Designing with Multiple Industrial Ethernet Protocols on the same FPGA Platform

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Industrial Ethernet offers lower cost, higher performance, and superior interoperability over traditional industrial field bus solutions. Many variations of Ethernet technology have been developed to address the various cycle time requirements of industrial applications. As a result, industrial customers must support a myriad of evolving Industrial Ethernet (IE) standards. Today, each new protocol standard may require a new design, and solutions might be offered by various suppliers, adding complexity to not only designs, but to supply chain management.

This article examines the key trends driving the growth of open-standard IE solutions and how FPGAs enable designers to evaluate, design, and deploy multiple IE protocols using the same hardware platform.

Industrial Ethernet refers to use of Ethernet-based protocols to address robust, timing-critical, and reliable communications for industrial automation and production machine control. Since these protocols are based on the same IEEE 802.3 standard for the Ethernet physical (or layer one) implementation, a single FPGA-based platform can be used to support all of the open-standard IE protocols regardless of their individual real-time attributes and implementations. For the protocols that demand very high-speed, real-time performance, the real-time functionality is implemented in hardware as a protocol-specific MAC. The remainder of the protocol functionality is implemented in software as a stack running on an embedded processor implemented in an FPGA.

The Industrial Ethernet Landscape

What factors are driving the adoption rate for Industrial Ethernet solutions? Today’s industrial communications environment is fragmented with many competing IE and legacy fieldbus standards, with many solutions implemented in ASICs, ASSPs, and MCUs. The lack of flexibility of such hardware usually means that the software stacks and hardware must be changed for each protocol required. FPGA-based Ethernet solutions, on the other hand, enable easy adaptation to the ever-changing industrial networking requirements using the same FPGA hardware platform.

Factories require easier to manage networks with higher bandwidth, higher performance, and a lower cost of ownership; all of which enables the sharing of real-time information within/across factories and offices over the Internet. Existing fieldbus solutions are adequate for device level communications but lack the performance for managed networks. Manufacturers are looking for easy ways to add Ethernet capability to their machines, making it easy to integrate standalone devices and fieldbus-based systems in to their Ethernet network. This will also allow them to use low cost, off-the-shelf networking equipment and cables.

In addition, factory operations are increasingly looking for open standards to support platform interoperability and avoid costly, proprietary solutions. Open IE standards alleviate potential design problems and make it easier to implement Ethernet-based communications on new and existing industrial products. This is why all IE standards are based on the 802.3 Ethernet
standard; however each standard addresses reliability, critical timing/determinism, and safety requirements in their own way. Many of the IE standards are designed to be compatible at the software level with legacy fieldbus communications to reduce the amount of integration effort required when connecting a fieldbus based device or system to an IE based connection.

The open-standard Industrial Ethernet protocols are CC-Link IE, EtherCAT, EtherNet/IP, Ethernet Powerlink, Modbus/TCP, PROFINET, and SERCOS III. (See Figure 1.) Factory automation applications typically use EtherNet/IP, Modbus/TCP, or PROFINET RT; motion control applications typically require EtherNet/IP with CIPsync, PROFINET IRT, Ethernet Powerlink, EtherCAT, or SERCOS III for precision motor control and network communications. Process automation applications typically require EtherNet/IP and PROFINET RT and often include sub systems that use fieldbuses like DeviceNet, ControlNet, and PROFIBUS PA.

Figure 1. Open-Standard Industrial Ethernet Protocols Categorized by Application Type

Benefits of an FPGA-Based Industrial Ethernet Architecture
Traditionally, MCUs, ASICs, or ASSPs have been used to implement cost-effective fieldbus solutions. These products work well when features, protocol standards, and I/Os are fixed or do not require hardware changes. However, with ever-changing industrial networking standards and the need for very long product life cycles (i.e., typically 10+ years), these products have their limitations. ASICs, ASSPs, and MCUs tend to lock the user into a single solution, and each new solution variant can require a re-spin of a board and countless software programming updates to migrate the code to a new platform and/or processor, a very time-consuming and expensive process.
FPGAs such as Altera’s Cyclone III Series and Cyclone IV Series offer increased flexibility to integrate whatever the designer may require – protocols, embedded processors, peripherals, custom logic for applications such as motion/motor control, and standard or proprietary interfaces - into a single FPGA, as illustrated in Figure 2. The FPGA can be re-configured with feature changes as needed, anytime, anywhere – allowing equipment to easily connect using any Ethernet standard, update product features and easily bridge to other fieldbus based products. As they are connected to the corporate network, FPGA-based IE solutions will also enable products that are easy to maintain/update in the field.

![Figure 2. Typical Block Diagram of an FPGA-Based Ethernet Implementation](image)

A single FPGA platform can support multiple IE standards by using off-the-shelf tools, IP, and software stacks to support each of the Industrial Ethernet standards. FPGAs enable faster time-to-market by allowing the reuse of a common hardware platform, reducing the number of board re-designs, and lower overall cost of ownership. Further, with a long FPGA product life cycle and the ability to migrate IP to new FGPA families, obsolescence risks are easily mitigated.

**A Typical Application Architecture Supporting Industrial Ethernet**

Industrial Ethernet protocol standards are based on the IEEE 802.3 Ethernet physical layer. This means that at the lowest architectural level as shown in Figure 3, the PHYs and magnetics at the bottom are always the same regardless of which IE standard is being implemented. In an ordinary office or even in factory networks, there is a standard media access controller (MAC) for the Ethernet function above the PHY. This is also how non real-time IE protocols such as EtherNet/IP, Modbus/TCP, and Ethernet Powerlink are implemented. These protocol standards use a standard Ethernet MAC and run a protocol-specific stack running on the embedded processor.
For protocols such as EtherCAT, PROFINET IRT, and SERCOS III that specify hard real-time requirements, a protocol-specific MAC is required. In an FPGA, the standard MAC can be easily swapped out with a protocol-specific MAC. Some Ethernet protocols may also require the IEEE 1588 time-stamp functionality, or the addition of a hub or switches to accelerate performance, or add additional features such as ring/loop redundancy. These are straightforward to implement on the same board design based on an FPGA.

With FPGA-based hardware in place, the packets from any IE standard can be received. Once stored in the system, they need to be passed to an embedded processor that runs the appropriate software stack and applications to manage both the network communication and application interface. This is easily achieved in the FPGA by implementing a soft embedded processor such as the Nios II processor. In many cases the processor will also be running a real-time operating system running to simplify the implementation of the packet processing and application. This implementation offers a consistent software platform able to support every flavor of software stack while keeping the software easy to maintain on a single-chip, multiple standard solution. With this kind of implementation, a system that can send and receive data over any IE protocol can now be achieved.

Enabling data flow to an application is best achieved by abstracting the interface to the Ethernet connection with a software API. This is extremely valuable when the IE standard is changed; only a minimum amount or even no changes will be required to run the application. This saves time and effort when multiple Ethernet standards are required in the design that could address several products. The software API communicates through a dual-port RAM, a serial I/O, or a parallel I/O. The application software can be run on either an internal embedded processor in the FPGA or on an external processor.
Industrial Ethernet Ecosystem
Specifications for the Industrial Ethernet standards can be obtained and IP licenses acquired from the various standards bodies (refer to [http://www.end-markets/industrial/trade-associations/ind-trade-associations.html](http://www.end-markets/industrial/trade-associations/ind-trade-associations.html) for a complete list). Altera has partnered with industry leaders such as IXXAT, Softing, Beckhoff, Automata, and other partners to provide a wide breadth of Industrial Ethernet solutions based on Cyclone series products such as the Cyclone III and Cyclone IV E. Altera and our partners also offer IE board solutions available for purchase (see Figure 4), IP for licensing, and design services to integrate or bridge Industrial Ethernet functionality into your products.

![Image of various Industrial Ethernet solutions](image)

**Figure 4. Industrial Ethernet Partner Ecosystem**

**IXXAT** offer their Industrial Ethernet Module (IEM) that supports multiple open IE protocols based on Altera FPGAs. The IEM solution is ideal for quickly adding IE to an industrial product or bridging fieldbus based products to any open IE standard such as EtherCAT, EtherNet/IP, Ethernet Powerlink, Modbus/TCP, PROFINET, and SERCOS III. If you are designing your own board, IXXAT can advise on the board layout and offer IP licenses along with the protocol stack software and application interface. Whether you use the IEM or design your own board, both approaches offer the flexibility to support multiple IE protocols on the same hardware platform through the Nios II embedded processor and reconfiguration of the Cyclone series FPGA.

The solution from **Softing** consists of their Real-Time Ethernet Module (RTEM) with software support for multiple IE protocols such as PROFINET, EtherCAT, EtherNet/IP, and Modbus/TCP on the same flexible and reconfigurable FPGA-based module. The RTEM serves as a piggyback (black box) solution to add IE capability to industrial products or bridge fieldbus products to the IE environment. If designing your own FPGA-based platform, the protocol-specific MAC IP (if any), protocol stack software, and application interface can be licensed from Softing. Again, both
design methods offer the flexibility to support multiple IE protocols on the same hardware platform through the onboard embedded processor and reconfiguration of the Cyclone series FPGA.

If you require only the EtherCAT Industrial Ethernet protocol, join the EtherCAT Technology Group (ETG) to gain access to the EtherCAT specification and ability to license the EtherCAT slave IP and software from Beckhoff to start your development. The ETG also markets an EtherCAT evaluation kit that can be used to evaluate or prototype EtherCAT implementations on FPGAs such as the Cyclone series. The IP can be delivered as a pre-built FPGA configuration or a configurable IP component that can be easily integrated within your own FPGA design. Alternatively, you might want to work with a systems integrator like IXXAT or Softing who can implement your EtherCAT solution for you.

SERCOS III features a deterministic real-time, high-performance communications interface over Ethernet between motion controls, digital servo drives, and input/output (I/O) devices. The SERCOS III protocol standard requires a custom MAC to achieve high performance and maintain compatibility with SERCOS I/II. Automata has demonstrated the SERCOS III protocol on an Altera Cyclone series development board.

**FPGA Design and Software Tools**

Quartus II is Altera’s design environment for creating FPGA systems. It includes a graphical system design tool called SOPC (System on a Programmable Chip) Builder that enables the designer to quickly create and edit IP based systems. The user-friendliness and flexibility of this design software and built-in tool are an integral part of the advantages of deploying FPGA-based solutions.

The design tool automates the delivery, configuration, and integration of IP modules, with operations through a windows-style graphical development environment - a complete custom CPU system can be created without seeing a single line of HDL code. This eliminates the time-consuming process of manual coding and allows designers to focus on optimizing their solution. Figure 5 is a screen shot of the SOPC Builder tool; in the left hand window there is a list of IP, or hardware modules. Compatible IP modules can be provided by Altera or many third party IP providers; however if a designer wants to integrate IP developed in house, the tool supports the import of HDL to create custom SOPC Builder-compatible IP modules.
When an IP module is clicked on, a configuration window opens and the component can be easily configured using the mouse and keyboard. Once complete the configuration window is closed and the component added to the system - the system being designed is shown in the right hand window pane. To design an IE system, a Nios II embedded processor, memory and appropriate MAC for the IE standard are needed, naturally other processor type IP modules like serial interfaces, parallel interfaces or even more complex interfaces like PCI and PCI Express can be easily added. It is also possible to create high performance processing pipelines using DSP and other IP that is available in the SOPC Builder IP Library.

Once all the desired IP has been added, including the IE components, all the selected components are be shown in the main window and automatically connected. In this window you can customize the component connections and change system properties like component base addresses, interrupt connections, and clocks. The individual component configurations and system properties can be easily edited at any time to create the ideal system for the application or create a modified system to support a new a feature or application.

Once the system design is complete, a click of the generate button will automatically create HDL for each of the components (in the correct configuration) and all interconnects between them to make a single system. This complex HDL system contains all the configured IP, connected in the way specified in the SOPC Builder GUI, however in the design software it appears as a single-integrated hardware module. The designer does not need to do anything else to use the system. SOPC Builder can also generate testbenches and simulation files.
Once the system appears as a module in the Quartus II environment it can be connected to other components or simply wired up to the external pins of the FPGA device – once this is done the design can be compiled to generate an FPGA configuration file, ready to download to the FPGA. If the SOPC system needs to be changed or upgraded, it is simply opened up in SOPC Builder again, make the changes and the system is re-generated.

**The Software Flow**

It is very easy to change the hardware and generate new configurations in an FPGA. For hardware designers, this means very little effort is required to continuously tweak the design and create an optimum system. However this hardware needs to be integrated into a software development process and keeping pace with a continuously and rapidly changing processor/hardware platform would normally be very challenging task for the software engineers. In many products more man hours are invested in developing software rather than hardware so software updates can be a lot of work and can take much longer to implement than changing the FPGA and soft processor configuration.

SOPC Builder generates a file that contains all of the hardware configuration information; this allows the Nios II software development environment to create a custom software build that creates a hardware-specific system support library. This library contains all of the device drivers the system requires and a hardware abstraction layer (HAL) that abstracts all application access to the hardware. If the hardware is changed, the software environment can re-build the system support library, when this is done the new hardware configuration is read into the software tools and the new library generated will support all of the changes made, including new components and changes to component settings, base addresses and interrupt connections. Thanks to the hardware abstraction provided by the system library, once the new library is built the application can be rebuilt and run on the new hardware. The automatic propagation of hardware changes into the software environment makes the integration of hardware design changes easier, faster and error free for both the hardware and software engineers.

**Summary**

Factory operations need to migrate to lower cost, higher performance, and easier managed networks. Industrial Ethernet is an emerging technology with high growth potential. Flexible FPGA-based solutions enable equipment manufacturers to overcome obstacles in migrating from legacy network interfaces to multiple versions of Industrial Ethernet using the same hardware platform. With an FPGA-based platform, all the advantages of performance, flexibility, interoperability are gained when designing reliable, cost-effective, multi-standard Ethernet applications for industrial products that stay in production for a long period of time. This is the factory of tomorrow.

**About the author**

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