of a 36 m cable as a function of frequency

Phase shift method

The second method we used was phase method using a crystal controlled signal generator and a two channel digital oscilloscope. We simply measured all frequencies which produced zero phase difference (modulo 2π) between the ends of the cable. In this case both ends of the cable must be available. The phase error in an oscilloscope and electrical length error of connecting cables was eliminated by interchanging the channels. Thus the dominating error is "manual" zero phase detection. The error seems to be about the same as that of the resonance method. We also used carefully calibrated Network Analyzer (Agilent PNA series) to check the delays up to 1 GHz.

Pulse delay method

Finally we tested the pulse delay method by using our automatic clock measuring system with active hydrogen maser as the main clock. After preliminary tests we had to abandon time interval methods where a separate clock was used as the pulse source because, due to random drift of a cheaper clock (like rubidium), the repeatability was worse than 100 ps.

We used the second pulse of our master clock as pulse source. The cable was simply connected/disconnected in series with our self check channel d0 and the corresponding time change was registered automatically every second. Due to the long (~ 100m) tick cable from reference clock laboratory (underground) to the time/frequency laboratory (2nd floor), the pulse shape was nicely shaped and rounded (filtered) to mach cable bandwidth, e.g. pulse shape did not change much due to the filtering effect of the cable anymore. Thus trigger point selection was not a problem and we could use our ordinary 1 V level.

Improving the accuracy of a time interval counter

To eliminate the nonlinearity of analog interpolators of the time interval counter (HP 53132A), we locked the counter time base to a frequency with an offset of $1 \cdot 10^{-9}$. This causes the counter time base to drift 1 ns/s and the 100 ns ranges of analog interpolators are covered within 100 s. Because the measurement rate of the automatic measuring system is 1/s, we obtain 100 readings in the above-defined 100 s time. After calculating the average value of those 100 readings, the nonlinearity is compensated at any time interval value (cable delay) to be measured and the random errors are decreased by one decade. We obtained 20 ps repeatability using 300 ps rms (spec.) time interval counter.

Trigger level error

The main problem is the trigger level error, which is proportional to the cable length. This can easily be 1 ns due to delay dispersion and signal attenuation. Thus the real delay in coaxial cables is a hard problem.

Fig. 2 depicts what happens in a cable due to delay dispersion. Input pulse is idealized to correspond 20 ns rise time. Output pulse is shifted left to conveniently start from the same origin. The beginning of the output pulse corresponds the contribution of high frequency (f >1 MHz) components and the remainder that of low frequency components. Naturally some low pass filtering effect (rounding-off) exists, too, but it is marginal compared to the effect of propagation dispersion.

The horizontal bar indicates the measurement error assuming that the beginning of the pulse is the "holy" point. What else could be used as the right point?

Naturally we can't set the trigger level down to zero volts to catch the right point. However, selecting a relatively low trigger level lowers the inherent error and eases the extrapolation of the pulse beginning. We have done this extrapolation job by studying the pulse shape with a fast digital oscilloscope (Tektronix TDS 2024, BW 200 MHz). This error dominates in case of medium and long cables.

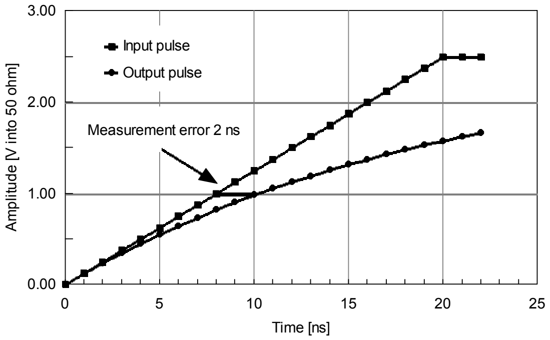

Fig. 2: The origin of measurement error

A S-shaped pulse occurs as an output pulse in long cables of bad quality, especially if the input pulse is too sharp. In this case the low pass effect is significant compared to the propagation dispersion effect. As a result of this high frequency attenuation, a low "pedestal" appears at the leading edge of the pulse. In this case the extrapolation back to the beginning of the pulse is practically impossible.

It is not necessary, however, because "pedestal" represents Fourier components outside the -3 dB boundary of the propagation media. In other words, those frequency components are not in the intended pass band. This is a good reason to omit them. The simplest way to omit the pedestal is to filter the input pulse to the cable, i.e. to use rounded pulse instead of a sharp one.

Pressure and physical stress effects

As a surprise we found very significant correlation between air pressure and cable delay. The correlation coefficient was from –5 to –10 ppm/mbar. When wondering about the explanation to this relationship, negative coefficient was difficult to understand. In later cable bending test, we collided to the same problem. The delay decreased when bending the cable. We wound 10 m cable around 25 cm (diameter) cylinder. It resulted -30..-80 ps delay change, which is mostly reversible.

Assuming that field components leak out from the cable, we submerged the cable (1.6 m long) into clean water (1.6 m) but this did not change delay significantly. In this case physical stress due to bending dominated causing up to 10 ps measurement noise.

Because group delay t_g in cables is proportional to $(l \cdot c)^{1/2}$, either inductance or capacitance has to decrease when air pressure or physical stress affects. It seems evident that capacitance is the “guilty” one. Stress may cause small air gaps between dielectric and outer conductor lowering the capacitance.

Fourier spectrum of a "tick" pulse

Fig. 3 depicts the envelope of the Fourier spectrum of a conventional tick pulse. Two essential zeros are marked up. The first one (100 kHz) corresponds pulse width τ ($f = 1/\tau$) and the second one (100 MHz) corresponds rise time tr ($f = 1/ t_r$). The actual spectra up to 50 MHz can be calculated from the well known sin(x)/x equation.

Frequency components up to 100 kHz ($f = 1/\tau$) define the basic “body” of the pulse. Components between 100 kHz and 100 MHz define the edges (rise & fall times). Because the spectrum follows 1/f –law, all components are important. The sum of those 1/f components approaches infinity when f increases without any limit. Amplitudes of frequency components after 100 MHz follow $1/f^2$-law, having only slight effect on pulse edges.

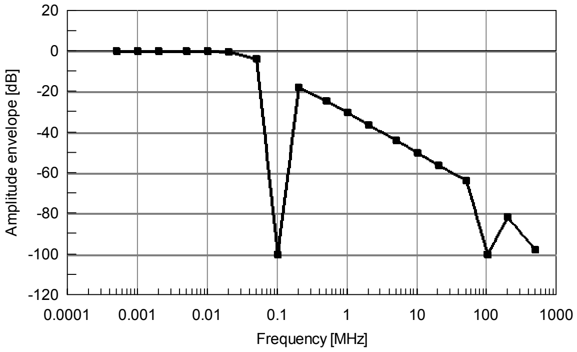

Fig. 3: Fourier Spectrum of a conventional tick pulse of 10 µs width and 10 ns rise time. Only essential zeros are marked up

IV. CONCLUSIONS

Applicability of conventional coaxial cables at picosecond range depends mostly on cable length. Cables up to 1 m in length are practically free of picosecond range problems assuming that anyone does not touch them. Touching may change the delay e.g. 10 ps and the change may not be reversible. When approaching the length of 100 m, even air pressure fluctuation may change the delay 100 ps. In fixed installations the cable movements are probably subtle and similar effects into nearby lying cables may compensate errors, when phase differences are measurement subjects. If the real cable delay is relevant, one has to be prapared to trigger level corrections. The magnitude of this correction seem to be about 30 ps/m at low (1 V) trigger levels but this correction is proportional to trigger level. Thus the above mentioned 100 m cable may cause 3 ns pulse delay error.

Final warning is, don’t use too sharp pulses! Pulse spectrum must fit into –3 dB bandwidth of the cable. In case of the above mentioned RG 223 or RG58 cables, the rise time of the pulse in ns should be longer than $L^2/100$, e.g. if the cable length L is 100 m the rise time should be more than 100 ns to avoid most troublesome pulse deformation effects.

To avoid dominating velocity dispersion effects, one has to use RF-pulse (e.g. 100 MHz) instead of conventional pulse. Then practically all frequency components are on the flat delay area and pulse distortion is negligible.

The use of optical cables seems to solve the above mentioned problems.

REFERENCES

[1] Kalliomäki, K., Mannermaa, J., Mansten, T., "The Effect of Counter's Trigger Level on Timing Below Nanosecond", Proceedings of the **19th** European Frequency and Time Forum (2005)

[2] L. Halme, Cable Transmission and Electromagnetic Shielding (in Finnish), pp. 170 (Otakustantamo, Espoo 1979)