A Flexible Solution for Industrial Ethernet

WP-01037-3.0 White Paper

This white paper describes the use of Altera® FPGAs to deliver a multistandard Industrial Ethernet capability from a single PCB implementation. The benefits of FPGA implementation are described and an overview of the FPGA development flow, tools, and technology used to create a universal but easy-to-maintain solution is given.

Introduction

Since its conception by Xerox in the mid-1970s and standardization as IEEE 802.3 in 1983, Ethernet has become the de facto standard for computer communication in the business world. Ethernet networks have evolved from coaxial cable-based systems delivering 3-Mbps performance to systems built from unshielded twisted pair (Cat5 UTP) cables that deliver high reliability, low cost, and 100-Mbps performance. With devices capable of 1-Gbps Ethernet already in the market and 10-Gbps on the horizon, the continuous evolution of Ethernet (see Table 1) will continue to service market requirements long into the future.

Table 1. Evolution of the Ethernet Standard

Year	Standard	Summary
1983	IEEE 802.3	Basic Ethernet standard
1985	IEEE 802.3a	10Base2 thin Ethernet standard
1990	IEEE 802.3i	10Base-T 10-Mbps Ethernet standard
1995	IEEE 802.3u	100Base-TX/T4/FX 100 Mbps (fast Ethernet)
1997	IEEE 802.3x	Full-duplex Ethernet standard
1998	IEEE 802.3y	100Base-T2 Fast Ethernet standard over UTP
1999	IEEE 802.3ab	1000Base-T 1 Gbps
2003	IEEE 802.3af	Power over Ethernet
2006	IEEE 802.3an	10GBase-T 10 Gbps

Factories want higher bandwidth (performance) and more easily managed networks using existing Ethernet equipment where possible to reduce the total cost of ownership. The range, availability, and ease of implementation of Ethernet, combined with the pressure to integrate the factory system with the corporate network, have driven industrial developers to create Industrial Ethernet-based networking solutions that are compatible with, or—in new or upgraded equipment—even replace, industrial fieldbus communication solutions.

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Many Ethernet-based industrial communication protocols exist today, each with its own individual pros and cons. Some of these protocols, including the popular PROFINET, EtherNet/IP, and EtherCAT protocols, have been standardized as “open” protocol standards so any developer can create an implementation of that protocol. These open protocols tend to be more popular and used more widely across the industry.

Some solutions simply bundle fieldbus or application data into standard Ethernet packets and require nothing more than a standard Ethernet TCP/IP implementation. This implementation lacks the real-time performance and determinism that is required of many industrial networks today. All industrial Ethernet protocols require additional custom software, and most of the higher performance protocols require custom hardware as well. This combination of protocol-specific hardware and software makes it difficult for developers to maintain a solution that supports multiple protocols.

Not only are there many Ethernet protocols in existence, but these protocol standards continue to evolve, leveraging changes in the base Ethernet standard and improvements in technology. In order to compete, industrial equipment manufacturers must find a cost-effective way to support as many Industrial Ethernet protocols as possible and be able to quickly adopt protocol changes, support new protocols, and incorporate other system improvements.

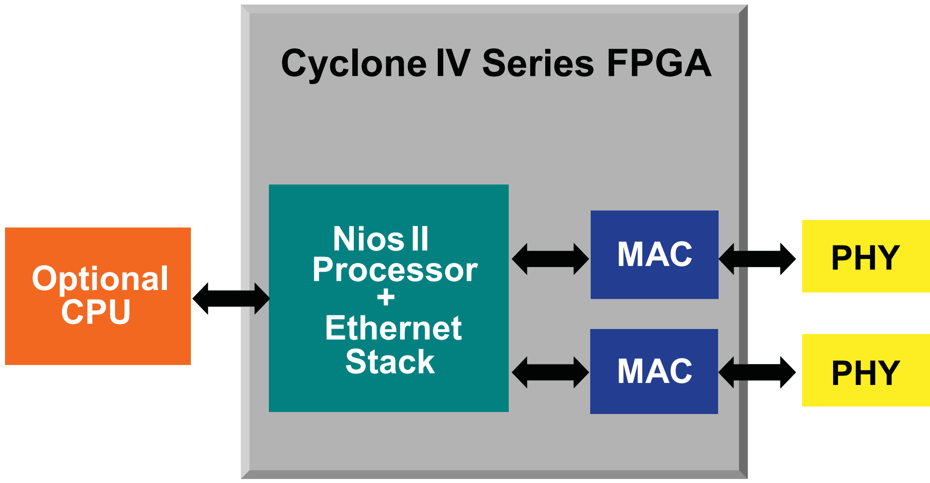
Implementing a Universal Industrial Ethernet Solution

Engineering a solution to support many protocols is clearly possible—all that is needed is a series of plug-in boards, one for each protocol. But with the number of standards on the market and their constant evolution, how can a multiboard solution be cost effective while supporting new features and additional protocols in a timely manner? Where standard Ethernet hardware is used, protocol-specific software must be developed or ported to run on the chosen processor device, and this takes time. Furthermore, with these ever-increasing product requirements, it is only a matter of time before the selected CPU runs out of processing power to run the application and the protocol standard concurrently.

Historically, ASICs and ASSPs provided a fixed solution for Industrial Ethernet communication. However, these devices may need to be changed when the protocol is revised and customers want to leverage the features or guarantee compatibility with the updated standard. When the Ethernet protocol is upgraded, it takes time to develop new ASICs and ASSPs, then new PCBs must be developed, bringing all the costs and delays involved with developing new hardware. Multiple boards may be required to support both legacy and new versions of the protocol. The reliance on ASICs and ASSPs can also bring supply issues and, with rapidly changing protocol standards and life cycles in excess of 10 to 15 years for industrial systems, potential obsolescence of the devices is a real problem. These types of multiboard solutions are likely to be expensive, difficult to support, and slow to deliver new features.

An alternative solution is to address these problems by using an FPGA to implement the networking solutions (see Figure 1). One of the key benefits of FPGAs is their flexibility. A designer can build one PCB and program (reconfigure) the hardware to work with any Industrial Ethernet protocol at any time. If a different protocol is required, or if the customer changes their order before the product ships, or even if the product is already in the field, it takes only seconds to reprogram the FPGA with the required configuration file. This type of multistandard solution greatly reduces development costs and minimizes inventory and supply chain issues. Creating a new configuration file for the FPGA may require the development of new software or hardware, but with Altera's Quartus® II development tools and off-the-shelf intellectual property (IP) from Altera's partners, developers can accomplish these updates with a few weeks of development time or less.

Figure 1. Generic FPGA-Based, 2-Channel Industrial Ethernet System



When combined with an Ethernet transceiver (known as a PHY), the FPGA can perform all of the functions required by the Ethernet interface. The PHY and board electronics deal with the physical (Layer 1) interface, and the (Layer 2) media access controller (MAC) hardware functions are configured as programmable logic to run in the FPGA. Higher level functions (Layer 3 and up) are implemented in software running on a processor core (such as the Nios® II embedded processor) configured into the FPGA logic. Implementing a communication channel between an existing application processor and the FPGA is also feasible because of the programmable nature of the FPGA logic, the multistandard support of the I/O pins, and the availability of a wide range of off-the-shelf interface IP. Usually, an existing interface in the processor device (e.g., I^2C, SPI, or some local parallel I/O bus) or on the system (e.g., PCI®, PCI Express® (PCIe®), CANopen, etc.) can be used to communicate with the FPGA. This approach offers the advantage of requiring minimal computing time and changes to the application software running on the existing processor. This FPGA-based approach preserves the status of the system software and brings additional processing resources to deliver a high-performance implementation of the Industrial Ethernet stack processing.

Because the FPGA hardware is reconfigurable, designers can create a system that contains two or more soft microprocessor cores, enabling integration of the application processing into the FPGA. Benefits of this type of system integration can include reductions in component count, cost, and power consumption. In addition, an FPGA IP-based design is protected against obsolescence due to the long device lifetime of the FPGA and the ability to migrate easily to newer generations of FPGAs. Devices such as Altera's Cyclone® IV family also provide the opportunity to accelerate system performance by implementing computationally intense functions as

FPGA hardware instead of software, thus delivering a more efficient implementation and bringing the benefits of higher performance, lower clock speed, and lower power consumption. For Industrial Ethernet, the FPGA hardware design can also include a hub, switch, or similar hardware that accelerates the Ethernet communication or implements special features like ring redundancy.

Not only does an FPGA allow the off-loading of application tasks to an embedded processor or hardware (e.g., DSP blocks) implemented in FPGA logic, the flexibility of the FPGA also allows the implementation of new interfaces in the system, including simple communication interfaces (e.g., UARTs, parallel I/O, PWM, etc.), more complex features like support for new memory standards (e.g., DDR2/3, etc.), and the latest communication technologies (e.g., Bluetooth, Gigabit Ethernet, PCIe, etc.).

Building a FPGA-Based Hardware Design

Although creating a processor and Ethernet MAC hardware design sounds difficult, it is a relatively straightforward task due to a tool called SOPC Builder and the availability of pre-built processor and Ethernet MAC IP components. As shown in Figure 2, SOPC Builder is integrated within the Quartus II development environment and is designed specifically to support the easy creation of IP-based system-on-a-programmable-chip (SOPC) designs. The developer designs a system using a graphical user interface (GUI) instead of coding HDL, and SOPC Builder accelerates and automates the configuration, integration and generation of IP-based systems.

Figure 2. Embedded Development Flow

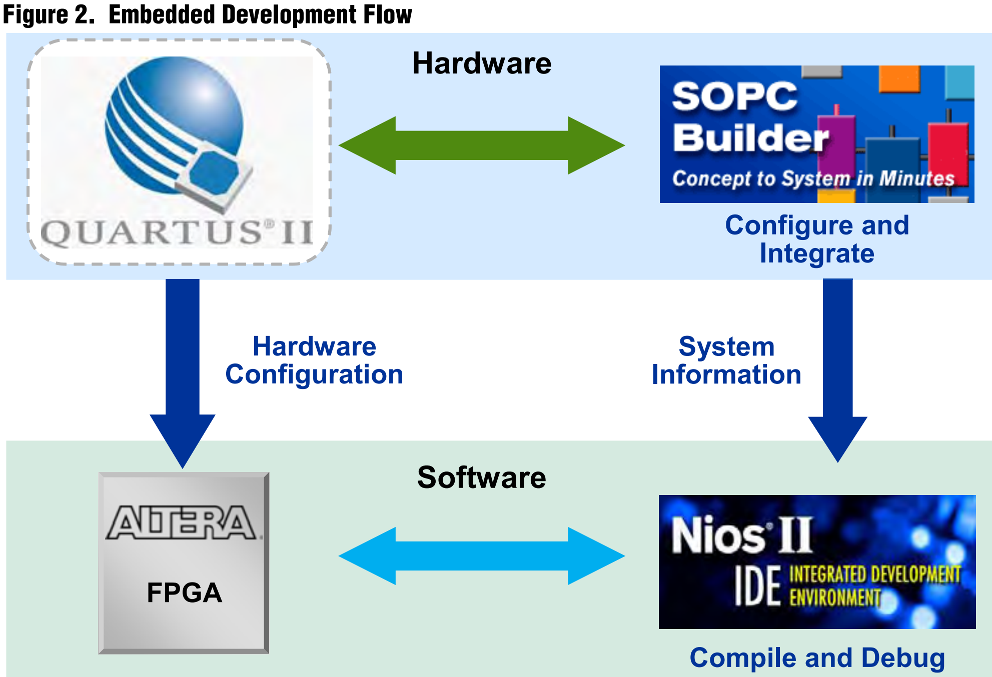
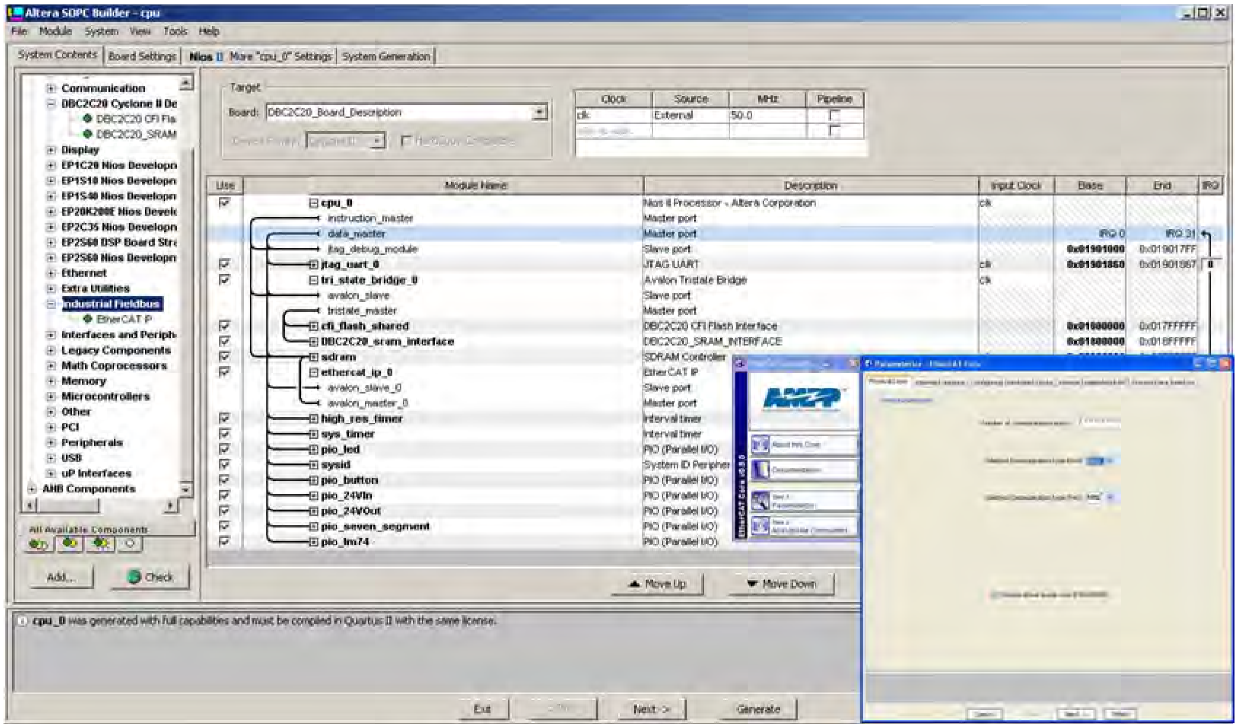


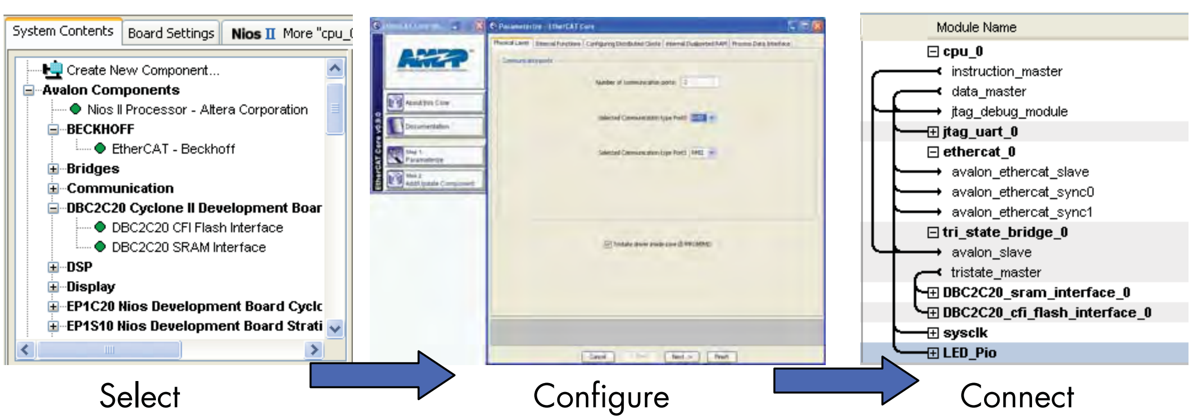
Figure 3 shows a screen shot of the SOPC Builder GUI with a list of the available IP in the left pane. To add an IP component to the current system, all the designer has to do is double-click on the IP module required.

Figure 3. Screen Shot of the SOPC Builder Tool



For each selected IP module, a configuration wizard appears that allows the selection of appropriate options (Figure 3, right). Once this selection is complete, the configured IP component will appear in the current system design in the pane on the right. The component base address or interrupt levels can then be changed, and the interconnect architecture of the system can be modified using the GUI to change the connections between the IP components. This process (illustrated in Figure 4) allows the quick design of modular and highly optimized systems. Design errors are flagged in the bottom window so the designer can easily identify and fix problems like address conflicts or incorrect component connections.

Figure 4. Using Hardware IP with SOPC Builder to Create an Industrial Ethernet-Capable System



Once the system design is complete, the designer clicks on the **Generate** button and the SOPC Builder tool generates all of the HDL required to build a working system. As the IP is pre-built and tested by the vendor, and as the system interconnect is machine-generated, the design is correct by construction and requires minimal effort to implement. Once the system is generated, it appears as a design block in the Quartus II schematic editor. Then hardware synthesis, a single-button operation for most SOPC Builder-generated systems, creates a configuration file that can be downloaded into the FPGA.

If, later on, a new or modified design is needed, the designer just opens the SOPC Builder tool, modifies the design through the GUI, regenerates the system, and resynthesizes it with the Quartus II software to create another configuration file. This means a hardware design for a new Industrial Ethernet protocol can be created by purchasing the hardware IP required and dropping it into the existing system design and regenerating. One click to resynthesize, and within a short time the new hardware configuration file is ready.

Running Software Protocols on the Nios II Processor

In embedded systems that include Ethernet support, the processor provides the higher layer functions (e.g., TCP, UDP, etc.). Altera's royalty-free, 32-bit RISC Nios II embedded processors come in three binary compatible variants, each optimized for different ratios of size and performance: the Nios II/f processor for high performance, the Nios II/e processor for minimum size, and the Nios II/s processor for a balance of size and performance. More details are shown in Table 2.

Table 2. Nios II Processor Clock Speed, Performance, and Logic Consumption

Processor	Cyclone III FPGAs			Stratix IV FPGAs		
	Clock Speed (MHz)	DMIPS	LEs	Clock Speed (MHz)	DMIPS	LEs
Nios II /f	175	195	1,800	290	340	1,020
Nios II /s	145	90	1,300	250	150	850
Nios II /e	215	30	650	340	48	520

Because the Nios II processor is delivered as an SOPC Builder IP component, it is easy to create processor-based systems that include Ethernet MAC IP, a range of other peripheral components, or even multiple Nios II processors. With the SOPC Builder GUI, it is easy and quick to build a Nios II processor system that meets the designer's exact requirements, and even to create different versions for different applications.

The SOPC Builder-ready Nios II processor is also compatible with both the free and the evaluation IP that is delivered with the Quartus II software. This IP includes modules for standard processor peripheral functionality (e.g., UART, PIO, memory controllers, etc.), as well as a wider range of licensable IP components available from Altera and Altera partners (e.g., Ethernet MACs, CAN, USB, PCI, PCIe, FFT, FIR, DSP, video processing cores, a selection of Industrial Ethernet IP, etc.). Where appropriate, these components come with a Nios II driver that is automatically integrated into the software build system by the powerful Nios II software development environment. This environment supports development in C and assembler, and is familiar to many developers because it is based on the well-known Eclipse and GNU operating systems.

Industrial Ethernet Hardware and Software IP

Today there are commercially available IP packages for many Industrial Ethernet protocols, some of which are shown in Table 3. Hardware IP is usually packaged as a SOPC Builder component that contains the MAC and any additional logic required by the protocol. Software IP is delivered as a library or software API written in C for the Nios II processor. Some vendors market pre-built FPGA configurations and board designs, enabling designers to use the FPGA as easily as an off-the-shelf ASIC or ASSP. It is even possible to purchase ready-made and tested board modules to add directly onto an existing product, effectively adding the programmability of the FPGA without the effort of creating a configuration file or designing the PCB to carry the device.

Table 3. Industrial Ethernet Protocol FPGA IP Vendors

Protocol	Vendor (1)	Approximate Cycle Time
Modbus TCP	IXXAT, Softing	200 ms–10 ms+
EtherNet/IP	IXXAT, Softing	200 ms–10 ms+
PROFINET RT (PROFINET IO)	IXXAT, Softing, ZHAW (Zürcher Hochschule für Angewandte Wissenschaften)	10 ms–1 ms+
ETHERNET Powerlink	IXXAT	<1 ms
SERCOS III	SERCOS International, Automata GmbH, IXXAT	<1 ms
VARAN	Sigmatek GmbH	<1 ms
EtherCAT	Beckhoff (hardware IP), Softing (software stack), IXXAT (software stack)	<1 ms
IEEE 1588	IXXAT, MoreThanIP	-

Note:

(1) Please verify availability with vendors as products are subject to change.

For further information on these Industrial Ethernet Protocol FPGA IP vendors, see Altera's Industrial Networking Partner Program (INPP). Each of these vendors has proven expertise in the field, robust IP solutions, and product evaluation packages that all work on the Industrial Networking Kit (INK) from Terasic. This means that with one board, a designer can easily evaluate different vendors and start development on the same board, even when using IP products from multiple vendors.

Although IEEE 1588 is not an Ethernet protocol standard, this packet time-stamping IP is often associated with Industrial Ethernet to improve determinism. Thus, the vendors for this IP have been included in Table 3. FPGAs are very flexible and can support many interface protocols and standards. For example, IP for industrial fieldbus standards such as SERCOS II, PROFIBUS, Interbus-S, CAN, and others can be found ready for implementation in FPGAs. Thanks to the flexibility and increasing cost effectiveness of FPGAs, the number of supported industrial communications standards continues to grow.

FPGA Family Overview

The low-cost Cyclone III and Cyclone IV FPGAs are the best devices for Industrial Ethernet applications as these FPGA families have been designed for high-volume, cost-sensitive, low power applications and are available as industrial grade devices. These families consist of devices that range from 5K to 120K logic elements (LEs) and from 82 to 531 user I/O pins across many different device packages. Cyclone series FPGAs also offer up to 4 Mb of embedded memory, 288 embedded 18-bit x 18-bit multipliers, dedicated external memory interface circuitry, phase-locked loops (PLLs), and high-speed differential I/O capabilities. With 6,272 LEs, even the smallest Cyclone IV E device (EP4C6F17) easily holds a Nios II processor with some additional IP components, and can support a basic Ethernet connection. For customers who need higher performance, Altera offers the low-cost Arria® II GX FPGA family (with built-in high-speed transceivers and PCIe cores), the high-performance Stratix® IV FPGA family, and its pin-compatible HardCopy® ASIC family.

Getting Started

To evaluate the Industrial Ethernet solution that best suits a system’s requirements, the first thing a designer will need is a development kit such as the new Cyclone IV E Industrial Networking Kit (INK) shown in Figure 5.

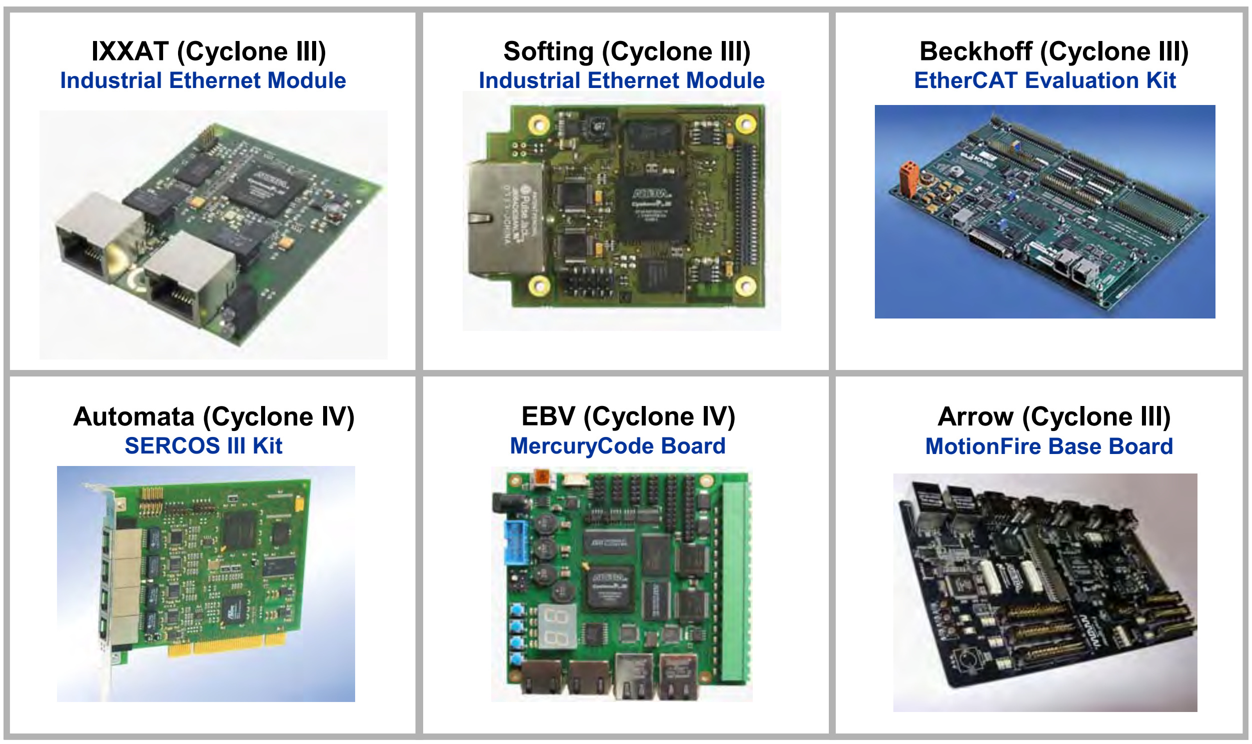
Figure 5. The Cyclone IV E INK

The INK has features such as dual 10/100/1000-Mbps Ethernet ports, 128-MB SDRAM, 8-MB flash memory, 2-MB SRAM and security EEPROM that make it ideal for developing Industrial Ethernet solutions. It also carries HSMC and GPIO expansion connectors that allow the board to support additional interfaces and applications. Included in the kits is a HSMC expansion board that supports dual CAN, dual RS-485, RS-232, and dual PROFIBUS interfaces to support a wide range of fieldbus communication standards. Other applications that the board can support include motor/motion control, video surveillance, and machine vision.

The INK is used by all of Altera's INPP members as an evaluation and development platform. The designer can use the INK to evaluate IP for multiple standards and multiple vendors on the same board, then use the same board for prototyping and product development.

Networking solutions providers such as Softing, Beckhoff, Automata, and IXXAT offer a wide breadth of Industrial Ethernet support on Cyclone III and Cyclone IV E FPGAs. Table 3 shows the Industrial Ethernet protocol standards supported by each partner. While the INK is used to support Cyclone IV designs, Altera partners also support a variety of Altera-based FPGA solutions, as illustrated in Figure 6.

Figure 6. Partner Industrial Ethernet Solutions



Softing offers the Real-Time Ethernet Module (RTEM), which targets PROFINET (IO), EtherCAT, and Modbus/TCP on the same Cyclone III FPGA platform. This module integrates "as is" directly into an existing product with minimal changes, and communicates with the product's main board via serial I/O, parallel I/O, or any similar proprietary interface. For systems with an Altera FPGA designed into the main PCB, Softing offers licenses for IP cores, protocol stack software, application interfaces, and any additional design services required.

With their Industrial Ethernet Module (IEM), IXXAT supports Ethernet Powerlink, EtherNet/IP, SERCOS III, EtherCAT, and Modbus TCP. The IEM is easily integrated with products to deliver a quick and easy drop-in Industrial Ethernet solution. IXXAT also provides hardware services and solutions to quickly integrate the IEM into an existing product so it can quickly support the required Industrial Ethernet standards. In addition, IXXAT licenses IP cores, protocol stack software, and application interfaces for developers who want to develop their own FPGA boards.

The SERCOS I/II networking standard has been around for many years but only the latest version, SERCOS III, is Ethernet based. SERCOS III upgrades the features of SERCOS I/II with a deterministic real-time, high-performance communications interface over Ethernet between motion controls, digital servo drives, and I/O devices. If the design requires the SERCOS III protocol, Automata offers software stacks, development boards, and design services.

The MotionFire (Motor Control) Development Kit from Arrow Electronics provides a versatile global platform for evaluation and development of both motor-control and Industrial Ethernet applications on the same board. The kit consists of a FireFighter Cyclone III FPGA-based board and a FireDriver power board that drive two BLDC motors (scalable up to 6 FireDriver boards). With open-source motor-control IP from Unjo AB and Industrial Ethernet IP from Softing, MotionFire delivers the means to evaluate motor-control applications across multiple Industrial Ethernet protocols. Ethernet protocols and motor-control IP from other vendors can also be ported to this platform.

If the design requires the EtherCAT Industrial Ethernet protocol, then the EtherCAT specification, slave IP license, and software license can be obtained from the EtherCAT Technology Group (ETG). Alternatively, systems integrators such as IXXAT and Softing can implement the EtherCAT solution for the design. The ETG also markets a Beckhoff evaluation kit that can be used to evaluate or prototype EtherCAT implementations on the Altera Cyclone III FPGA.

The MercuryCode (DBC4CE55) development kit from EBV (Europe only) is another comprehensive solution for implementing protocol-independent Industrial Ethernet systems. The board has two RJ-45 Ethernet sockets, each driven by an Ethernet PHY connected to the FPGA. With this board, all a designer needs to implement any Industrial Ethernet standard is the upper-layer software, the Layer-2 hardware IP (or MAC IP), and the Nios II processor. Reference designs for many Industrial Ethernet protocols have been proven on the MercuryCode board (or its predecessor, the DBC3C40 board) and are available today. The board also carries transceivers for CAN, USB, UART, and LVDS interfaces for high-speed communication or for driving LCD displays.

Summary

Ethernet technology for the industrial market brings many benefits and is expected to show strong growth over the next five years. There are many Industrial Ethernet protocol solutions available, each with their own particular set of advantages. What is clear is that Ethernet technology will continue to advance, driving the evolution of both new and current Industrial Ethernet solutions. Technologies like 1-Gbps and

10-Gbps Ethernet and real-time improvements to the current IEEE 802.3 standard will deliver higher performance and better reliability. In addition, the focus on other industrial areas such as security, redundancy, and safety protocols will undoubtedly continue to drive change in Industrial Ethernet standards, providing a constant challenge to industrial equipment manufacturers.

The advent of low-cost devices such as Cyclone IV FPGAs and embedded processor IP such as Nios II processors has enabled cost-effective programmable solutions for Industrial Ethernet. FPGAs deliver the ability to support any Ethernet-based industrial communication protocol from the same base hardware as well as the benefits of system integration, flexibility, and obsolescence protection that come with programmable logic devices. The combination of reconfigurable hardware, SOPC Builder, and the Nios II processor enables developers to easily modify both the upper and lower layers of the Ethernet protocol without changing the physical hardware. As existing protocols evolve and augment or supplant legacy fieldbus implementations, and new protocols emerge, it is increasingly important to have a flexible, cost-effective platform solution that can support any Industrial Ethernet protocol standard. Implementing Industrial Ethernet in FPGAs has become necessary for all industrial equipment manufacturers to help lower their total cost of ownership.

Further Information

- Industrial Market:
www.altera.com/industrial
- Nios II Processor: The World's Most Versatile Embedded Processor
www.altera.com/nios
- Cyclone III FPGAs: Unlimited Possibilities:
www.altera.com/cyclone3
- Cyclone IV FPGAs: Lowest Cost, Lowest Power, Integrated Transceivers:
www.altera.com/cyclone4
- Embedded Processing:
www.altera.com/embedded

Industrial Ethernet Products

- Industrial Networking Partner Program:
www.altera.com/b/industrial-networking-partner-program.html
- Industrial Networking Kit:
www.altera.com/end-markets/industrial/automation/ethernet/protocols/ind-networking-kit.html
- EtherNet/IP, PROFINET RT, ETHERNET Powerlink, Modbus-TCP, EtherCAT, and IEEE 1588 stack:
http://ixxat.com/altera_cooperation_en.html
- EtherNet/IP, PROFINET RT, Modbus-IDA, and EtherCAT:
www.softing.com/home/en/industrial-automation/products/real-time-ethernet/altera-industrial-networking-kit.php
- EtherCAT:
www.beckhoff.com/english/ethercat/et1810_et1811.htm
- SERCOS III:
www.automataweb.com/ALTERA_INK_EN
- PROFINET IRT, easyIRT:
www.ines.zhaw.ch
- MercuryCode (or DBC4CE55) board and reference designs:
  - Europe: www.ebv.com
  - Rest of World: www.devboards.de
- MotionFire:
www.arrownac.com/mktg/motionfire
- openPOWERLINK:
http://sourceforge.net/projects/openpowerlink
- VARAN:
www.sigmatek.at

Industrial Ethernet Organizations

- CC-Link Partner Association (CLPA):
  www.cc-link.org
- EtherCAT Technology Group:
  www.ethercat.org
- ETHERNET Powerlink Standardization Group (EPSG):
  www.ethernet-powerlink.org
- Fieldbus Foundation:
  www.fieldbus.org
- Modbus:
  www.modbus-ida.org
- ODVA for Ethernet/IP:
  www.odva.org
- PROFIBUS and PROFINET:
  www.profinet.com
- Safety Network International e.V.:
  www.safetybus.de
- SERCOS interface:
  www.sercos.org
- SynqNet:
  www.synqnet.org
- VARAN Bus User Organization:
  www.varan-bus.net

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- Prof. Hans Doran, ZHAW InES

Document Revision History

Table 4 shows the revision history for this document.

Table 4. Document Revision History

Date	Version	Changes
November 2010	3.0	■ Minor text edits ■ Updates to Introduction, Implementing a Universal Industrial Ethernet Solution, Industrial Ethernet Hardware and Software IP, FPGA Family Overview, and Getting Started sections. ■ Updates to Figure 1, Table 3, and Figure 6. ■ Added Figure 5.
July 2009	2.0	Minor text edits.
November 2008	1.1	Minor text edits.
October 2007	1.0	Initial release.