Lessons Learned in High Frequency Data Transmission Design: ATLAS Strips Bus Tape

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ABSTRACT

Requirements of HEP experiments lead to highly integrated systems with many electrical, mechanical and thermal constraints. A complex performance optimisation is therefore required. High speed data transmission lines are designed, while simultaneously minimising radiation length. Methods to improve the signal integrity of point to point links and multi-drop configurations are described. FEA calculations are an essential guide to the optimisation which allow data rates of 640 Mbps for point to point links over a length of up to 1.4m, as well as 160 Mbps for multi-drop configuration. The designs were validated using laboratory measurements of S-parameters and direct BER tests.

INTRODUCTION

The strip bus tapes will be located in the barrel section of the inner tracker of the ATLAS detector at the Large Hadron Collider. Due to the location there are unique material, space, mass and radiation hardness constraints. The 1.4m tapes must transmit data at 640Mbps along point-to-point links and 160Mbps along multi-drop links. This project studies the tradeoffs between optimization to satisfy the constraints and signal integrity in a HEP experiment environment.

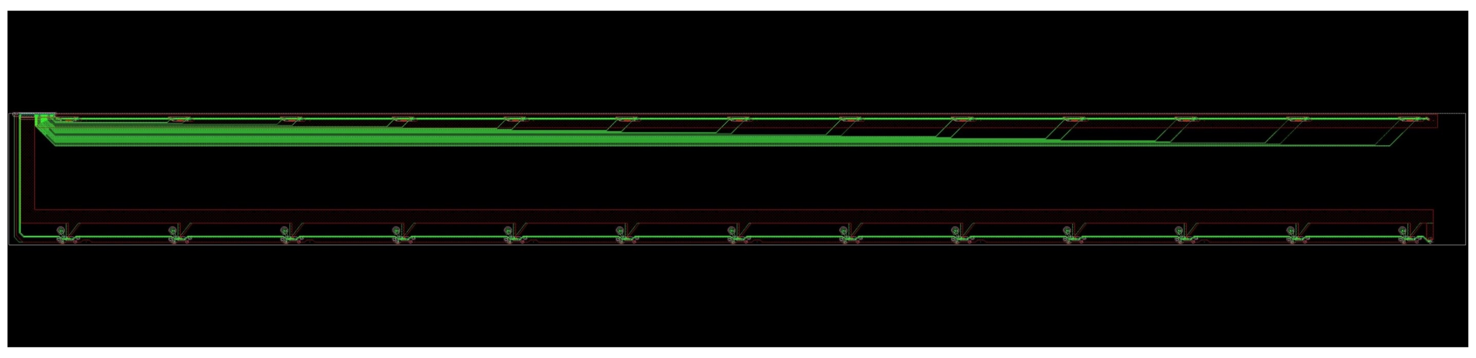

Figure 1 Strips barrel bus tape

TRANSMISSION LINE THEORY

- First solve Laplace's equation → C and L, compute* $Z_0 = \sqrt{L/C}$
- Needs 2D field solver (e.g. ANSYS HFSS)
- Main loss mechanisms [1]
  - Resistive (skin effect): $\exp(-R/2Z_0)$
  - Dielectric loss (loss tangent): $\exp[-\omega\varepsilon_r \tan\delta\, l/c]$
- Dispersion*: $1/v = \sqrt{LC} + \dfrac{R}{2Z_0}\dfrac{1}{\sqrt{\omega\omega_0}}$

  R depends on skin depth and geometry. HFSS can predict loss and attenuation for line.
- *Approximations
- Electric fields can be simulated.
- S-parameters plot transmission and reflection properties.

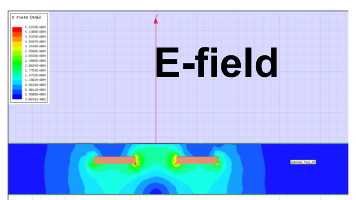

Figure 2 Field lines in a microstrip transmission line.

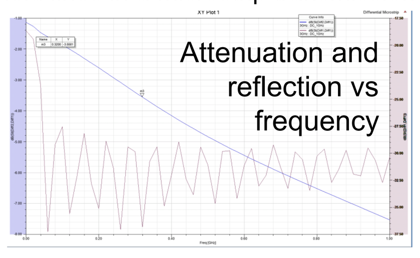

Figure 3 Simulated S-Parameters

Cable Composition

Bus Tape Construction

The bus tape is a flexible tape that provides both structural and electrical support for the strip modules. It is made of layers of polyimide and acrylic glue with embedded copper traces. The tape is co-cured to a carbon fibre support layer. The carbon fibre provides mechanical strength as well as electrical grounding.

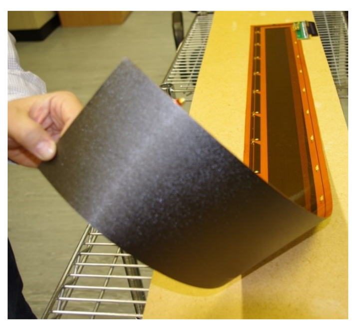

Figure 4 Carbon fibre backed bus tape

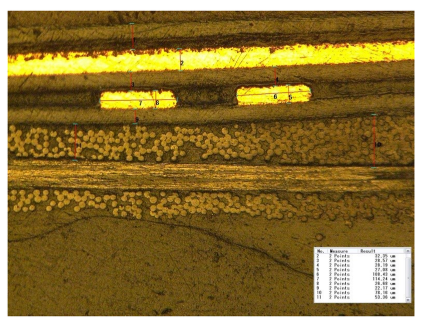

Figure 5 Cross section of bus tape showing top shield, differential signal line and 3-layer carbon fibre.. This is not an ideal tape design due to the proximity of signal layer and carbon fibre.

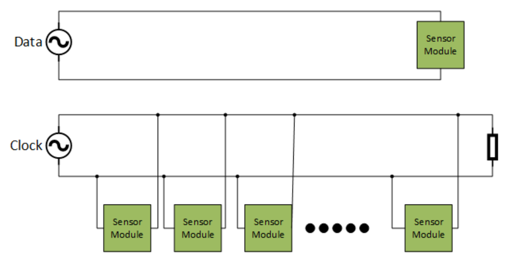

Figure 6 Point-to-point data line and a multi-drop clock line.

Multi-Drop Lines

On the strips bus tape, there are point-to-point transmission lines for data and multi-drop lines for clock and command signals. An lpGBT transmitter will be mounted at the end of the tape and multiple modules will be mounted along the tape. Three clock and command lines will originate at the lpGBT and will be connected to each module along the line. A multidrop system reduces the number of transmitters and cables required, therefore reducing the space and power requirements.

Multidrop transmission lines have been used for slow speed transmissions for many different applications [2]. However, at high speeds, impedance matching is difficult because the receiver capacitance at each drop leads to impedance distortion to the transmission line due to Z = 1/(jωC) term. This causes distortion of the signal. Slowing down the transceiver rise time can be used to ameliorate this effect if the required bandwidth allows.

CARBON FIBRE IN TRANSMISSION LINES

Carbon fibre is a conductor and it is possible to use the carbon fibre structure as part of a DC grounding scheme. However, carbon fibre is a poor conductor at high frequencies. While carbon fibre's radiation length is two orders of magnitude higher than for copper, it's conductivity is three orders of magnitude lower. Changes in carbon fibre layup can change the electrical transmission properties. Therefore, it is undesirable to use carbon fibre for electrical transmission even in applications with low radiation length requirement.

Figure 7 50 Ohm microstrip with carbon fibre on FR4

Lab Test of Carbon Fibre Transmission Line

Dimensions
- 240 mm length, (too short)
- 4mm width, (too wide)
- 2.4 mm FR4 thickness (too thick)

Transmission
- -1.9 dB at 320MHz
- -6.2dB at 960MHz

MEASUREMENT TECHNIQUES

Point-to-point lines can be measured using either a network analyzer or TDR. Both instruments can produce S-Parameters. See [3] for detailed instructions on measurement techniques. Signals can be transmitted on both point-to-point and multi-drop lines to measure eye diagrams and bit error rate.

S-Parameters

S-Parameters are a set of plots showing transmission, reflection and cross-talk at a range of frequencies. S-Parameters can be interpreted directly, converted to time domain impedance plots or used to simulate eye diagrams. S-Parameters are most useful for quickly assessing potential to operate at different frequencies.

Figures 8-9 Placing probe for TDR measurement. Probes can be placed directly on the wire bond pads with no adaptors required.

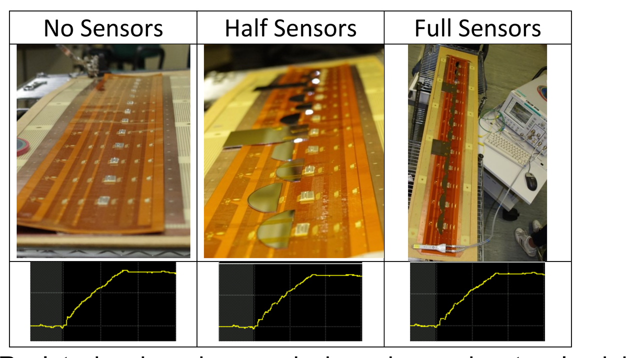

Figure 10 TDR plot showing changes in impedance due to aluminized silicon 'sensors' placement on a point-to-point transmission line.

TDR

Time Domain Reflectometry (TDR) is a technique to monitor reflections from an input pulse and then calculate the impedance along the line. On a point-to-point transmission line, time correlates directly with distance. TDR plots of multi-drop lines are difficult to interpret. TDR plots can be measured directly or calculated from S-Parameters. Time domain impedance plots are most useful for locating defects in the hardware.

Eye Diagrams

Eye diagrams show the overlayed waveforms on the cable output for different bit sequences on the input. Eye diagrams are the easiest plots to interpret, but only give a simplistic overview of potential performance. Eye diagrams can be simulated from S-Parameters or measured directly.

BERT

Bit error rate test (BERT) evaluates the number of errors transmitted through a cable for a given bit sequence, transmission speed, and signalling standard. The primary objective is to verify that the error rate is low enough to satisfy the experiment's requirements. A scan of the transmission speed gives the cable bandwidth for a given error rate tolerance. Effects of the transmission parameters, such as amplitude, pre-emphasis level, and encoding techniques (8/10b, 64/66b, etc), on the bandwidth can be studied.

RESULTS

Point-to-Point

Point-to-point lines were studied to determine the optimal tape material stack-up. An earlier tape design had a carbon fibre layer too close to the data traces, resulting in very poor signal quality. The following generation of tapes had additional polyimide and a bottom copper shield underneath data lines screening the lossy influence of the carbon fiber. We studied data transmission on this tape for different top shield configurations and trace widths with eye diagrams and BER tests. The effect of 8/10b encoding was assessed as well. No errors were observed despite running tests for between 3 and 39 hours. The measured bandwidth is in excess of the required 640 Mbps transmission.

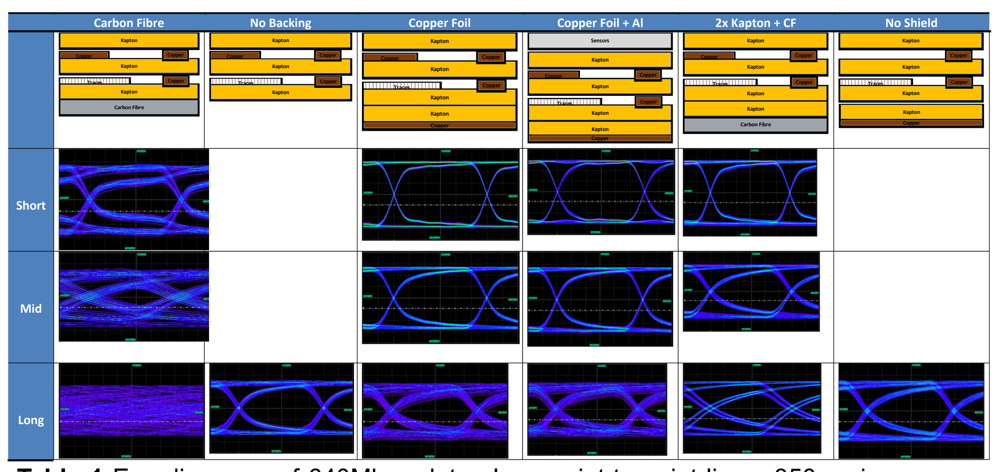

Table 1 Eye diagrams of 640Mbps data along point-to-point lines. 350ps rise time transmitter.

Trace track and gap [mill]	Top Shield	Tranmission Bandwidth with PRBS [Mbps]	Tranmission Bandwidth with PRBS and 8/10 b [Mbps]	Payload Bandwidth with PRBS and 8/10 b [Mbps]
4	Solid	777 < BW < 1244	1244 < BW < 1555	995 < BW < 1244
4	Hatch	777 < BW < 1244	1244 < BW < 1555	995 < BW < 1244
4	Sparse Hatch	1244 < BW < 1555	1555 < BW < 2488	1244 < BW < 1990
4	Absent	777 < BW < 1244	1244 < BW < 1555	995 < BW < 1244
6	Sparse Hatch	1244 < BW < 1555	1555 < BW < 2488	1244 < BW < 1990
6	Hatch	777 < BW < 1244	1244 < BW < 1555	995 < BW < 1244

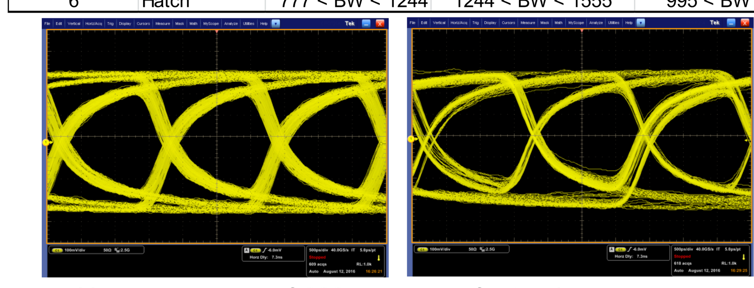

Figure 11 Eye diagrams of 622Mbps data for the line without top shield. The left diagram is for PRBS data. The right diagram is for PRBS data with 8/10b.

Multi-Drop

For multi-drop transmission of the TTC data we instrumented the test tape without top level shield in the configuration for the longest such line on the stave: 1) It ran the full length of the stave. 2) The last 10 hybrid location (out of 26) had capacitive loads imitating the line loading with the receivers. 3) The run of the line before the loads was covered with silicon sensors to simulate the effect of the modules loaded on top of the line. We anticipate the loading of less than 3 pF and the operational speed of 160 Mbps. For testing purposes we ran the line loaded with alternatively 3 pF or 6 pF loads at either 160 or 320 Mbps. All transmitters and receivers were based on commercial drivers, TI SN65LVDx10x series. BER tests used PRBS-31. No transmission errors were observed in data runs as long as 20 hours.

	Data at 160 Mbps, loads at 3 pF			*Data at 320 Mbps, loads at 3 pF*		
Hybrid number (out of 26)	**Time [minutes]**	**Number of errors**	**Error Rate Limit**	**Time [minutes]**	**Number of errors**	**Error Rate Limit**
18	1200	0	8.70E-14	30	0	1.74E-12
22	46	0	2.26E-12	78	0	6.67E-13
26	42	0	2.48E-12	90	0	5.78E-13
	Data at 160 Mbps, loads at 6 pF			*Data at 320 Mbps, loads at 6 pF*		
Hybrid number (out of 26)	**Time [minutes]**	**Number of errors**	**Error Rate Limit**	**Time [minutes]**	**Number of errors**	**Error Rate Limit**
18	811	0	1.28E-13	44	0	1.18E-12
22	51	0	2.04E-12	205	0	2.54E-13
26	54	0	1.93E-12	100	0	5.21E-13

Table 2 BERT testing of multi-drop line.

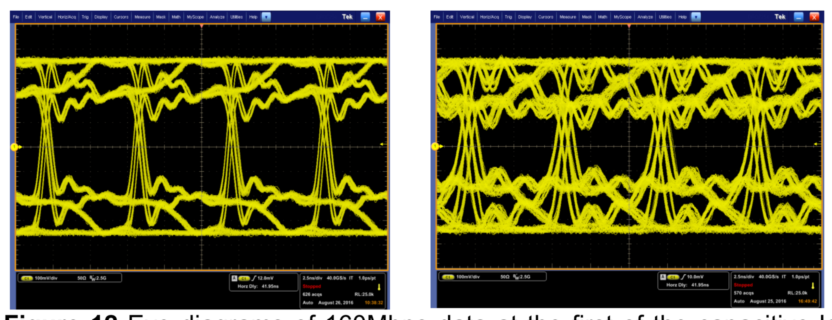

Figure 12 Eye diagrams of 160Mbps data at the first of the capacitive loads on the multi-drop line. The left diagram is with all loads at 3 pF, and the right diagram with all loads at 6 pF.

In another investigation we loaded all 26 hybrid connections with 3.7 pF loads and used a GBTx as the transmitter. The eye diagrams were open in all cases. Interestingly, the worst opening was in the middle of the tape, far away from the driver and the termination.

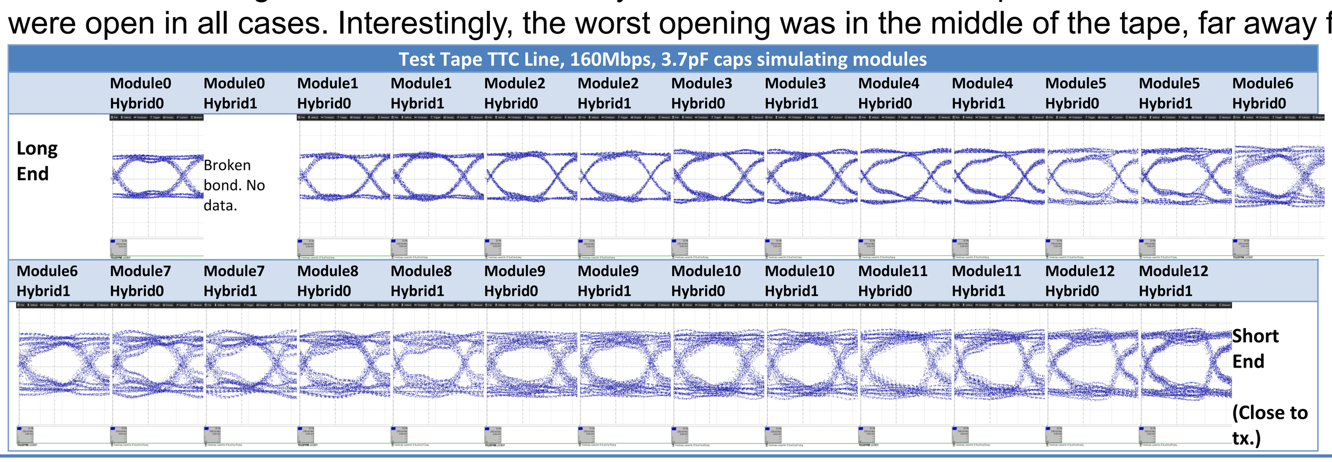

Table 3 Eye diagrams of 160Mbps data measured at each module location along a multi-drop line loaded with 3.7pF capacitors in place of modules.

CONCLUSIONS

When data transmission speeds were slower, basic DC electrical design practices could be used to design a data transmission line. As speeds increase, proper transmission line design techniques become vitally important. Many simulation software packages are available to simulate transmission line performance. These simulations should be used early in the design process to study options and immediately before production to identify unexpected issues.

Both simulations and lab testing showed that the initial design of the bus tapes are unlikely to perform well at the desired speeds. By adding appropriate insulation above and below the transmission lines, the modified bus tapes were shown to work with point-to-point transmission at 640 Mbps and multi-drop at 160 Mbps with realistic capacitive loading. The worst eye diagrams on multi-drop lines were in the middle of the tape, which was unexpected.

Carbon fibre is a poor conductor. It is difficult to model the electrical properties due to the variabilities in layups, fibres, resins and build processes. For the purposes of the strips bus tapes, the recommended option is to avoid the use of carbon fibre for AC grounding.

FUTURE WORK

Future tapes will be built with a new stackup as shown in Figure 13. This design should be an appropriate balance of signal integrity and material budget for the intended transmission speeds. It has the ground layer on the bottom separating the data transmission from the dissipative effect of the carbon fibre.

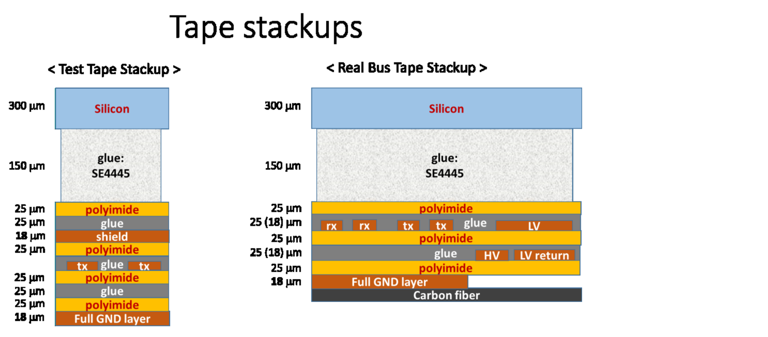

Figure 13 Recommended bus tape stack-up for strips barrel (right hand side).

References

1) Johnson, H. Graham, M. (06 Mar. 2003) "High-Speed Signal Propagation: Advanced Black Magic". *Print*. Ed. Upper Saddle River, NJ: Prentice Hall.
2) TIA/EIA-899 standard, "ELECTRICAL CHARACTERISTICS OF MULTIPOINT-LOW-VOLTAGE DIFFERENTIAL SIGNALING (M-LVDS)"
3) Sullivan, Stephanie. (accessed 21 Sept. 2016) "S-Parameter Measurement Instructions". https://twiki.ppe.gla.ac.uk/bin/view/ATLAS/PUUKA/ServicesAndIntegration

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