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 using copper-polyimide flexible bus tapes rather than cable harnesses to minimise radiation length. Methods to improve the signal integrity of point-to-point links and multi-drop configurations in an ultra-low-mass system are described. FEA calculations are an essential guide to the optimisation of a tape design which supports data rates of 640 Mbps for point-to-point links over a length of up to 1.4 m, as well as 160 Mbps for multi-drop configuration. The designs were validated using laboratory measurements of S-parameters and direct bit error ratio tests.

KEYWORDS: Special cables; Particle detectors; Data Handling; Data acquisition circuits; Optical detector readout concepts.

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Contents

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1. Introduction

Bus tapes, also known as flex tapes or "Kapton" flexes[1] are flexible, printed circuit boards. They can be used to transmit signals and distribute power. Bus tapes are normally used to connect two rigid objects with a flexible joint. Multiple commercial vendors have the capability to fabricate small bus tapes.

Within high-energy physics experiments, there are very strict mass, volume and radiation hardness requirements. Bus tapes have a lower mass than a cable harness. Tapes can be designed to allow connections with solder or wirebonds, instead of plastic cable connectors, further decreasing the system mass and eliminating the need for plastics. Bus tapes can be integrated into the mechanical support structure, saving space and mass of the overall system.

For the upgraded inner tracker of the ATLAS detector at the Large Hadron Collider, bus tapes will be used in the silicon-strip detector. We have studied bus tape design for the barrel section, but a similar design will likely be used for the end-cap region. The 1.4 m tapes must transmit data at 640 Mbps along point-to-point links and 160 Mbps along multi-drop links. This project studies the tradeoffs between optimisation to satisfy the constraints and signal integrity in a HEP experiment environment. A preliminary tape design is shown in Figure 1.

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[1] The tapes are normally made of layers of polyimide, copper and glue. Kapton is the brand name for a proprietary form of polyimide.

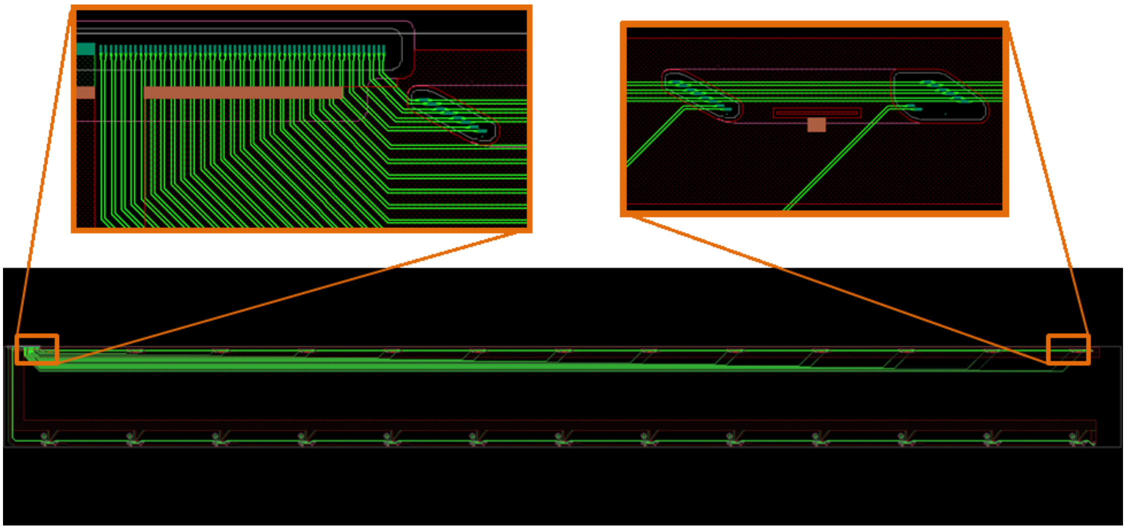

Figure 1 – Original layout of the bus tape for the barrel silicon strip detector. Tape is 1.2 m long. The top 3 pairs of lines on the tape are multi-drop clock and command lines. The rest of the lines on the top half are point-to-point data lines. The lower half of the tape is for power distribution. Shield layers are not shown.

2. Transmission Line Concepts

For high-speed transmission lines operating over “long” distances, the signals will be distorted by dispersion and losses. For the range of parameters used in this study, the most important loss mechanism is resistive loss. The transmitter, transmission line, and load should all have the same impedance so as to minimise reflections. They must also be designed to limit the dispersion and losses, such that the signal integrity is acceptable. There are standard techniques to achieve these requirements but they require wide lines to limit the resistive losses and correspondingly thick insulator layers between the signal and ground layers to control the impedance. This results in unacceptably wide and thick (too much material) tapes for our application. We have therefore studied the optimisation of the transmission lines to obtain acceptable signal quality with minimal material.

2.1 Bus Tape Construction

The bus tape is a flexible tape that provides both structural and electrical support for the strips 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 DC electrical grounding. An early tape design is shown in Figure 2.

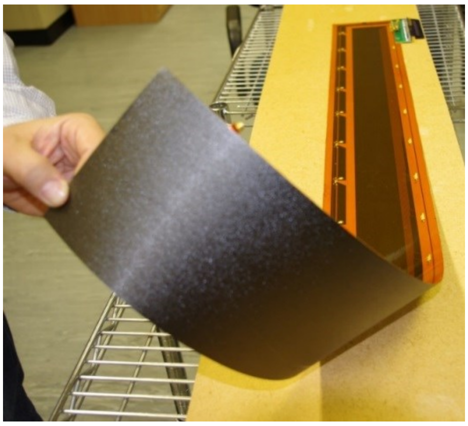

Figure 2 – Prototype carbon fibre backed bus tape.

2.2 Multi-drop Lines

On the silicon strip detector bus tape, there are point-to-point transmission lines for data and multi-drop lines for clock and command signals. These two transmission methods are shown in Figure 3. A Low Power GigaBit Transceiver (lpGBT) [1] 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 multi-drop system reduces the number of transmitters and cables required, therefore reducing the space and power requirements.

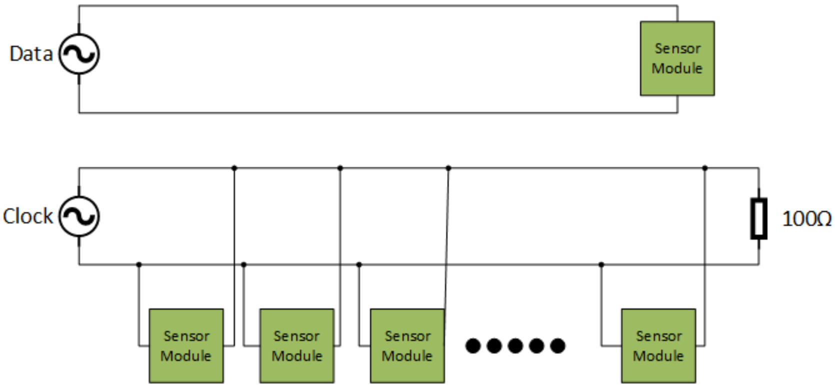

Figure 3 – Point-to-point (640Mbps) and multi-drop (160Mbps) connection diagrams.

Multidrop transmission lines have been used for slow-speed transmissions for many different applications [2]. Use of multidrop lines for high-speed applications is more difficult because at high speeds, the receiver capacitance can lead to reflections [3]. Slowing down the signal rise-time can ameliorate distortion if the required bandwidth allows.

3. Signal Quality Measurements

Point-to-point lines can be measured using either a network analyser or a time domain reflectometer (TDR). Both instruments can produce S-Parameters. See [4] 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 rates.

3.1 S-Parameters

S-Parameters are a set of plots showing transmission, reflection and cross-talk signal strength 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. The Touchstone (.s#p) file format [5] is commonly used to store S-Parameters and can be read by many different simulation programs.

3.2 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 can be 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. Both TDR and S-parameters measure only the passive components of a transmission line.

3.3 Eye Diagrams

Eye diagrams show the overlaid 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 because they are highly dependent on the transmitter used for the tests. Eye diagrams can be simulated from S-Parameters or measured directly.

3.4 BERT

Bit Error Ratio Tests (BERT) evaluate the fraction 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 requirements. A scan of the transmission speed gives the cable bandwidth for a given BER tolerance. Effects on the bandwidth of the transmission parameters, such as amplitude, pre-emphasis level, and encoding techniques (8/10b, 64/66b, etc), can be studied.

4. Best Practices for Bus Tape Design

Simple calculations should be used to determine approximate suitable combinations of trace thickness, trace width, substrate height and substrate dielectric constants. The resulting transmission lines should have impedances to match sources and loads (normally 100 Ω differential). The substrate properties and trace thickness options will be constrained by what materials are available on the commercial market and are allowed to be used inside ATLAS. For example, polyimide sheets are commonly available in 1, 2, 3 and 5 mil thicknesses with copper thicknesses of 0.5, 1.0 or 2.0 oz/ft^2. Other thicknesses, such as whole integers of SI units, would be difficult and expensive to source. These simple calculations are only sufficiently accurate for preliminary designs; therefore the layout of the transmission line should then be optimised by using Finite Element Analysis (FEA) software. The FEA starts by solving Maxwell's equations for a 2D cross section through the transmission line to determine the capacitance and inductance per unit length and hence the impedance. Once the impedance has been tuned to be close to the target value, a full tape design can be made. Techniques for designing high-speed data transmission lines are documented in detail in [6] [7] [8]. The full design should be simulated using a 3D software tool to obtain predicted S-Parameters. A detailed simulation tool is required because the effect of elements required in a real design, such as turns in the transmission line, or changes in trace widths to accommodate connectors, can have significant complex effects on the signal integrity for very high-speed signals. The simulated S-Parameters can then be used by signal integrity analysis software to predict eye diagrams for expected input signals.

5. Results

Multiple copies of two different tape designs were available for testing in the laboratory. Additional material was added to the top or bottom of the tapes for testing the impact of different stack-ups. All results presented in this paper come from laboratory measurements of these tapes.

5.1 Point-to-Point

Point-to-point lines were studied to determine the optimal tape material stack-up. Eye diagrams in Figure 4 were generated by measuring tape S-Parameters, then simulating an eye diagram based on the expected lpGBT transmitter performance. The first tape stack-up had a carbon fibre layer too close to the data traces, resulting in very poor signal quality. The second stack-up was just the tape, with no backing. This tape had excellent signal quality, but the tape will be mounted to the carbon fibre mechanical structure of ATLAS to be used, so once installed, it will have the same electrical properties as the first tape. The following generation of tapes had additional polyimide insulation and a lower copper shield underneath data lines screening the lossy influence of the carbon fibre. Tapes with a copper shield on the bottom can be mounted to carbon fibre with no impact on the signal quality.

The first tape design had a copper shield on the top of the signal traces to prevent the sensors that will be placed on the top of the tape from impacting the signal quality. To test the need for this shield, we placed sensors on top of un-shielded traces. We did not observe a change in signal quality; therefore the top shield is unnecessary and will be removed in future designs.

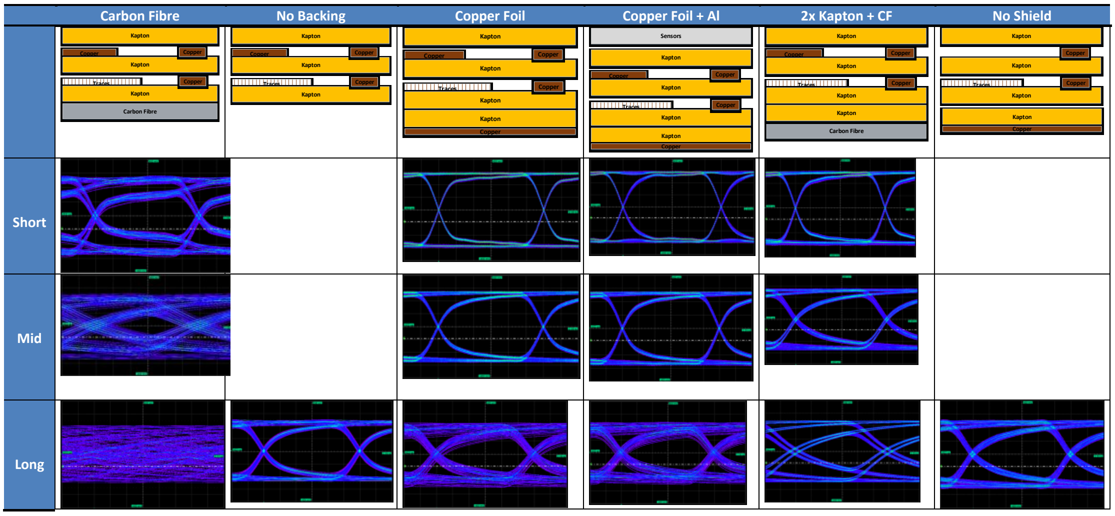

Figure 4 - Eye diagrams of 640 Mbps data along different bus tapes. Short (about 10 cm), mid (about 60 cm) and long (about 1.2 m) traces shown.

We studied point-to-point data transmission for different top shield configurations and trace widths with eye diagrams and BER tests. See results in Table 1. The effect of 8b/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. These results confirm that a top shield is not necessary for 640 Mbps data transmission.

Table 1 - Transmission bandwidth was evaluated with PRBS-31 for a pre-defined set of data rates: 622, 777, 1244, and 1555 Mbps. The highest working data rate is shown. The number of observed errors was zero in all these cases, and their fraction was typically below 10^{-13} of the data transmitted.

Trace track / gap [mill]	Top Shield	Highest Working Data Rate with PRBS-31 [Mbps]
4 / 4	Solid	777
4 / 4	Hatch	777
4 / 4	Sparse Hatch	1244
4 / 4	Absent	777
6 / 4	Sparse Hatch	1244
6 / 4	Hatch	777

5.2 Multi-drop

Tests of the point-to-point lines showed that the optimal tape had no shield on top of the data traces, but a shield on the bottom. Two layers of polyimide are required between the traces and the shield. Multi-drop tests were performed on this tape configuration.

The first multi-drop test used a GBTx transmitter (predecessor to the lpGBT) [9] at 160 Mbps to send data down a bus tape. Each hybrid receiving circuit location had a 3.7 pF capacitor installed between the differential signal lines to simulate the effect of a hybrid on the signal quality. The short end of the tape, closest to the transmitter, showed significant reflections. The long end of the tape showed attenuation of the signal. The middle of the tape had both reflections and attenuation, resulting in the worst signal quality. Measured data are shown in Figure 5. While there is noticeable degradation in the signal quality, the signal is usable at each location along the tape.

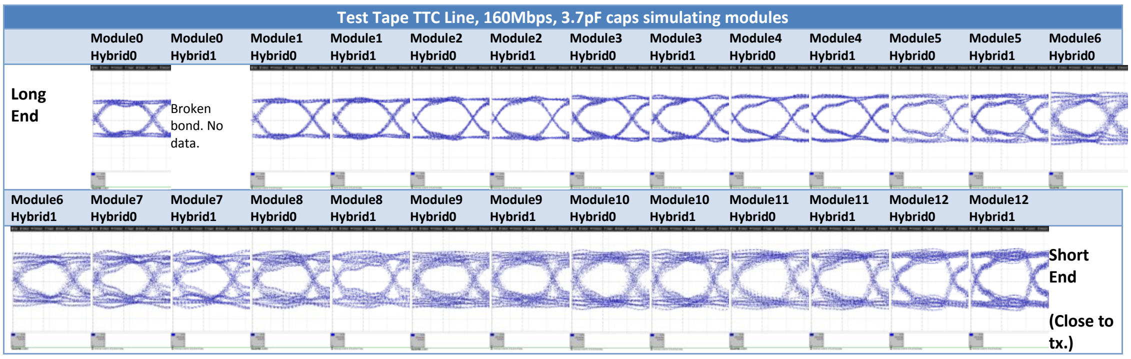

Figure 5 - Eye diagrams along the multi-drop line. The data is transmitted by a GBTx sending 160 Mbps PRBS.

After the first test was complete, it was decided to replace the single set of TTC lines with 4 sets, each servicing a sub-section of tape, to improve system reliability. This means that there will be a maximum of 10 drops on each line. A BER test was conducted with only the longest such line and 10 hybrid locations populated with capacitive loads. The portion of the line between the transmitter and the first load was covered with silicon sensors to simulate the effect of the modules mounted on top of the line. We anticipate the capacitance of each hybrid to be less than 3 pF and the operational speed to be 160 Mbps. For testing purposes, we ran the line loaded with 3 pF and 6 pF loads at both 160 and 320 Mbps. All transmitters and receivers were based on TI SN65LVDx10x series commercial drivers. These transmitters have rise-times significantly faster than the GBTx in our test configuration, resulting in more high-frequency components of the signal and therefore more reflections. BER tests used PRBS-31. No transmission errors were observed in data runs as long as 20 hours, but capacitive losses in the 6 pF eye diagrams lead to increased noise. Test results are shown in Table 2 and Figure 6.

Table 2 - BER test results for multi-drop line. 90% confidence level limits are derived using Poisson statistics, given the zero observed errors.

	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 (90%CL)**	**Time [minutes]**	**Number of errors**	**Error Rate Limit (90%CL)**
18	1200	0	2.00E-13	30	0	3.99E-12
22	46	0	5.20E-12	78	0	1.53E-12
26	42	0	5.71E-12	90	0	1.33E-12

	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 (90%CL)**	**Time [minutes]**	**Number of errors**	**Error Rate Limit (90%CL)**
18	811	0	2.95E-13	44	0	2.72E-12
22	51	0	4.69E-12	205	0	5.84E-13
26	54	0	4.44E-12	100	0	1.20E-12

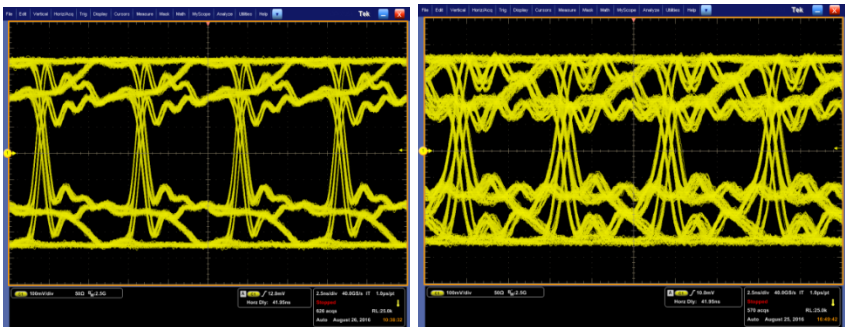

Figure 6 - Eye diagrams of 160 Mbps data at the first (closest to the data source) of the capacitive loads on the multi-drop line. The left diagram is with all loads at 3 pF, and the right diagram with all loads at 6 pF.

6. 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 is 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.

Future tapes will be built with a new stackup as shown in Figure 7. 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.

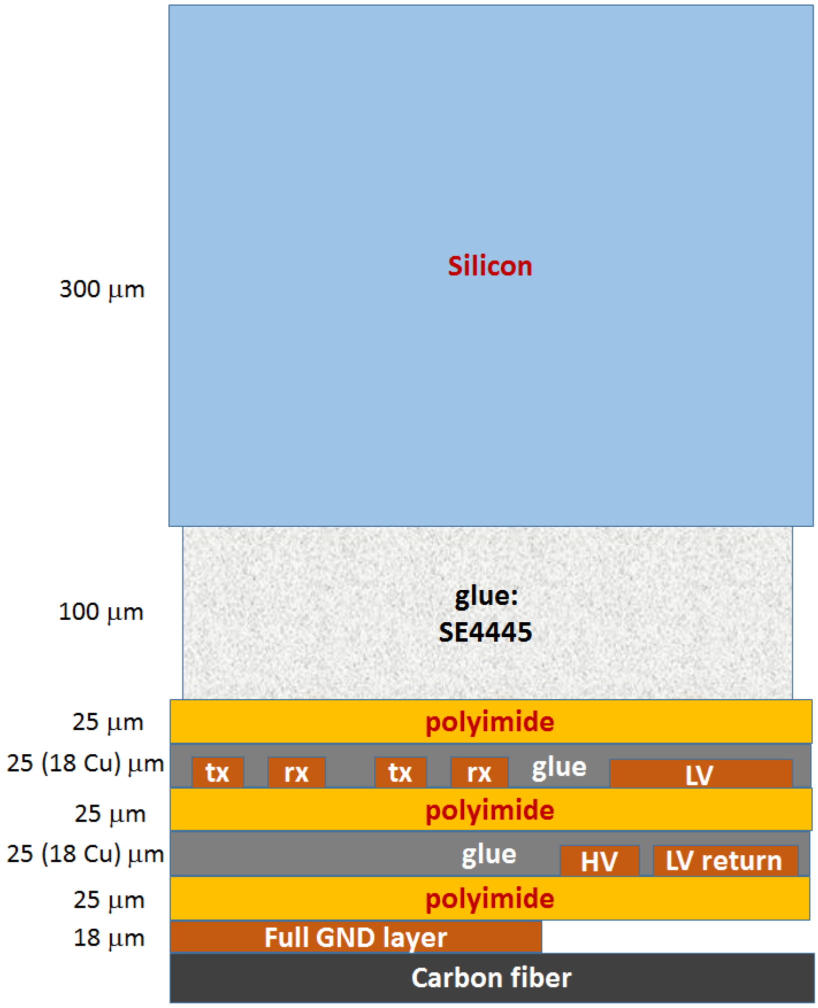

Figure 7 - Recommended future bus tape stackup.

Acknowledgments

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