40 Ms/s Analog transmission on Shielded Twisted Pair cable.

Study for LHC-B vertex readout.

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Abstract: Measurements are presented on noise, linearity, attenuation and waveform distortion (resulting in sample-to-sample crosstalk) over various lengths of shielded twisted pair cable. Quality of transmission is judged in terms of the deterioration of the original S/N ratio of the transmitted signal. The transmission of an analog data stream at 40 Ms/s over a distance of 10 meter will not deteriorate signals with a S/N up to a value of 19. The most limiting factor is the sample-to-sample crosstalk.

1. Introduction.

An important decision needed to be taken for the readout of the LHCB vertex detector (1), namely whether digitisation of the signals needs to be very close to the detector or could happen at a distance of roughly 10 meter away from the detector. The latter case would obviously minimise LHCB-specific designed rad-hard components at the benefit of commercial solutions (at least rad-tolerant), easier access to the electronics, less remote control, more flexibility (upgrades and maintenance) and even more possibilities of data-processing.

Quality of transmission is measured in terms of deterioration of the S/N ratio, which is of extreme importance to the vertex detector's performance (2). The S/N will degrade from 20 to 8, after full irradiation dose.

Clearly, differential and shielded signal transmission is preferred for noise immunity. An a-priori decision was taken to only consider (group- or individual-) shielded twisted pair (STP) cable for its lower cost compared to twin-axial cable, despite the latter's higher bandwidth producing less signal distortion.

No published data was readily available to determine the maximum (i.e. to maintain a given S/N) attainable distance for transmitting analog samples in a time-multiplexed way at rate of 40 Ms/s . This relation can neither be easily deduced from basic cable parameters given by manufacturers or cable testers. Results from pulse transmission applications are insufficient, as distortion producing sample-to-sample crosstalk is not relevant for pulse transmission. Application notes on digital transmission are useful sources of information (3–8).

All this justified a study of analog multiplexed transmission quality as a function of distance over shielded twisted pair cable.

2. The test setup and simulated analog data streams.

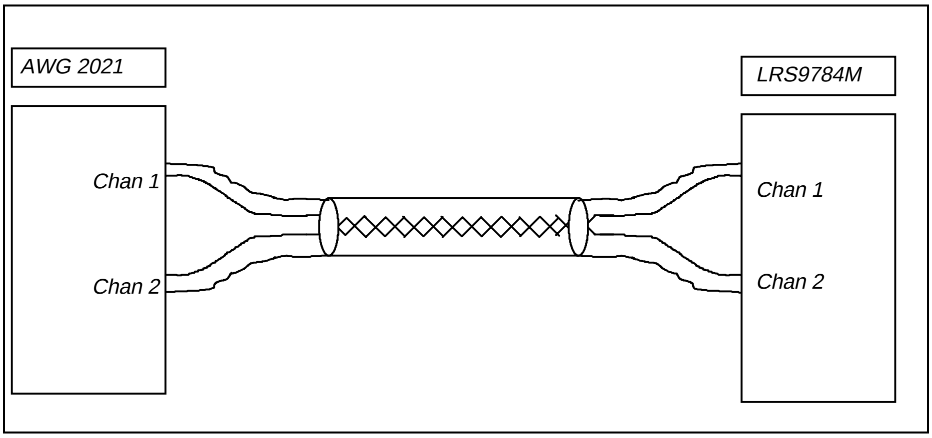
2.1 Test setup.

As the analog requirements are below 8 bit resolution and precision, the most flexible setup consists of an arbitrary waveform generator (AWG) as a signal source and a digital sampling oscilloscope (DSO) as a fast ADC on the receiver end (fig 1).

The AWG is a Tektronix AWG2021, producing waveform points spaced every 4 nsec and with an amplitude resolution of 12 bit. Its fast rise-time (4.2 nsec) and settling time (to 5% after 20 nsec) make it well suited to simulate the analog data stream. The complementary signal pair is obtained using the two channels, programmed with complementary waveforms. The twisted pair and shield are connected through a cable adaptor.

The DSO is a Lecroy 9784M, 8-bit, 1Gs/s single-shot sampling (all measurements are taken in this mode). A second cable adaptor connects the twisted pair and shield to two DSO input channels. The differential signal is obtained by mathematical subtraction (in the DSO)

Figure 1 Schematic of test setup.



of the two channels.

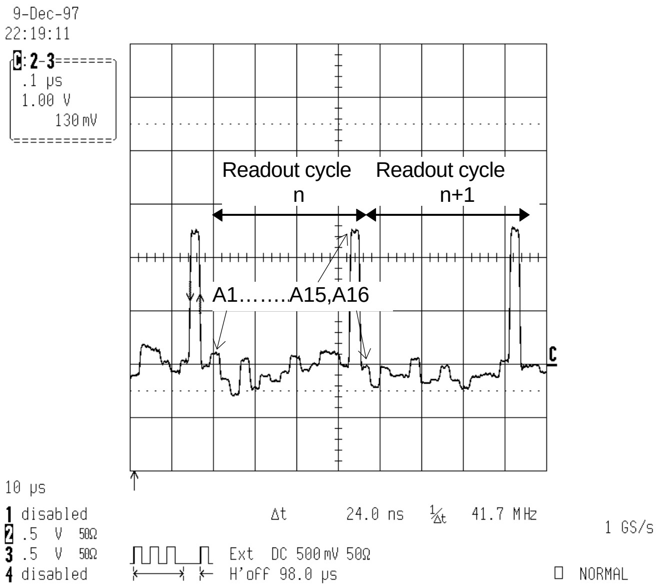
A measurement with a short (< 2cm) cable serves as a '0 meter' reference for all measurements.

2.2 Simulated analog data streams.

Both the AWG and DSO are controlled by LabView. The generated waveform (fig 2) simulates 256 consecutive 'readout cycles' of 16 analog data values at ~41.7 MHz (~ 24 nsec). These numbers are the best fit, given the 4 nsec time spacing between AWG points and the DSO memory limitation. In every readout cycle the last two analog data values (amplitude A15, A16) are of interest, while the first 14 are optionally filled with (programmed) random data. The waveform is recorded by the DSO and transferred into LabView, where an 'ADC reading' is defined as the value at 6 ns before the 50% point of trailing edge of the analog data value.

- For **noise** measurements A15 has a constant value of 50 mV (differential) in successive readout cycles. Noise is calculated as the rms deviation of the ADC readings of A16 from a constant value.
- For **crosstalk** measurement A15 increases linearly from 0 to 5V (differential) in successive readout cycles. The ADC readings in A16 vs. the value of A15, after a linear fit, gives the crosstalk coefficient.
- For **linearity** measurements, A15 increases linearly from 0 to 5V (differential). A linear fit is applied to the ADC readings in A15 vs. the AWG value of A15. The rms deviation in units of the least significant bit (lsb) is defined as the non-linearity.

Figure 2 Simulated waveform.



3. Measurements.

3.1 Characteristics of the STP cable used.

The nominal characteristics of the cable used in all tests are;

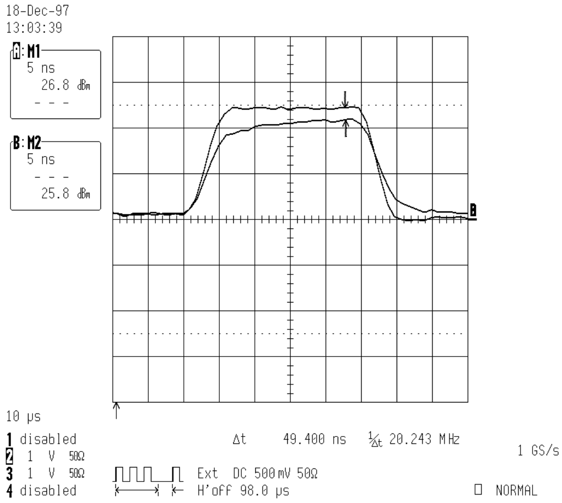
conductor type	copper (stranded,tin plated), AWG24 0.22 mm^2
isolation	polyethylene
shield	stranded copper (tin plated)
char. impedance	90 Ohm +- 5%
mutual capacitance	60 pF / m
linear resistance	0,094 Ohm / m
attenuation	-0.89 dB/10m @ 10 MHz
CERN SCEM	04.21.51.055.4 (Nokia)

3.2 Attenuation.

Attenuation is dependent on the conductor cross-section (so called AWG number) and frequency. Miniature STP has the lowest possible cross-section (AWG 36, 0.013 mm^2) resulting in a high attenuation of -8.9dB (64% loss) @ 100MHz per 10m), whereas 'conventional' STP (AWG 24, 0.22 mm^2) has an attenuation of only –2.2dB (23%) @ 100MHz per 10m.

The attenuation of the analogue data stream (i.e. a broad spectrum signal) was measured as –1.0db (11%) per 10 m of STP AWG24. (fig 3). Lower AWG (larger conductors) will only result in marginally less transmission losses. Higher AWG may not result in significant cable cost saving, but on the contrary could possibly require additional amplification in the cable driver if the signal/pickup-noise ratio becomes unacceptable at the receiver end (see 3.3 noise).

Figure 3 Attenuation of 10 m STP AWG24



Note that detector and front-end electronics noise that is already present (or added) in the analogue data-values themselves are affected identically by the attenuation.

3.3 Noise.

Noise is picked up on the individual wires of the pair, but by the nature of twisted pair these are ‘equalised’ to a great extent and thus cancel out in the differential signal (fig 4 and 5).

The S/N will deteriorate only due to differential noise (i.e. noise appearing on the two wires with opposite phase). As the final noise environment is unknown, shielding is a wise precaution. Individual shields per pair represent a cost increase of approx. 20% compared to unshielded pairs. The cost of a common screen around a multiconductor cable becomes insignificant, once more then several pairs (e.g. 50) are bundled per cable. Fig 6 shows the much higher (x15) noise picked up when no shield is present (same environment as in fig 4).

Figure 4 DSO with 10 m STP cable *Figure 5 DSO without input cable*

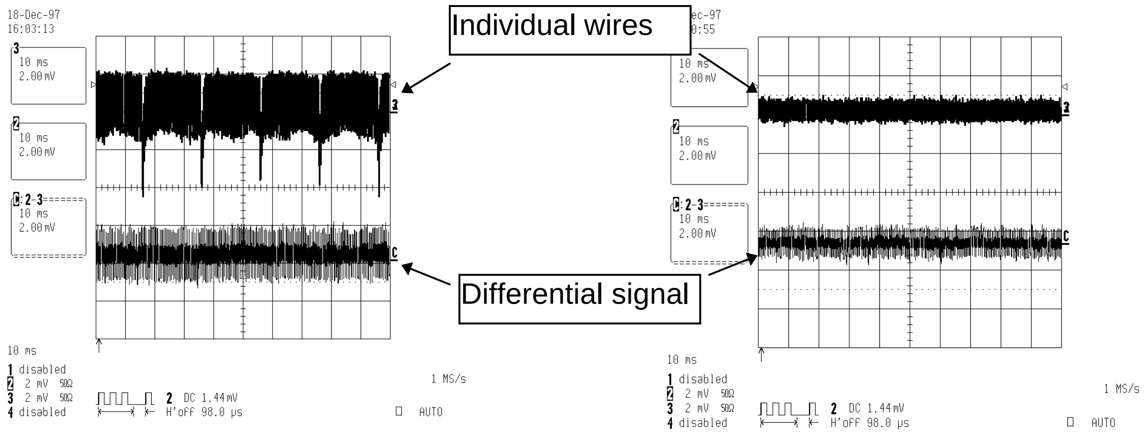
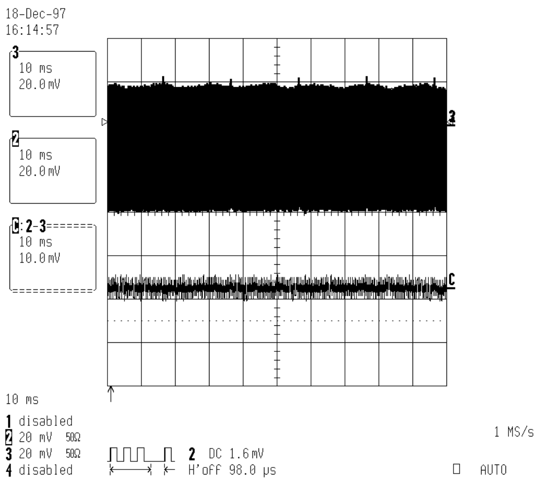


Figure 6 Pickup noise on 10 unshielded TP (same environment as fig 4)



The received signal should be higher then the differential pickup-noise, by at least a factor equal to the expected-maximum-S/N-ratio (~ 20). Therefor, assuming a pessimistic diff. pickup-noise of the order of 5mV (in the lab 1 mV was the worst that could be obtained), the driver-signal amplitude for a MIP needs to be > ~110 mV (= 20x5mV / 0.91).

3.4 Crosstalk.

Amplitude attenuation and phase velocity are dependent on frequency, causing signal distortion. Whereas in pulse transmission this can often largely be ignored, in time multiplexed readout it results in crosstalk between data samples.

The underlying main frequency-dependent physical phenomena are skin-effect ($f^{-1/2}$) of the conductors and $\varepsilon_r(f)$ (i.e. dispersion) of the isolation dielectrics. The quality of the conductors used (cross-section, rigid or flexible, tin- or silver-coated, etc.) merely changes the magnitude of the attenuation vs. frequency curve and therefor does not lower signal distortion. Use of dielectrics, such as polyethylene or Teflon (PTFE), that have a lower and far more constant ε_r (i.e. lower capacitance and dispersion) and also posses a much lower dissipation factor then conventional PVC, decreases the signal distortion. Their cost is only marginally higher, but they are more flammable (except Teflon).

Distortion is illustrated in fig7 and table 1, for different cable lengths. The crosstalk factor is defined as the fraction of sample n that persists in the amplitude of sample n+1. As the persistence decays exponentially, this factor is slightly dependent on the exact moment (time from trailing edge) on which the samples are taken (fig 8). The crosstalk factors for several cable distances are given in table 2 and fig 8.

This crosstalk can be viewed as adding noise, which is tolerable as long as it stays below the noise already present in the signal itself (S/N). Thus for a S/N of 20, the crosstalk factor should be less then 1/20. If required, the effect of crosstalk could be corrected for by further digital processing.

Figure 7 Distortion for 0,5,10 and 35 m STP AWG24.

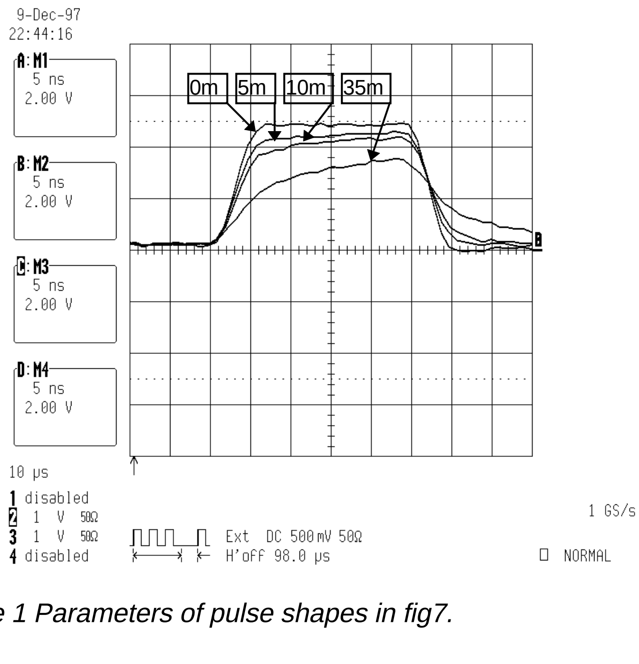


Table 1 Parameters of pulse shapes in fig7.

Length (m)	Amplitude (V)	risetime (ns)	falltime (ns)
0	4.71	2.6	2.3
5	4.23	2.9	2.7
10	4.02	3.5	3.3
35	3.40	8.6	8.2

Figure 8 .

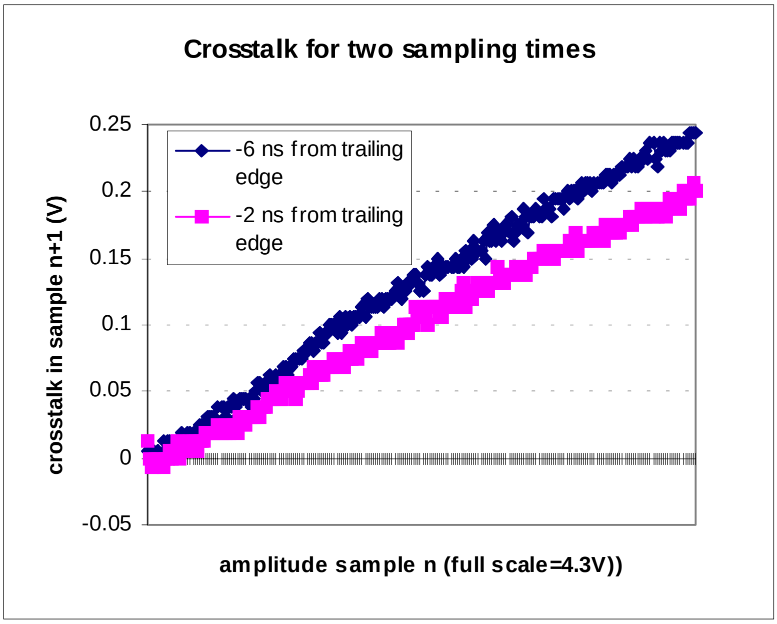


Figure 9 Crosstalk for different lengths.

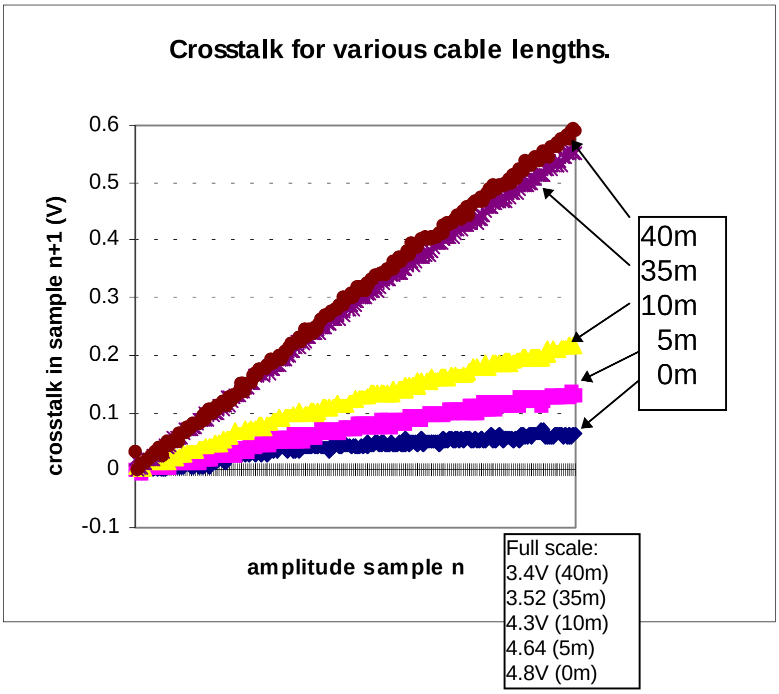


Table 2 Crosstalk factor as a function of cable length

cable length	crosstalk factor
0 m	0.062/4.8 = 1/ 77
5 m	0.130/4.64 = 1/ 36
10 m	0.220/4.3 = 1/ 19
35 m	0.550/3.52 = 1/ 6.4
40 m	0.588/3.4 = 1/ 5.8

3.5 Linearity

Although electromagnetic fields are linear, non-linear media (such as isolation dielectrics) could give rise to non-linear transmission. Linearity is measured on several cable lengths and the rms deviations are always lower then one lsb, which is the measurement's resolution=1/256 ~ 0.4%).

4. Cost.

Cost of cables would be around 70 kCHF (7000 cables x 10 m x 1 CHF/m). Cost of drivers/connectors/receivers will amount to approx. 70 KCHF(7000 x 10CHF).

5. Conclusion.

The transmission of an analog data stream at 40 Ms/s over a distance of 10 meter will not deteriorate signals with a S/N up to 19. The limitation in length is due to distortion resulting in sample-to-sample crosstalk. Pickup of noise (~1 mV in lab environment), attenuation (11% for AWG24) and transmission linearity are of much less importance at these distances. Cable parameters (AWG, individual or common shield, isolation material, cost) can be further optimised.

6. References.

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(6) Cypress. Driving copper cables with HOTlink™ .

(7) Cypress. HOTlink™ copper interconnect – Maximum distance vs. frequency.

(8) Cypress. Using HOTlink™ with long copper cables.

(9) Lossy transmission lines. (F.E. Gardiol) Artech House, inc . ‘87