It's about time: How TDR enables predictive maintenance for industrial Ethernet

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Introduction

With the increasing need to accelerate deployments of solutions and reduce downtime, there is an increasing need to diagnose industrial Ethernet cables in a timely and effective manner.

Time-domain reflectometry (TDR) enables developers to see through meters of copper and find opens, shorts, crosses and many more issues that can impact the reliability of industrial Ethernet communication in factory floors, process plants, logistics centers or even large indoor farming locations.

This article covers the basics of TDR, including how to implement a relatively simple TDR-measurement setup without relying on a high-speed analog-to-digital converter (ADC) or digital-to-analog converter (DAC). Also included is how the integration of such measurement setups into TI Ethernet physical-layer (PHY) devices can perform diagnostics directly.

A TDR overview

TDR measurements provide direct information about the electrical integrity of an Ethernet cable. A TDR circuit sends a fast test pulse down the cable; any returning reflections indicate discontinuities of impedance. These discontinuities can be an open or a short, or even damage to the dielectric.

Theoretically, TDR involves mathematics for wave propagation and transmission line impedance,[1, 2] but the physical understanding is more intuitive. As the test pulse encounters obstacles or impedance discontinuities in the transmission line, some of the pulse energy is reflected back such that the amplitude and time at which the reflection arrives reveals the position and relative impedance mismatch. Anyone who observed the ripple of a stone in a lake has an intuitive understanding of a wave (pulse) and its reflection. A slightly less intuitive property of TDR is that a wave encountering an open circuit would have an echo twice the amplitude of the transmitted wave, while a wave encountering a short would have a negative amplitude echo. On the other hand, quite expectedly, in the case of no impedance mismatch, no echo would be detected.

The theory of TDR claims that the faster the pulse rise time, the smaller the features the instrument can resolve. Today, some TDR instruments with rise times in the picoseconds are used to inspect printed circuit boards (PCBs) and integrated-circuit (IC) package-bound wires.

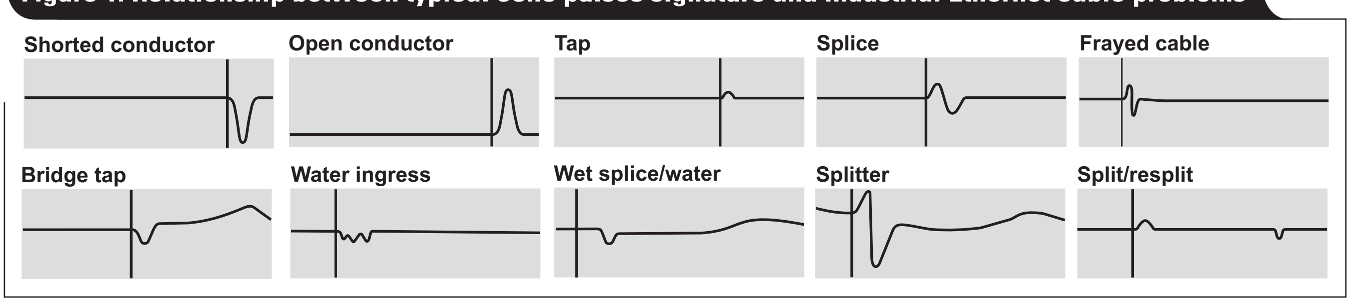
What is a TDC?

Although ADC stands for analog-to-digital converter, it would be more accurate to say that most ADCs today are voltage-to-digital converters (VDCs), a subset of ADCs. TDCs are another subset of ADCs which convert time intervals to digital values. ADCs were invented mostly to address increasing telecommunications needs as voice was captured as a voltage. However, the European Organization for Nuclear Research, also known as CERN, needed a device that would convert the time between two edge signals generated by particles in their measurements. This need led to the design and production of the first TDC. Since then TDCs are finding an ever increasing usage in the industry where ADC (VDCs) cannot be used or are not the perfect match.

How to use a TDC for TDR measurements

It is important to understand the objectives for a discrete measurement system. Figure 1 shows the different echoes that can be received in relation to the different types of problems that need to be diagnosed. From the waveforms it is clear that only a few points are needed to know when the echo is received and if it is a positive, negative or a more complex waveform.

Figure 1. Relationship between typical echo pulses signature and industrial Ethernet cable problems



To set up a TDC to take TDR measurements, triggers are correlated to specific voltage increments and decrements. Much like how an ADC triggers at regular time intervals, TDCs can trigger at regular amplitude intervals and provide ultra-low power at high resolution for sensing the location of edges in the signal.

How to set up a TDC

Figure 2 shows a typical TDR measurement with a TDC. The rising and falling edges of the transmit pulse will trigger the TDC and measure the multiple arrival times of the echo pulses.

Consider the simple case of the waveform for an open-conductor as shown in Figure 1. As soon as the received wave passes the threshold set by one of the digital potentiometers (DPOTs), the comparator will trigger and fire the stop line of the TDC. Since TDCs like TI's TDC7201 can capture multiple stops with rising and falling edges, it's possible to configure multiple thresholds for rising and falling edges with multiple comparators and multiple DPOTs (or DACs), thus enabling fuller feature extraction from the simple or multiple echoes that an Ethernet cable could exhibit.

TDR measurements with Ethernet PHY

TI's DP83822 and DP83867 Ethernet-PHY devices support a cable-diagnostic function block as part of the medium dependent interface (MDI), into which TDR is integrated (Figure 3). This integrated cable diagnostic is used for predictive maintenance for industrial Ethernet and Ethernet failure diagnostics on the factory floor. TDR measures disconnected cables as well as cuts in cable pairs, single cables and bad connector terminations. Such failures can occur in factories with harsh environments, moving robots or automated units, as well as through the actions of careless operators.

TDR is an active-measurement technique and requires an inactive Ethernet link. The PHY-integrated TDR function generates multiple TDR pulses and measures any reflection on the Ethernet cable. The TDR results register stores as many as five reflections, including time delay, reflection amplitude, and amplitude prefix.

Figure 2. A TDR measurement setup with a TDC

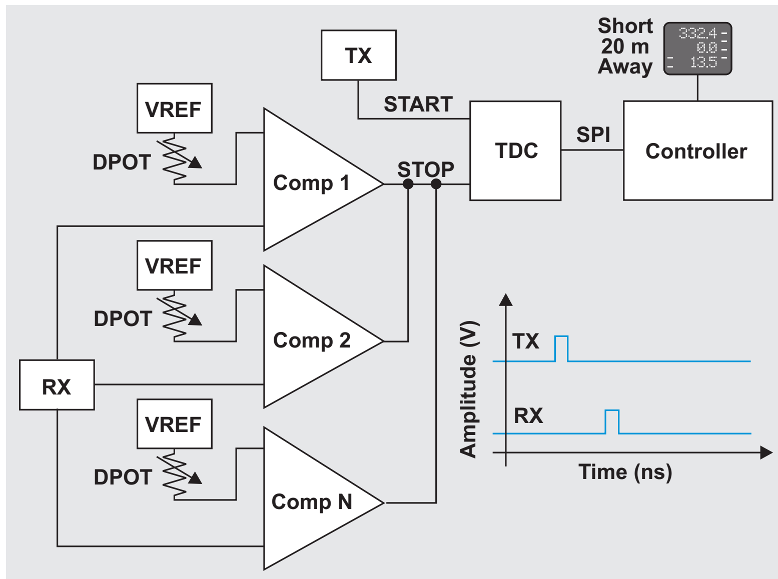
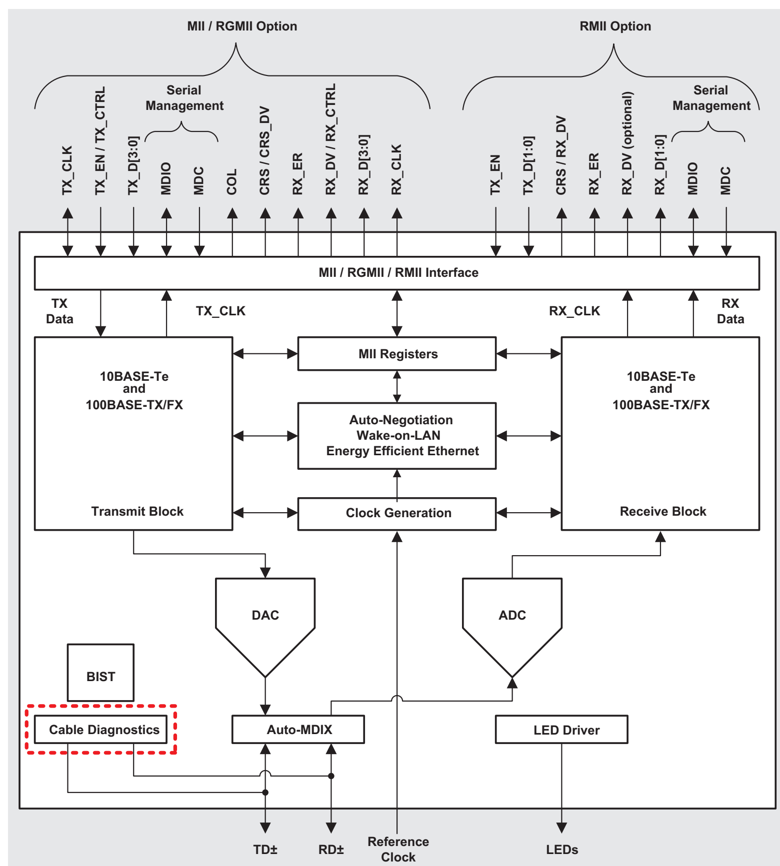


Figure 3. Cable diagnostics block as part of a MDI layer



The microcontroller (MCU) host configures, starts, and reads out results through the management-data input/output (MDIO) and management-data clock (MDC) interface between the MCU and Ethernet PHY. The cable-diagnostic function is part of the extended register space within the PHY and is accessed over the MDIO function block inside the MCU host. This is shown in Figure 4.

The MCU host configures the TDR function for the desired operating mode. The TDR pulse can be generated manually through software or auto-triggered on an Ethernet link-down event. There are configurations for receiver/time domain pairs, cross modes, and TDR averaging cycles, as well as self-reflection, detection of long cable reflections, and a threshold for strong reflections in short cables.

Once TDR has been triggered, the PHY sends out a short pulse on the Ethernet cable, which is reflected at the far end by an open, short, or impedance-mismatch faulty condition (Figure 5). A good condition is a matched termination of 100 Ω, which does not generate any reflection at the far end. In such cases, the TDR block will not record any reflections.

The MCU host analyzes the TDR result for signal delay, amplitude and amplitude prefix to derive the type of cable error and the cable fault distance from the PHY.

The oscilloscope measurement in Figure 6 shows a TDR measurement example for a shorted Ethernet cable fault. The PHY generates the first pulse. The second pulse is reflected by a shorted cable fault on the far end, which travels back to the PHY. Any electrical signal travels about 5 ns per meter in a copper cable.

The delta time (Δt) is 244 ns. As the pulse travels to the cable fault and then back again to the PHY, divide the result by 2: 244 ns ÷ 5 ns ÷ 2 = 24.4 m.

The negative prefix of the reflected pulse indicates a shorted cable fault.

Conclusion

TDR is a very powerful testing technique that allows diagnostics to determine the location of an open or short, and also identify whether a cable has water ingress, which influences the dielectric of the cable. With this information, factory owners can more effectively plan repairs and improve productivity.

TI offers multiple options for designers that need to implement TDR in their products. These solutions range from a simple TDC-based TDR setup to fully-integrated systems where TDR is a feature of TI's industrial Ethernet PHY.

Figure 4. MDIO/MDC interface between the MCU host and Ethernet PHY

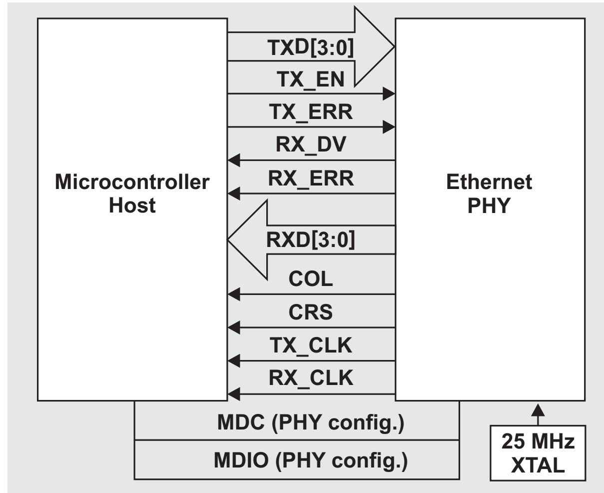


Figure 5. TDR pulse from the PHY and the reflection of an open-cable condition

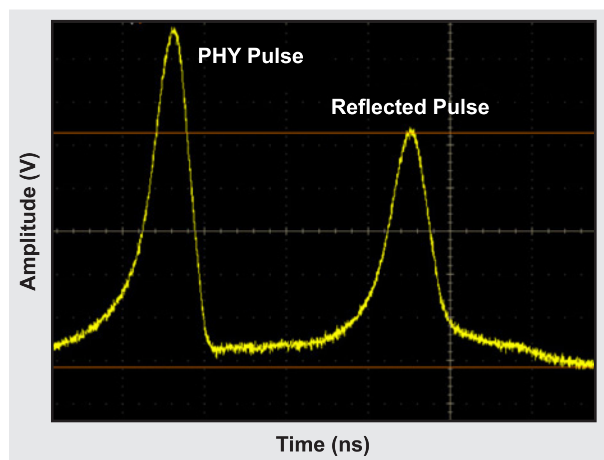
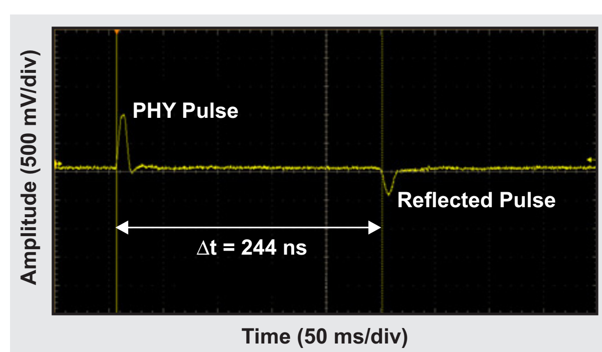


Figure 6. Example of a TDR pulse measuring a shorted-cable fault



References

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2. “Time Domain Reflectometry Theory,” Agilent Application Note 1304-2, 1988.
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Product information:
Ethernet PHY Overview
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