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High speed electrical transmission line design and characterisation

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Many experiments require high data rates, implying custom link design using transmission line theory.

Transmission line theory is presented including FEA analysis of energy dissipation in exemplar designs. The choice of transmission line designs are reviewed.

Transmission line design principals and testing equipment are presented. The characterisation techniques of time-domain reflectometry and frequency-domain measurements are discussed and compared.

Bit-error-rate testing is presented and its limitations for design discussed. Finally, the gains in error free transmission rates due to signal equalization that corrects for signal degradation, including; pre-emphasis, CTLE or adaptive methods, is given.

Summary

For data rates up to a few Mbps transmission hardware can be designed using DC electrical principals. PCB traces and cables are adequate if they pass a simple conductivity test. New design and testing rules are required for higher speed data links to function as required.

Vertex and tracking subdetectors of HEP experiments can delivery data rates up to 5Gbps, which would commercially be transmitted optically. However, due to the high radiation environment and low radiation length requirements electrical transmission is often required with custom designs.

The electrical engineering community has established basic design principals for high frequency transmission lines. Transmission line theory is presented, with different types of transmission lines analysed, including; two wire (twisted pair and twinaxial cables) and the stripline. Simulations of the electrical properties are performed using ANSYS Q3D Extractor. Q3D performs finite element analysis of defined structures based on the geometric layout and dielectric properties of materials. For expediency, 2D simulations based on datalink cross-sections were used as the link is assumed to be uniform over distance. Simulations calculated the expected electric performance over a range of frequencies. Complete electromagnetic characterization of different designs is obtained in the form of scattering parameters (S-parameters) from which reflection and transmission is assessed. Connection features such as differential signaling, impedance and length were adjusted to suit the simulation. Geometric representations of fields at a given frequency were used to illustrate flow of charge and hence data transmission through the design.
From the simulation of exemplar designs of transmission lines the choice of design for a given set of boundary conditions is reviewed.
When designing high-speed transmission lines, there are a many key rules to follow. We discuss, based on our experience, several of these, including; using tightly coupled differential traces; using a continuous small signal return line following the data line; using guard traces between signal traces to reduce cross talk; matching the impedance of all cables and connectors to avoid reflections; using dedicated high-speed materials dielectric and copper layers. Moreover, great care has to be taken in connector and via layout.
The characterisation techniques of time-domain reflectometry and frequency-domain measurements (obtained via a network analyser) to measure signal distortion introduced by the transmission line are discussed and compared. The network analyser produces an S-parameter by measuring the magnitude and phase of the

incident, reflected, and transmitted signals and is related to the familiar quantities of transmission coefficient, insertion loss and gain of the link. The time domain analysis further helps to identify transmission features in the physical item, for example layer stack-up and interconnects that cause crosstalk and reflections. Based on our experience we discuss the best methods to determine defects in transmission lines from S-parameters and TDR measurements.
Bit-error-rate testing is presented and its limitations for design discussed. Finally, gains in error free transmission rates due to signal equalization methods that corrects for signal degradation, including; pre-emphasis, CTLE or adaptive methods, are given.

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