WHITE PAPER

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EtherCAT® on Sitara™ AM335x ARM® Cortex™-A8 Microprocessors

Executive summary

EtherCAT is among the leading communications standards based on Ethernet that is used increasingly for networking and communications in the industrial or factory environment. The EtherCAT communication technology was invented by Beckhoff Automation in Germany and later standardized by the EtherCAT Technology Group (ETG).

Texas Instruments, Inc. (TI) is world's first semiconductor company to license EtherCAT technology and integrate it into the Sitara AM335x ARM generation of ARM Cortex-A8-based microprocessors (MPUs). To enable EtherCAT, TI has built upon its programmable real-time unit (PRU)-based programmable technology to create a unified front-end for industrial communications and bring EtherCAT and other industrial standards to its growing platform of ARM-based microprocessors. This integration enables best-in-class functionality at ultra-low power and significantly lower cost. The AM335x ARM MPU-based implementation meets or exceeds all required features and performance benchmarks for EtherCAT, including key features such as distributed clocking and end-to-end latency of less than 700ns.

TI has also brought the software, hardware and tools together to streamline the development of EtherCAT-based products with AM335x ARM MPU devices. Additionally, the industrial grade temperature support and long-term supply guarantee make the AM335x ARM MPU generation a compelling choice for EtherCAT and other industrial networking applications.

Introduction to EtherCAT

Overview

EtherCAT (Ethernet for Control Automation Technology) is an emerging real-time industrial Ethernet standard for industrial automation applications, such as input/output (I/O) devices, sensors and programmable logic controllers (PLCs). It was originally developed by Beckhoff Automation GmbH but is now overseen by the EtherCAT Technology Group that was set up to help with proliferation of the EtherCAT standard. Today, there are over 1,900 member companies from 52 countries that create and deploy EtherCAT-compatible products.

Ethernet has seen unparalleled adoption in diverse applications, but in industrial environments, it is still not efficient enough for small amounts of data exchange, it has low determinism for real-time operation, and it works with only star topology in which the network nodes much be connected through switches. EtherCAT technology adds certain features on Ethernet and enforces certain configurations to make it a very efficient network technology for automation while fully conforming to the Ethernet specifications.

The design of EtherCAT enables any standard PC to be used as an EtherCAT master and communicate with EtherCAT slaves, which are specialized devices compliant with the EtherCAT specification. Together, the master and slave EtherCAT devices can be used in all devices in the factory network – automation controllers, operator interfaces, remote input/output units, sensors, actuators, drives and others.

Technology

EtherCAT improves upon traditional Ethernet by implementing "on-the-fly" processing where the nodes in the EtherCAT network read the data from a frame as it passes through. All EtherCAT frames originate from the EtherCAT master which sends commands and data to the slaves. Any data to be sent back to master is written by the slave into the frame as it passes

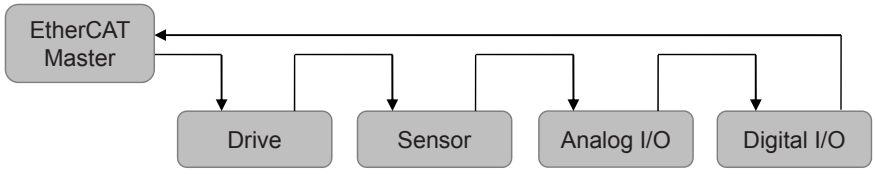

Figure 1. Example EtherCAT network

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through. This helps eliminate the need for point-to-point exchange of small-sized frames between master and individual slaves and drastically improves the efficiency of communication. However, it also means that each slave must have two Ethernet ports and be able to let the frame pass through while reading from or writing to the passing frame and therefore, specialized hardware is required in the slave devices. As a result of these improvements, the usable bandwidth in a 100-Mbps network running EtherCAT® is more than 90 percent as compared to less than 5 percent for networks where the master must separately communicate with each slave node.

EtherCAT telegram

As illustrated in Figure 2, the EtherCAT telegram is encapsulated in an Ethernet frame and includes one or more EtherCAT datagrams destined to the EtherCAT slaves. Such Ethernet frames use the EtherCAT type in the header or they can be packed with the IP/UDP header. When the IP header is used, the EtherCAT protocol can also be used across network routers.

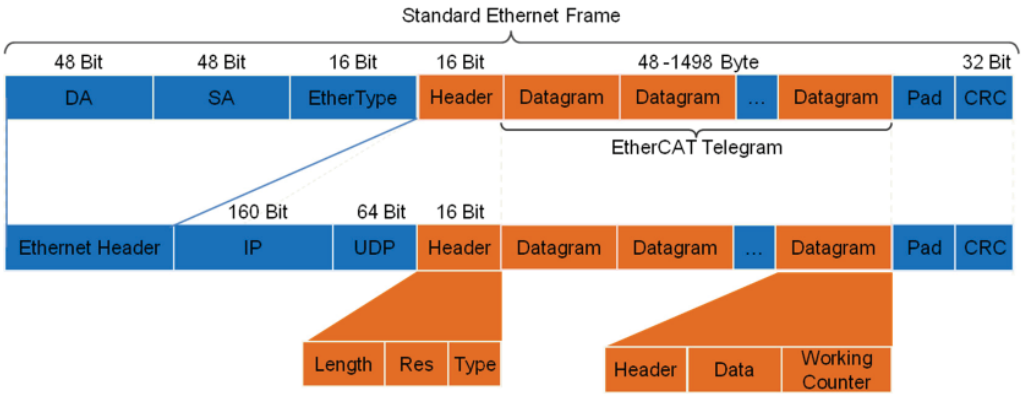

Figure 2. EtherCAT telegram

Each EtherCAT datagram is a command that consists of a header, data and a working counter. The header and data are used to specify the operation that the slave must perform, and the working counter is updated by the slave to let the master to know that a slave has processed the command.

Protocol

Each slave processes EtherCAT packets "on-the-fly" in that it receives the frame, parses it and takes action if the address specified in an EtherCAT datagram matches its own address, and forwards the entire datagram from its second port while also updating the contents and the CRC of the packet. Through the datagrams, the EtherCAT master addresses the entire address space of up to 4 GB in which up to 65,536 EtherCAT slaves, each with 65,536 addresses, can be located. The EtherCAT datagrams do not have any restriction on the order in which the slaves are addressed with respect to the actual position of slave nodes in the network.

There are different types of EtherCAT data transmissions – cyclic and acyclic. Cyclic data are the process data that are transferred at periodic intervals or cycle times. Acyclic data is usually non-time-critical data that

can be large in size and usually exchanged in response to a controller command. Some acyclic data, such as diagnostic data, can be critical and have demanding timing requirements. EtherCAT® handles these different data transmission requirements through optimized addressing schemes – physical addressing, logical addressing, multiple addressing and broadcast addressing.

To handle various addressing schemes, each slave has a fieldbus memory management unit (FMMU). The FMMU units in each slave enable the EtherCAT protocol to treat various slave devices as part of a 4 GB large memory space with slave spaces mapped in it. The EtherCAT master assembles a complete process image during the initialization phase and then makes even bit-level accesses to slave devices via a single EtherCAT command. This capability makes it possible to communicate practically with any number of input/output (I/O) channels across large and small devices spanning the entire fieldbus network via a standard Ethernet controller and standard Ethernet cable.

Performance

As a result of hardware-based FMMU and on-the-fly processing, the EtherCAT network performs at very high levels of efficiency. It enables cycle times of the order of microseconds to communicate from controllers to field devices. The communication efficiency is no longer a bottleneck in industrial networks and brings it in line with the computation speeds of contemporary industrial PCs. For instance, the increased performance makes it possible to run the current loop, in addition to the position loop, for distributed drives over EtherCAT.

Topology

The EtherCAT standard supports any topology – line, star or tree – and the bus structures common in fieldbus networks can also be realized with EtherCAT. Since the EtherCAT interface is present on I/O devices, there is no requirement for any Ethernet switching hardware. With the 100m range of copper links and even longer with optical links, EtherCAT can span over thousands of devices spread across a large geographical area. For short distances, such as on back-plane, EtherCAT uses E-bus, a differential signaling technology.

Distributed clocking

To realize simultaneous actions in industrial nodes installed away from each other, it is necessary to synchronize their internal clocks. EtherCAT accomplishes this by sampling the timestamps for the ingress and egress of an EtherCAT packet on every slave node as it traverses the network. The master uses the timestamp information provided by the slaves to accurately calculate the propagation delay for each individual slave. The clocks in each slave node are adjusted based on this calculation and thus, these clocks are synchronized to within 1µs of each other. An additional advantage of the accurately synchronized clocks is that any measurements taken can be linked to the synchronized time and remove the uncertainty associated with the jitter in the communication between devices.

Device profiles

In industrial automation, use of device profiles is a very common method to describe the functionality and parameters of the devices. EtherCAT® provides interfaces to existing device profiles so that legacy fieldbus devices can be easily upgraded to use EtherCAT. Some of such interfaces are CAN application layer over EtherCAT (CoE) and Servo drive profile over EtherCAT (SoE) that enable use of CANOpen® and SERCOS® by taking advantage of the mapping of their data structures to EtherCAT.

Components of an EtherCAT node

Each EtherCAT node has three components – the physical layer, the data link layer and an application layer as shown in Figure 3.

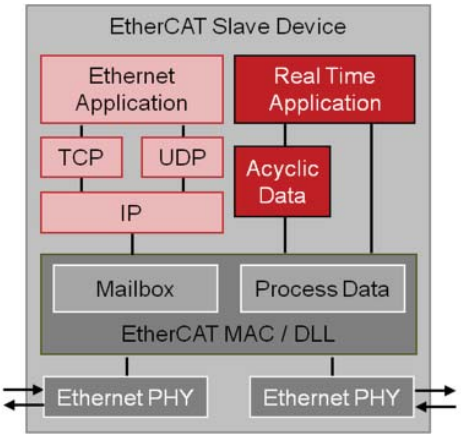

Figure 3. Components of an EtherCAT node

The physical layer is implemented using 100BASE-TX copper, 100BASE-FX optical fiber or E-bus based on LVDS signaling. The MAC is implemented either in a specialized ASIC or an FPGA as per the EtherCAT standard specifications. Beyond the MAC is the industrial application that takes care of application-specific behavior and a standard TCP/IP and UDP/IP stack to support Ethernet-based device profiles. Depending on the complexity of the device, the EtherCAT node can be implemented in hardware or it could be a combination of hardware and software running in an embedded CPU.

Compliance

To ensure broad interoperability among devices designed with EtherCAT interfaces, the EtherCAT Technology Group (ETG) has several programs for ensuring compliance with the technical specifications. These programs include the Conformance Test Tool (CTT), which is a software program for testing compliance; the plug-fests where members can meet and test against one another's devices; and certification labs in Germany and Japan where formal certification tests are performed. To meet minimum conformance requirements a device has to pass the protocol test using the Conformance Test Tool at the time of its first release to the market. Optionally, vendors can choose to get their products certified in any of the authorized certification labs. The ETG website provides detailed information on procedure and location of certification labs.

Typical EtherCAT® node

A typical EtherCAT node that is in use today has architecture similar to one of the illustrations below.

Figure 4. Basic Digital I/O EtherCAT device

Many of the simple EtherCAT devices such as Digital I/O can be created using single FPGA or ASIC solutions available today. A simplified version of such architecture is shown in Figure 4. Such architecture is well suited for cost-sensitive simple I/O nodes that do not require software and all functionality is implemented in hardware.

Figure 5. EtherCAT with ASIC and external processor

In the EtherCAT nodes where additional processing power is needed, an external processor, often with on-chip flash memory, is connected to the EtherCAT ASIC/FPGA for handling the application-level processing. Such devices could be sensor applications, for instance, where the processor is required to operate the sensor, implement the device driver and run the EtherCAT protocol stack. The cost of such architecture is higher than that for simple digital I/O devices and it comes with the flexibility that developers can select a processor that suits their needs and cost targets.

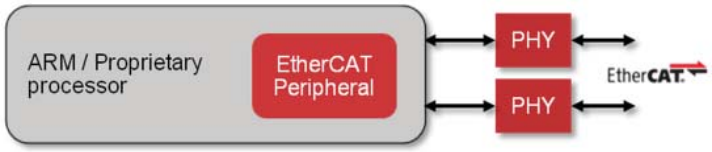

Figure 6. Integrated EtherCAT with processor

In yet another approach, the EtherCAT implementation is one of the peripherals in the device that has an integrated CPU. Many FPGA devices have the capability to configure a processor in the FPGA or already have an integrated processor. Some vendors provide ASICs with both EtherCAT and a suitable processor on the device. The FPGA are flexible but depending on the CPU selection, there is a risk that cost or operating frequency targets are challenging to meet.

EtherCAT® solution from Texas Instruments

Texas Instruments Inc. (TI) has integrated EtherCAT functionality in the generation of Sitara™ AM335x ARM® Cortex™-A8 microprocessors. These devices integrate the ARM Cortex-A8 processor with a slew of other peripherals and interfaces that make the AM335x ARM MPUs attractive devices with which to build industrial automation equipment.

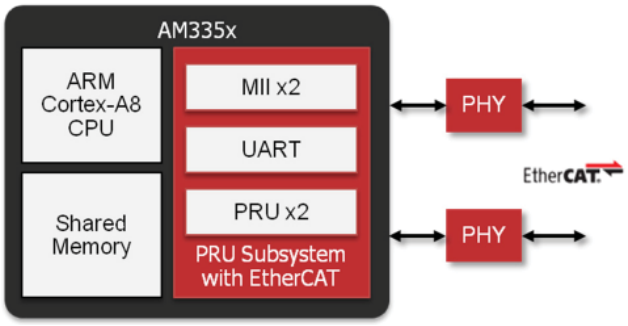

Figure 7. EtherCAT slave on a TI AM335x ARM microprocessor

The AM335x ARM MPU generation of Sitara ARM microprocessors integrates the second-generation programmable real-time unit (PRU) subsystem, which supports very low level interaction with the MII interfaces. This capability enables the PRU subsystem to implement specialized communication protocols such as EtherCAT. The entire EtherCAT MAC layer is encapsulated in the PRU subsystem through firmware. The PRUs process EtherCAT telegrams on-the-fly, parse them, decode the address, and execute the EtherCAT commands. Interrupts are used for any communication required with the ARM processor where the EtherCAT stack (Layer 7) and the industrial application run. The PRU subsystem also performs the frame forwarding in the reverse direction. Since the PRU subsystem implements all EtherCAT functionality, the ARM processor can be utilized for complex applications or a lower speed variant can be used for simpler and cost-constrained applications, such as distributed I/O.

To complete the EtherCAT solution with AM335x ARM MPUs, Ethernet PHY devices such as the TLK110 from Texas Instruments, are required. The TLK110 is optimized for low latency in between MII and PHY interfaces, which is an important attribute for EtherCAT performance. It also has advanced cable diagnostics features that can quickly locate cable faults.

AM335x block diagram

The AM335x ARM MPUs are low-power devices based on the ARM Cortex-A8 RISC core with a broad range of peripherals integrated on the device. For industrial applications, it supports two operating frequency ranges, from 275 MHz for simple applications such as industrial I/O devices up to 720 MHz for complex applications such as industrial controllers. Each variant is capable of implementing EtherCAT. (See Figure 8 on the following page.)

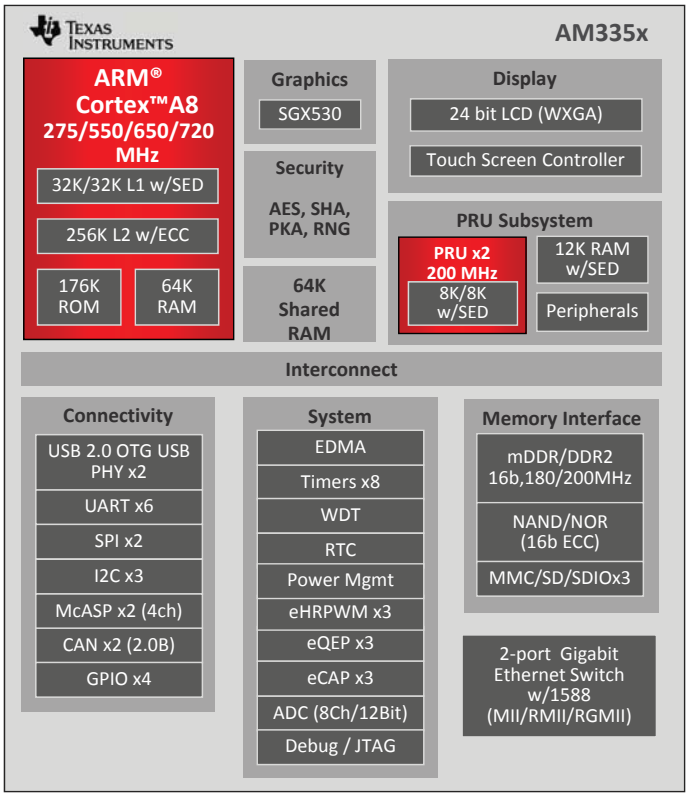

Figure 8. AM335x block diagram

Additional details about the AM335x ARM MPUs, on-chip peripherals and features are available in the data sheet on the AM335x webpage at **www.ti.com/am335x**.

EtherCAT® software architecture

There are three major software components in the EtherCAT slave implementation on TI devices. The first is the micro-code that implements Layer 2 functionality in the PRU; the second is the EtherCAT slave stack

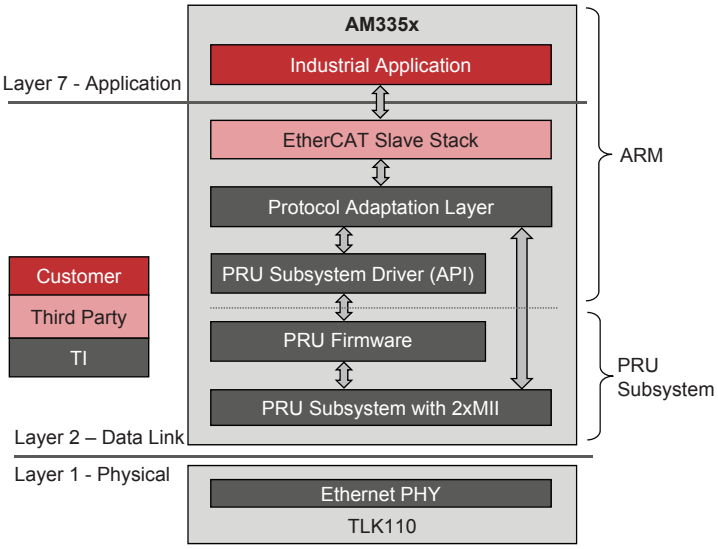

Figure 9. Software architecture for EtherCAT slave

that runs on the ARM MPU and the third is an industrial application that is dependent on the end equipment in which this solution is used. There are additional supporting components, such as the protocol adaptation layer and device drivers that are provided by TI in the software development kit.

Irrespective of whether a TI-tested EtherCAT® stack is used by the customer or another, the architecture illustrated in Figure 9 on the previous page is designed to work without any changes. This EtherCAT solution is also independent of the OS and any required adaptations can be made by referring to the PRU subsystem firmware API guides.

In EtherCAT Layer 2, the PRUs share the tasks of datagram processing, distributed clocking, address mapping, error detection and handling and host interface.

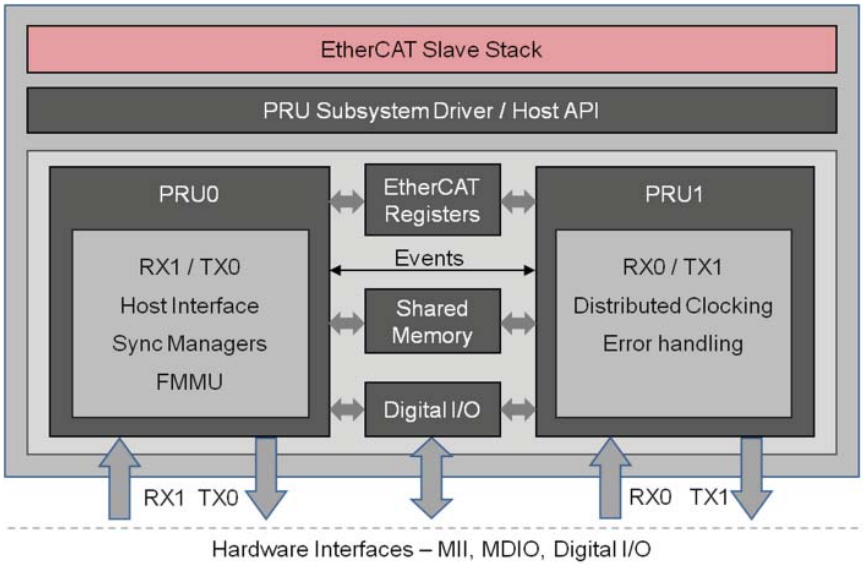

Figure 10. EtherCAT firmware architecture

The PRUs also emulate EtherCAT register space in the internal shared memory. With the deterministic real-time processing capability, the PRUs handle EtherCAT datagrams with consistent and predictable processing latency. The AM335x with TLK110 exhibits a latency of less than 700ns which makes it one of the leading EtherCAT slave solutions.

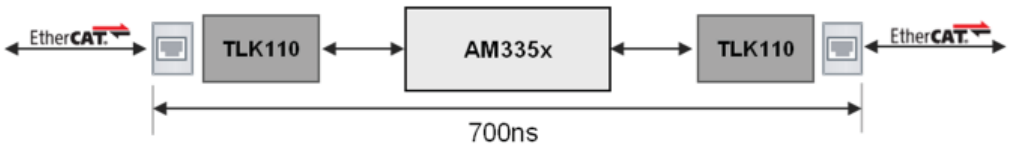

Figure 11. EtherCAT RX-TX latency

A list of key attributes of the EtherCAT implementation in AM335x ARM MPUs is provided in following section.

Key EtherCAT® parameters

The key parameters for the EtherCAT slave operation are listed in the table below.

Feature	Description
ARM frequency	1. Up to 275 MHz 2. Up to 720 MHz
Ethernet ports	Dual MII 100-Mbps full-duplex with 700-ns RX-TX latency using TI's TLK110 Ethernet PHY
Architecture	PRU firmware based implementation
FMMUs	4 or 8
Sync managers	4 or 8 (configurable as mailbox or buffer type)
LRW	Supported
Timer	32 bit (64-bit in software)
Distributed clocks	Supported
Sync signals	Sync 0 and Sync 1 supported
Latch signals	Supported
Host interrupts	Supported
Bitwise operations	Supported with some restrictions
Digital I/O	Supported
Watchdog	Supported (PDI and PD watchdogs)
Operating system	OS Independent. SDK supplied with SYS/BIOS™ real-time kernel

Easy EtherCAT integration

TI has streamlined the process of integrating EtherCAT with AM335x ARM MPUs. All the tools and software code required to integrate EtherCAT slaves are available as part of the software development kit (SDK). On each development platform, the SDK includes firmware for the EtherCAT protocol, software drivers, hardware initialization routines, adaptation layer for the stack API, EtherCAT protocol stack and the application itself. The supporting documentation with the SDK enables one to modify and build new features into the application.

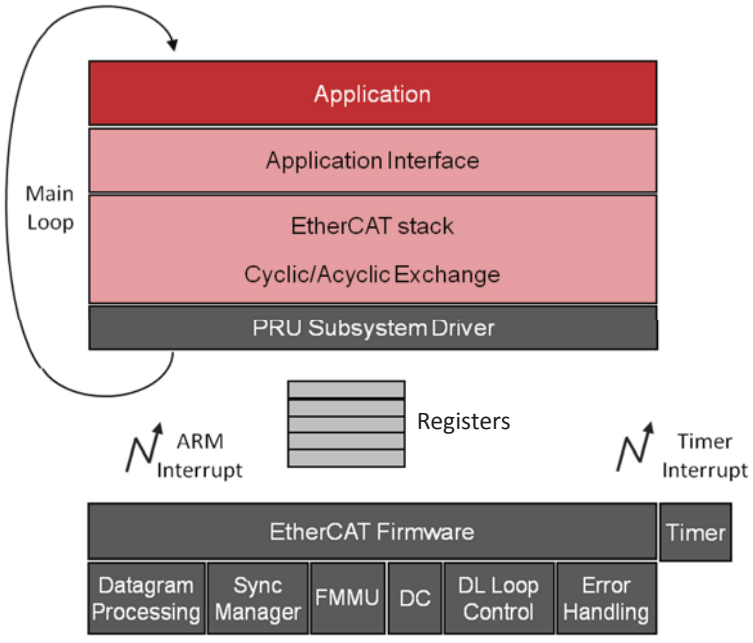

Figure 12. EtherCAT software integration

To facilitate the integration of the EtherCAT® protocol stack, Texas Instruments has also closely collaborated with Beckhoff Automation to validate EtherCAT Slave Stack Code on the TI platform. The Beckhoff code has been adapted to work on TI hardware and has been tested to ensure that the integration is seamless for customers. Customers are expected to become ETG members (required to market EtherCAT products) and get entitled to obtain a free copy of the Beckhoff stack directly via the ETG website before taking their product to market. A copy of the EtherCAT stack from Beckhoff is also included in the TI Industrial SDK for evaluation, development and test purposes.

For a typical use case, the EtherCAT® firmware, the stack, the drivers and the high-level operating system (if needed) or a real-time OS kernel are all reused from the respective software development kit. There is usually only one file to be modified by the user where the use application is developed.

Power consumption

The EtherCAT implementations on TI devices benefit from the low-power architecture of TI's Sitara™ ARM® MPU platform, which eliminates the need for a fan or heat sink. In most use cases, the peak power of AM335x ARM MPUs is under 1W. For EtherCAT applications, the power consumption is less than 1mW per MHz of ARM CPU speed.

Device	ARM frequency (MHz)	Active power consumption (approx.)
AM335x	275	300 mW
AM335x	720	650 mW

Integrating EtherCAT on end products

In order to integrate EtherCAT slave into industrial equipment, customers can use TI's EtherCAT slave implementation and complete their design process using the evaluation copy of the EtherCAT Slave Stack Code provided in the SDK. The Slave Stack Code is originally obtained from Beckhoff and it is available to all ETG members for no charge. If so desired, customers can also use a slave stack from a different vendor or develop their own. The customer should use Conformance Test Tool to pass all tests. Optionally, they can then get the product certified by EtherCAT certification labs and may also perform broader interoperability tests at the EtherCAT plug fests.

Devices for EtherCAT implementation

TI provides several Sitara ARM microprocessors appropriate for EtherCAT implementation, as well as complementary analog products for the signal chain and power circuitry. A brief description of these products is provided in the table below. These products are available in industrial grade temperature range and have long term availability.

Product	Description
AM335x	ARM® Cortex™-A8 32-bit microprocessor available in two speed grades. Integrated EtherCAT® slave/master and several other industrial Ethernet standards Integrated fieldbus standards such as PROFIBUS® and CANopen®.
AM3517	ARM Cortex-A8 microprocessor for EtherCAT master applications
AM1810	ARM926 microprocessor for EtherCAT master and PROFIBUS master/slave applications
TLK110	Ethernet PHY optimized for high-performance industrial Ethernet such as EtherCAT
TPS65910	Advanced low-footprint power management solution for AM335x microprocessors

Development tools for EtherCAT implementation

TI provides AM3359 industrial hardware development platforms with comprehensive design data to assist customers with their implementation. All design data for these hardware platforms, such as schematics and layout is available for accelerating development of customer designs. In addition, TI also collaborates with an external vendor for an additional development platform targeted for industrial applications.

Development platform	Supported EtherCAT modes
AM3359 Industrial Development Kit (IDK)	EtherCAT slave/master
AM3359 Industrial Communication Engine (ICE)	EtherCAT slave/master

AM3359 Industrial Development Kit

The AM3359 Industrial Development Kit (IDK) is designed for industrial applications such as industrial communication, programmable logic controllers (PLCs) and motion control. The software supplied with the IDK includes TI's SYS/BIOS™ real-time kernel, EtherCAT firmware and an evaluation version of EtherCAT application level stack.

Figure 13. AM3359 Industrial Development Kit (IDK)

The board includes EtherCAT®-optimized PHY devices, debug hardware, SD/MMC, Ethernet, UART and more. For motion-control applications, the IDK includes multiple pulse width modulation (PWM) drivers and motor feedback hardware such as analog-to digital converters (ADCs). For motor control, the IDK contains a C2000™ Piccolo™ microcontroller (MCU) and a Stellaris® ARM® MCU. The IDK supports development of practically all types of industrial equipment that incorporate EtherCAT. In addition, the IDK also supports other industrial communication standards such as PROFIBUS® and CAN and is capable of other real-time Ethernet standards such as Ethernet/IP™, POWERLINK, PROFINET®, and SERCOS® III.

Detailed hardware and software information is available at **www.ti.com/tool/tmdxidk3359**.

AM3359 Industrial Communications Engine

The AM3359 Industrial Communications Engine (ICE) is a small form factor (70 mm × 90 mm) platform for industrial communication applications such as communication modules, I/O devices, sensors and other similar applications. where the key is simple design and minimal cost.

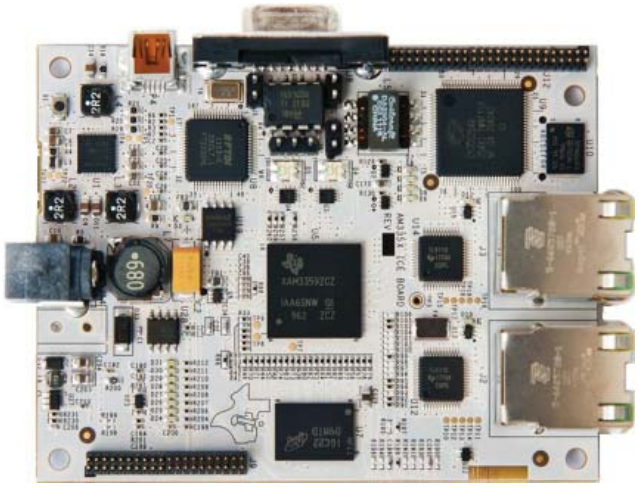

Figure 14. AM3359 Industrial Communications Engine (ICE)

The ICE board includes the essential peripherals for communication standards such as EtherCAT and PROFIBUS® and the included software is designed to keep the memory footprint small enough to ensure small capacity flash devices can be used for code storage. The SDK includes a SYS/BIOS™ based real-time kernel with application-level communication stack and device drivers. The development and debug tool chain is also included with this platform.

Additional details on hardware, software and pricing are available at **www.ti.com/tool/tmdxice3359**.

Summary

TI offers integrated EtherCAT slave capability on Sitara™ AM335x ARM MPUs and EtherCAT master capability on several Sitara ARM microprocessors targeted for industrial I/O, sensor, PLC, and human machine interface (HMI) systems. The integration of EtherCAT with a powerful yet low-power ARM core results in

lower-cost end products without compromise on the functional or operational requirements. TI also offers the transceivers with built-in isolation for the industrial communication interfaces such as EtherCAT®, PROFIBUS®, CAN, RS-485 and more. With comprehensive software and hardware development tools, worldwide support and an active E2E™ developer community, customers can look forward to greatly simplified EtherCAT integration with the added benefit of significant cost savings – as much as 30 percent!

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