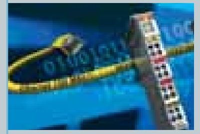
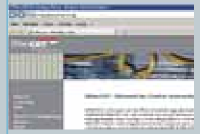
EtherCAT for Embedded Systems

EtherCAT®

Content





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It's faster

- The fastest system available, with outstanding synchronization features
- Performance widely independent of topology
- No underlying sub-system required any more
- Meets today's and tomorrow's requirements

It's cost effective

- Meets or even undercuts fieldbus cost levels
- No special master cards required – on-board MAC or low cost standard NIC is fine
- Highly integrated Slave Controllers for lower interface costs
- No active infrastructure components required

It's easy to implement

- Real-time protocol handling in hardware
- Device application determines µC performance – not the fieldbus protocol
- Simple I/O slaves do not require µC at all
- Universal slave interface modules available
- Evaluation kits and stacks for master and slave available

It's easy to use

- No manual address setting
- No switch configuration
- Auto configuration features
- Diagnosis with exact localization

It's flexible topology

- All topologies supported: line, tree, star, ring
- No node, switch or hub cascading issues
- Up to 65,535 nodes per segment
- Redundancy, Hot Connect, Hot Swap options

It's versatile

- master-slave, slave-slave and master-master communication
- Cyclic and acyclic services for process data and parameter data
- Suitable for centralized and distributed control architectures
- Machine control, robotics, embedded systems, building automation, transport systems, ...

It's Industrial Ethernet

- Standard Ethernet frames used
- Supports all Internet technologies
- HTTP, FTP, TCP/IP – without degrading the real-time behavior
- Simplifies vertical integration

It's Safety on Ethernet

- Functional Safety and standard application with one network
- Safety Protocol according to international safety standard IEC 61508
- Suitable for safety I/O and safety drives
- Routable via gateways and fieldbus systems

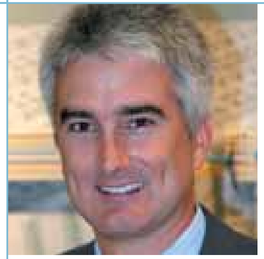
It's open

- Open Technology, fully disclosed
- Supported by the worlds largest Industrial Ethernet Organization
- EtherCAT is IEC and ISO standard
- Supports well established device profiles

It's well proven

- Deployed in series applications since 2003
- Wide range of applications
- Implemented on variety of controllers and operating systems
- Large product selection

User and Vendor Statements



Martin Rostan, Head of Technology Marketing, Beckhoff Automation GmbH, and Executive Director, EtherCAT Technology Group:

"The strong growth of the EtherCAT Technology Group reflects the tremendous worldwide interest in this exiting technology. Manufacturers and end users recognize the benefits: future-proof performance, flexible network topology, simple configuration, and low costs. Nevertheless, while the number of members is an important criterion for the success of a technology organization, it is not the crucial one. Acceptance of the technology resulting in product developments and applications is even more important. Here too, EtherCAT is setting standards."

Dieter Hess, Managing Director, 3S Smart Software Solutions GmbH:

"3S decided to implement EtherCAT as the first real-time Ethernet protocol, since EtherCAT utilizes the maximum performance of Ethernet. For us as a software manufacturer, the fact that the master implementation is independent of special plug-in cards is particularly attractive. The software can be based on the universally available standard Ethernet controller. The openness of the system and active support of Beckhoff for ETG are further significant factors."

Erich Hutflesz, Manager Control Systems, Schuler SMG, and ETG Board Member:

"EtherCAT enables us to realize fast drive and hydraulic controls for all applications currently used in the Schuler Group. Another crucial factor is that, due to EtherCAT's performance, we still have enough potential for solving complex control tasks in future without speed problems. Apart from the functional features of a technology, availability of a wide range of components is very significant for users of automation devices. The fact that so shortly after ETG was established so many member companies were already presenting EtherCAT products and that further products are in preparation is clear evidence for the success of this technology. The main factor determining user acceptance continues to be simple and effective handling of the EtherCAT system in terms of configuration and diagnosis."

Kenichi Karigane, General Manager, Drive Systems Division, Product Marketing & Sales Engineering Center, Hitachi IES Co., Ltd.:

"We have investigated major Industrial Ethernet Solutions and are very interested in the EtherCAT technology. The EtherCAT performance together with its synchronization capabilities make it particular suitable for demanding motion control applications. The ease of use and the real-time features will make EtherCAT the network of choice also for other application areas, and Hitachi-IES has joined the ETG.

We expect the EtherCAT technology to become an approach to success for our motion control business."

Dr. Peter Heidrich, R&D Manager, Baumüller GmbH, and ETG Board Member:

"Baumüller decided to use EtherCAT due to the significant benefits it can offer, particularly in terms of price/performance ratio and availability. This decision was underlined through our active collaboration in the ETG executive committee. We continue to be convinced that the decision for EtherCAT was the right one. As soon as EtherCAT Slave Controllers became available, Baumüller started producing connections for the bmaXX 4400 system in August 2004. ETG has demonstrated that, due to the universality of the EtherCAT technology, EtherCAT-based systems can be developed and realized very quickly."

Kim Hartman, VP Sales & Marketing, TenAsys Corporation:

"The EtherCAT standard has potential to be a significant and disruptive technology in lowering costs and improving performance of hard real-time Ethernet based fieldbus applications. As a 25-year supplier of the RTOS iRMX and INtime for Windows TenAsys is particularly aware of the highly optimized structure used in EtherCAT telegrams. We're very pleased to be associated with the ETG, and in putting forth effort towards supplying a robust, and high performance real-time EtherCAT master for OEM application."

Hans Beckhoff, Managing Director, Beckhoff GmbH:

"Naturally, EtherCAT is particularly suitable for fast PC-based controls. The master requires no plug-in card and can be implemented on any existing Ethernet controller using a very simple interface. EtherCAT is therefore also well suited to small and medium control technology, where it opens up new areas of application for distributed control. Therefore EtherCAT is the communication backbone of Beckhoff system architecture and we are very pleased about the worldwide success of this technology."

Norbert Hauser, VP Marketing, Kontron AG:

"EtherCAT is currently the most successful Ethernet-based fieldbus. This is also visible in the strongly growing number of members of renowned companies. A major advantage of EtherCAT is its openness, high performance and the excellent price-performance ratio. Kontron's embedded computing customers have identified the advantages of EtherCAT for their business. Therefore, Kontron, one of the leading companies in the Embedded Computing market, has decided to offer the embedded portfolio also with EtherCAT."

Thomas Porath, System Architect General X-Ray, Philips Medical Systems:

"We believe that EtherCAT is the right technology for the next step towards a system control architecture that enables us to further reduce costs and allows for new innovations, which the current architecture is not suitable to serve for. The performance of EtherCAT will allow us to implement hard real-time, safety, and control-functions on one single cable, while simultaneously offering flexible topologies, which will reduce cable-costs significantly.

Not only performance, but also international standardization and worldwide acceptance are important features of EtherCAT. Our changeover to EtherCAT is simplified through the use of CANopen device profiles and the availability of gateways and converters, since we are not able to convert all of our subsystems and components in one big step."

Chris Choi, Director of Technology, Husky Injection Molding Systems Ltd.:

"Keeping our customers in the lead is never easy! One of the means to sustain this capability is a continuous renewal of our controls technology. In our pursuit of the next generation of controls, EtherCAT stands out as a fieldbus technology with the best value. No PCI interface card means lower fieldbus cost, lower PC cost and ultimately lower system cost. The unique address mapping technique of EtherCAT brings the real-time industrial Ethernet to reach its highest potential. We are yet to be convinced otherwise by other contenders that they are both technically and economically superior to EtherCAT."

Pat Boland, Managing Director, ANCA Pty Ltd.:

"ANCA's interest in EtherCAT as the standard fieldbus in our CNC machines has been driven by three main features. Firstly there is the practically unlimited bandwidth offered by EtherCAT which gives our designers freedom to imagine, scalability and long product lifetime. Secondly the two physical layers give the option of choosing low cost, electrically rugged and widely available hardware components. Finally the software only master allows easy use of high reliability, relatively low cost industrial motherboards as system controllers."

Dmitry Dzilno, Manager, Controls Group, Applied Materials Inc.:

"We have evaluated EtherCAT and find especially exciting that this communication technology allows to connect fieldbus scanner cards, digital motion amplifiers as well as fast I/O using just one Ethernet port instead of multiple PCI slots. Introducing EtherCAT hence does not require abandoning all well established fieldbus systems right away but provides a smooth migration path especially in demanding motion control applications."

EtherCAT Technology Group

Everyone should be able to use and implement EtherCAT. The EtherCAT Technology Group stands for this philosophy. The ETG is a forum for end users from different sectors, and for machine manufacturers and suppliers of powerful control technology with the aim of supporting and promoting EtherCAT technology. The wide range of industry sectors that are represented ensures that EtherCAT is optimally prepared for a large number of applications. With their qualified feedback, the system partners ensure simple integration of the hardware and software components in all required device classes.

The ETG Technical Committee meets frequently to review the technology. Technical Task Forces look after topics like device profile integration, safety, wiring, standardization or test and certification.

In Training Classes and Seminars the ETG provides detailed information about the Technology.

The Management Board of the International Electrotechnical Commission (IEC) approved the Liaison of the EtherCAT Technology Group with the IEC Committee for Digital Communication: The ETG is official standardization partner organization.

Benefits of membership

- Member companies receive access to specification drafts, specifications, white papers, tools, prototype evaluation products and initial batch products and thus have a head start in evaluating, using or implementing the EtherCAT technology.
- Members are eligible to participate in working groups and gain influence on future enhancements of the EtherCAT technology specifications.
- ETG represent the member's interest in international standardization committees such as IEC and ISO.
- ETG members have access to the members-only part of the EtherCAT website, which provides specifications still in development, a developers forum and up-to date information regarding the technology.
- The ETG offices answers technical inquiries regarding EtherCAT, provide marketing assistance, publish product guides, issue press releases and articles, promote EtherCAT via its website and organize joint fair and exhibition booths.

International Standardization

The EtherCAT specification is an international IEC and ISO standard: EtherCAT is part of the international fieldbus standard, IEC 61158 (Digital data communication for measurement and control – Fieldbus for use in industrial control systems). As part of the IEC 61784-2 (Industrial communication networks – Part 2: Additional profiles for ISO/IEC 8802-3 based communication networks in real-time applications) profiles for specific EtherCAT device classes are defined.

The IEC 61800-7 is particularly important for Motion Control applications. The integration of EtherCAT in this standard makes it a standardized communication technology for the SERCOS™* and CANopen drive profiles.

Also the SEMI (Semiconductor Equipment and Materials International) has approved EtherCAT for their applications by accepting the EtherCAT SEMI standard. The leading standards organizations thus respond to the growing interest of the industry in the fastest Industrial Ethernet solution.

Membership Development

Founded in 2003, the EtherCAT Technology Group grew so fast that it can be considered the world's largest Industrial Ethernet organization. With members from all over the world and still growing, the ETG is a strong international community. The current membership list can be found on the EtherCAT website.

"SERCOS Interface" is a trade name of SI e.V.

Technical Introduction and Overview

This section provides an in-depth introduction into EtherCAT, the Ethernet-based fieldbus system. EtherCAT sets new performance standards. Handling is straightforward and similar to a fieldbus, thanks to flexible topology and simple configuration. Moreover, since EtherCAT can be implemented very cost-effectively, the system enables fieldbuses to be used in applications where fieldbus networking was not an option in the past.

Introduction

Fieldbuses have become an integrated component of automation technology. They have been tried and tested and are now widely established. It was fieldbus technology that enabled the wide-scale application of PC-based control systems. While the performance of controller CPUs – particularly for IPCs – is increasing rapidly, conventional fieldbus systems tend to represent "bottlenecks" that limit the performance control systems can achieve. An additional factor is the layered control architecture consisting of several subordinate (usually cyclic) systems: the actual control task, the fieldbus system and perhaps local expansion buses within the I/O system or simply the local firmware cycle in the peripheral device. Reaction times are typically 3–5 times higher than the controller cycle time – an unsatisfactory solution.

Above the fieldbus system level, i.e. for networking controllers, Ethernet has already been the state of the art for some time. What is relatively new is its application at the drive or I/O level, i.e. in areas that were dominated by fieldbus systems in the past. The main requirements for this type of application are high real-time capability, suitability for small data quantities, and naturally cost-effectiveness. EtherCAT meets these requirements and at the same time makes internet technologies available at the I/O level.

With EtherCAT the controller can update the input and/or output information at the time when the data is needed. The I/O response time contains all hardware relevant delays (IPC, EtherCAT and I/O system) from the physical input signal to the physical reaction on the output. With a time of ffi 100 µs this offers a performance to the PLC level that has been available up to now only within servo drives with a digital signal processor (DSP), (see **Fig. 1**).

Ethernet and real-time capability

There are many different approaches that try and provide real-time capability for Ethernet: for example, the CSMA/CD media access procedure is disabled via higher level protocol layers and replaced by the time slice procedure or polling; other propositions use special switches that distribute Ethernet packets in a precisely controlled timely manner. Whilst these solutions may be able to transport data packets more or less quickly and accurately to the connected Ethernet nodes, the times required for the redirection to the outputs or drive controllers and for reading the input data strongly depend on the implementation.

If individual Ethernet frames are used for each device, the usable data rate is very low in principle: The shortest Ethernet frame is 84 bytes long (incl. inter-packet gap IPG). If, for example, a drive cyclically sends 4 bytes of actual value and status information and accordingly receives 4 bytes of command value and control word information, at 100 % bus load (i.e. with infinitely short response time of the drive) a usable data rate of only 4/84 = 4.8 % is achieved. At an average response time of 10 µs, the rate drops to 1.9 %. These limitations apply to all real-time Ethernet approaches that send an Ethernet frame to each device (or expect a frame from each device), irrespective of the protocols used within the Ethernet frame.

EtherCAT operating principle

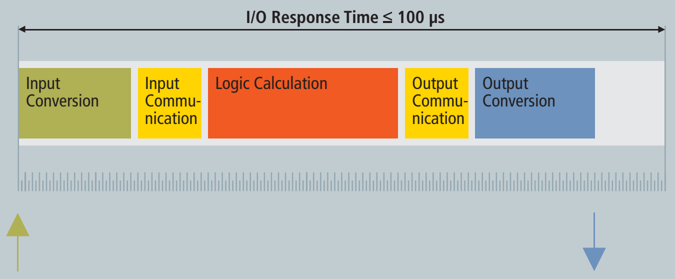
EtherCAT technology overcomes these inherent limitations of other Ethernet solutions: On the one hand the Ethernet packet is no longer received then interpreted and process data then copied at every device, but the EtherCAT slave devices read the data addressed to them while the frame passes through the node. Similarly, input data is inserted while the telegram passes through (see **Fig. 2**). The frames are only delayed by a few nanoseconds. The frame send by the master is passed through to the next device until it reaches the end of the segment (or branch). The last device detects an open port and therefore sends the frame back to the master.

On the other hand, an EtherCAT frame comprises the data of many devices both in send and receive direction within one Ethernet frame. The usable data rate increases to over 90 %. The full-duplex features of 100BaseTX are fully utilized, so that effective data rates of > 100 Mb/s (> 90 % of 2 x 100 Mb/s) can be achieved (see **Fig. 3**).

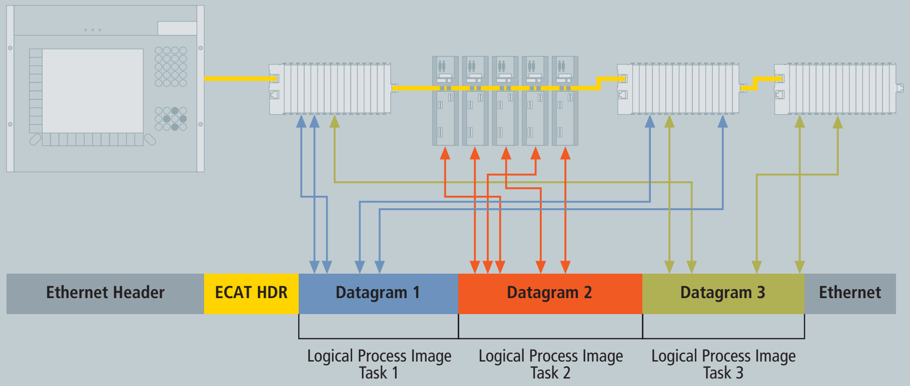
The EtherCAT master uses standard Ethernet Medium Access Controllers (MACs) without extra communication processors. Thus an EtherCAT master can be implemented on any equipment controller that provides an Ethernet interface, independently of the operating system or application environment.

The EtherCAT slave uses an EtherCAT Slave Controller (ESC) for processing the data on-the-fly. Thus the performance of the network is not determined by the microcontroller performance of the slave but is handled complete in hardware. A process data interface (PDI) to the slave's application offers a Dual-Port-RAM for data exchange.

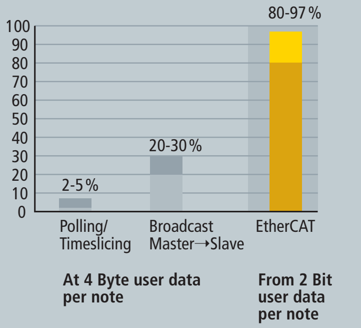
■ Figure 1: Ultra short cylce times with I/O response time < 100 µs



■ Figure 2: Process data is inserted in datagram



■ Figure 3: Comparison of Bandwidth Utilisation



Protocol

EtherCAT only uses standard frames according to IEEE 802.3 – the frames are not shortened. EtherCAT frames can thus be sent from any Ethernet controller (master), and standard tools (e.g. monitor) can be used.

The EtherCAT protocol is optimized for process data and is transported directly within the Ethernet frame thanks to a special Ether type. It may consist of several EtherCAT datagrams, each serving a particular memory area within the 4 gigabyte address space. This memory is available in the segment for process data and is used as a distributed memory. For small I/O devices the EtherCAT Slave Controller also supports bitwise mapping. The bits of an input device can be inserted individually anywhere within the logical address space. If an EtherCAT datagram is sent that reads or writes a certain process image area the input terminal inserts its data at the right place within the data area. This is done by the Fieldbus Memory Management Unit (FMMU) within the ESC. So the data sequence becomes independent of the physical order of the Ethernet terminals in the network; addressing can be in any order. Broadcast, Multicast and communication between slaves are possible. Direct Ethernet frame transfer is used in cases where maximum performance is required and the EtherCAT components are operated in the same subnet as the controller.

However, EtherCAT applications are not limited to a single subnet: EtherCAT UDP packages the EtherCAT protocol into UDP/IP datagrams (see **Fig. 4**). This enables any control with Ethernet protocol stack to address EtherCAT systems. Even communication across routers into other subnets is possible. In this variant, system performance obviously depends on the real-time characteristics of the control and its Ethernet protocol implementation. The response times of the EtherCAT network itself are hardly restricted at all: the UDP datagram only has to be unpacked in the first station.

To access the local memory of the devices for example for configuration either the position of the devices in the segment can be addressed or the device is addressed via an assigned fixed address. This means: No manual address adjustment on the devices is needed!

The position addressing is used for the boot-up of the network. The master can identify each device in the segment (Vendor-ID, product code, etc.) and can read in the link status of the device's ports. Therefore the complete information about all devices and about the topology is available and can be compared to an expected configuration. Additionally, the master assigns a fixed address to all devices.

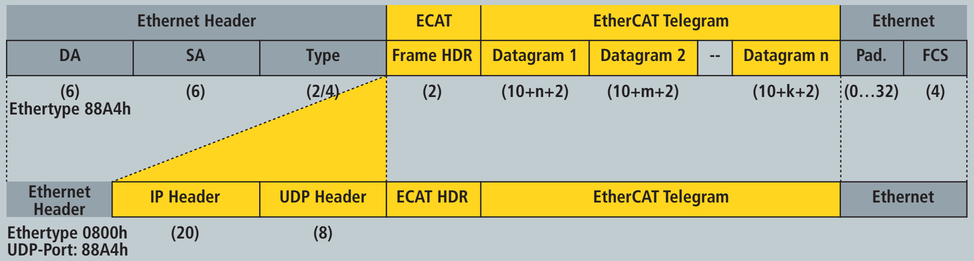
This fixed address is used afterwards and addresses the devices reliably even if one or more devices are not connected (e.g. Hot-plug groups) and therefore the position in the segment is not the same.

In addition to data exchange according to the master/slave principle, EtherCAT is also very suitable for communication between controllers (master/master). Freely addressable network variables for process data and a variety of services for parameterization, diagnosis, programming and remote control cover a wide range of requirements. The data interfaces for master/slave and master/master communication are identical.

For slave-to-slave communication, two mechanisms are available. Upstream devices can communicate to downstream devices within the same cycle – and thus extremely fast. Since this method is topology-dependent, it is particularly suitable for slave-to-slave communication relationships given by machine design – e.g. in printing or packaging applications. For freely configurable slave-to-slave communication, the second mechanism applies: the data is relayed by the master. Here, two cycles are needed, but due to the extraordinary performance of EtherCAT this is still faster than any other approach.

EtherCAT only uses standard frames according to [3] – the frames are not shortened. EtherCAT frames can thus be sent from any Ethernet MAC, and standard tools (e.g. monitor) can be used.

Figure 4: EtherCAT: Standard Frames according to IEEE 802.3 [3]



Topology

Line, tree or star: EtherCAT supports almost any topology (see **Fig. 5**). The bus or line structure known from the fieldbuses thus also becomes available for Ethernet, without the quantity limitations implied by cascaded switches or hubs.

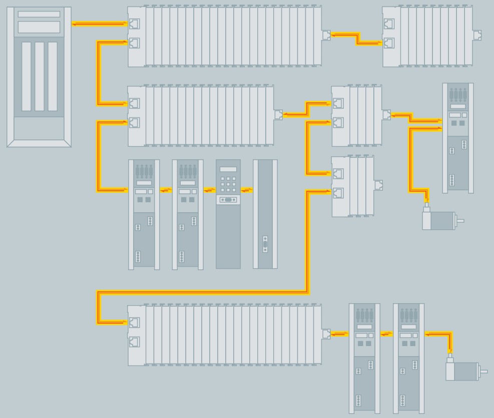
Particularly useful for system wiring is the combination of line and branches or stubs: the required interfaces exist on many devices (e.g. on I/O modules); no additional switches are required. Naturally, the classic switch-based Ethernet star topology can also be used.

Wiring flexibility is further maximized through the choice of different cables. Flexible and inexpensive standard Ethernet cables transfer the signals in 100BASE-TX mode. Plastic optical fibers (POF) will complement the system for special applications. The complete choice of Ethernet wiring – such as different optical fibers and copper cables – can be used in combination with switches or media converters.

The Fast Ethernet physics (100BASE-TX) enables a cable length of 100 m between two devices. Since up to 65,535 devices can be connected, the size of the network is almost unlimited.

The Ethernet protocol according to IEEE 802.3 remains intact right up to the individual device; no sub-bus is required. In order to meet the requirements of a modular device like an electronic terminal block, the physical layer in the coupling device can be converted from twisted pair or optical fiber to LVDS (alternative Ethernet physical layer, standardized in [4,5]). A modular device can thus be extended very cost-efficiently. Subsequent conversion from the backplane physical layer LVDS to the 100BASE-TX physical layer is possible at any time – as usual with Ethernet.

Figure 5: Flexible Topology: Line, Tree or Star



Distributed clocks

Accurate synchronization is particularly important in cases where spatially distributed processes require simultaneous actions. This may be the case, for example, in applications where several servo axes carry out coordinated movements simultaneously.

The most powerful approach for synchronization is the accurate alignment of distributed clocks, as described for example in the IEEE 1588 standard [6]. In contrast to fully synchronous communication, where synchronization quality suffers immediately in the event of a communication fault, distributed aligned clocks have a high degree of tolerance versus possible fault-related delays within the communication system.

With EtherCAT, the synchronization of the devices is fully based on a pure hardware machine. Since the communication utilizes a logical (and thanks to full-duplex Fast Ethernet also physical) ring structure, a timestamp can be sampled within each device for the incoming and the returning frame. With these timestamps the master can determine the propagation delay offset to the individual slave clocks simply and accurately (see **Fig. 7**). The distributed clocks are adjusted based on this value, which means that a very precise network-wide time base with a jitter of significantly less then 1 microsecond is available (see **Fig. 6**). External synchronization, e.g. across the plant, is then based on IEEE 1588. However, high-resolution distributed clocks are not only used for synchronization, but can also provide accurate information about the local timing of the data acquisition. For example, motion controllers typically calculate velocities from sequentially measured positions. Particularly with very short sampling times, even a small temporal jitter in the position measurement leads to large step changes in the computed velocity. With EtherCAT, timestamp data types are introduced as a logical extension. The high resolution system time is linked to the measured value, which is made possible by the large bandwidth offered by Ethernet. The accuracy of a velocity calculation then no longer depends on the jitter of the communication system. It is orders of magnitude better than that of measuring techniques based on jitter-free communication.

Performance

EtherCAT reaches new dimensions in network performance. Thanks to hardware integration in the slave and direct memory access to the network controller in the master, the complete protocol processing takes place within hardware and is thus fully independent of the run-time of protocol stacks, CPU performance or software implementation. The update time for 1,000 I/Os is only 30 µs – including I/O cycle time (see **Table 1**). Up to 1486 bytes of process data can be exchanged with a single Ethernet frame – this is equivalent to almost 12,000 digital inputs and outputs. The transfer of this data quantity only takes 150 µs. The communication with 100 servo axes is also extremely fast: every 100 µs, all axes are provided with command values and control data and report their actual position and status. The distributed clock technique enables the axes to be synchronized with a deviation of significantly less than 1 microsecond. And even at this pace, there is more than sufficient bandwidth for asynchronous communications such as TCP/IP, parameter download or diagnostic data upload.

The extremely high performance of the EtherCAT technology enables control concepts that could not be realized with classic fieldbus systems. With EtherCAT, a communication technology is available that matches the superior computing capacity of modern Industrial PCs. The bus system is no longer the bottleneck of the control concept. Distributed I/Os are recorded faster than is possible with most local I/O interfaces. The EtherCAT technology principle is scalable and not bound to the baud rate of 100 Mbaud – extension to Gbit Ethernet is possible.

Diagnosis

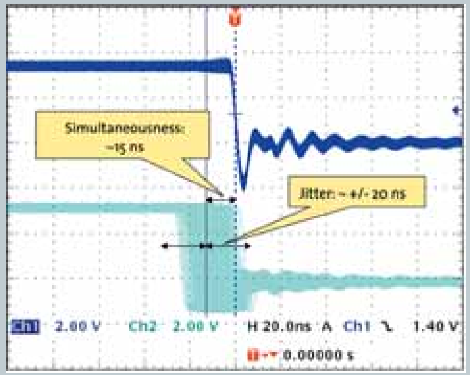
Experience with fieldbus systems shows that availability and commissioning times crucially depend on the diagnostic capability. Only faults that are detected quickly and accurately and located unambiguously can be rectified quickly. Therefore, special attention was paid to exemplary diagnostic features during the development of EtherCAT. During commissioning, the actual configuration of the nodes (e.g. drives or I/O terminals) should be checked for consistency with the specified configuration. The topology should also match the configuration. Due to the built-in topology recognition down to the individual terminals, this verification can not only take place during system start-up, automatic reading in of the network is also possible (configuration up-load).

Bit faults during the transfer are reliably detected through evaluation of the CRC checksum: The 32 bit CRC polynomial has a minimum hamming distance of 4. Apart from broken wire detection and localization, the protocol, physical layer and topology of the EtherCAT system enable individual quality monitoring of each individual transmission segment. The automatic evaluation of the associated error counters enables precise localization of critical network sections. Gradual or changing sources of error such as EMI influences, defective connectors or cable damage are detected and located, even if they do not yet overstrain the self healing capacity of the network.

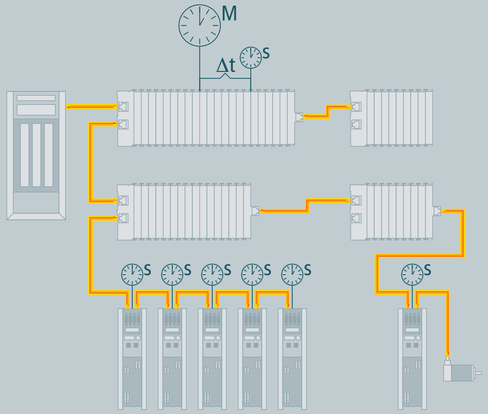
High availability

Increasing demands in terms of system availability are catered for with optional cable redundancy that enables devices to be exchanged without having to shut down the network. Adding redundancy is very inexpensive: the only additional hardware is another standard Ethernet port (no special card or interface) in the master device and the single cable that turns the line topology into the ring (see **Fig. 8**). Switchover in case of device or cable failure only

■ Figure 6: Synchronicity and Simultaneousness: Scope view of two distributed devices with 300 nodes and 120m of cable between them



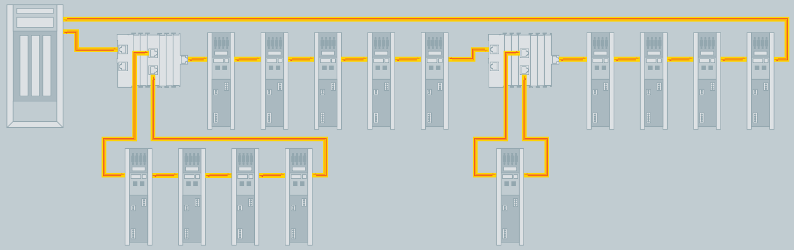
■ Figure 7: Setting the indivual clocks of each device to the network-wide time base.



■ Table 1: EtherCAT Performance Overview

Process Data	Update Time
256 distributed digital I/O	11 µs = 0,01 ms
1000 distributed digital I/O	30 µs
200 analog I/O (16 bit)	50µs ↔ 20 kHz
100 Servo Axis, with 8 Bytes input and output data each	100 µs
1 Fieldbus Master-Gateway (1486 Bytes Input and 1486 Bytes Output Data)	150 µs

■ Figure 8: Low cost cable redundancy with standard slaves



takes one cycle, so even demanding motion control applications survive a cable failure without problems. EtherCAT also supports redundant masters with hot standby functionality. Since the EtherCAT Slave Controllers immediately return the frame automatically if an interruption is encountered, failure of a device does not necessarily lead to the complete network being shut down. Drag chain applications, for example, can thus be specifically configured as stubs in order to be prepared for cable break.

Safety

Conventionally, safety functions are realized separately from the automation network, either via hardware or using dedicated safety bus systems. Safety over EtherCAT enables safety-related communication and control communication on the same network. The safety protocol is based on the application layer of EtherCAT, without influencing the lower layers. It is certified according to IEC 61508 and meets the requirements of Safety Integrity Level (SIL) 3. The data length is variable, making the protocol equally suitable for safe I/O data and for safe drive technology. There are no restrictions regarding the communication medium or the transfer rate. Like other EtherCAT data, the safety data can be routed without requiring safety routers or gateways. First fully certified products featuring Safety over EtherCAT are available since 2005.

EtherCAT instead of PCI

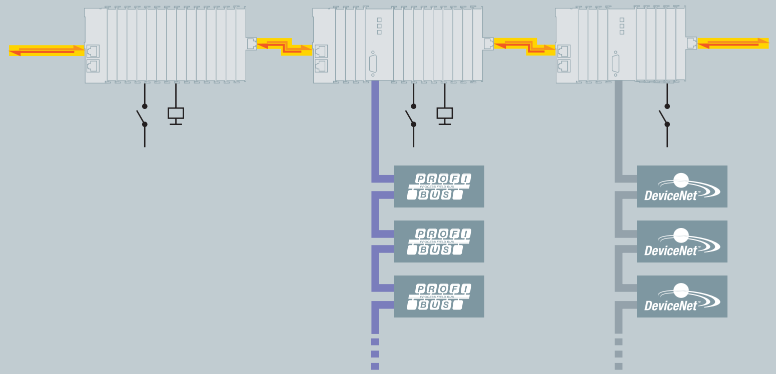
With increasing miniaturization of the PC components, the physical size of Industrial PCs is increasingly determined by the number of required slots. The bandwidth of Fast Ethernet, together with the process data width of the EtherCAT communication hardware enables new directions: classic interfaces that are conventionally located in the IPC are transferred to intelligent EtherCAT interface terminals (see **Fig. 9**). Apart from the decentralized I/Os, drives and control units, complex systems such as fieldbus masters, fast serial interfaces, gateways and other communication interfaces can be addressed.

Even further Ethernet devices without restriction on protocol variants can be connected via decentralized switchport devices. The central IPC becomes smaller and therefore more cost-effective. One Ethernet interface is sufficient for the complete communication with the periphery (see **Fig. 10**).

Device profiles

The device profiles describe the application parameters and the functional behavior of the devices including the device class-specific state machines. For many device classes, fieldbus technology already offers reliable device profiles, for example for I/O devices, drives or valves. Users are familiar with these profiles and the associated parameters and tools. No EtherCAT-specific device profiles have therefore been developed for these device classes. Instead, simple interfaces for existing device profiles are being offered (see **Fig. 11**). This greatly assists users and device manufacturers alike during the migration from the existing fieldbus to EtherCAT. At the same time the EtherCAT specification keeps it simple because all the protocols are optional. The device manufacturer only has to implement the protocol that the device application needs.

■ Figure 9: Decentralized Fieldbus Interfaces



CANopen over EtherCAT (CoE)

CANopen device and application profiles are available for a wide range of device classes and applications, ranging from I/O components, drives, encoders, proportional valves and hydraulic controllers to application profiles for plastic or textile machinery, for example. EtherCAT can provide the same communication mechanisms as the familiar CANopen [7] mechanisms: object dictionary, PDO (process data objects) and SDO (service data objects) – even the network management is comparable. EtherCAT can thus be implemented with minimum effort on devices equipped with CANopen. Large parts of the CANopen firmware can be reused. Objects can optionally be expanded in order to account for the larger bandwidth offered by EtherCAT.

Servo drive profile according to IEC 61800-7 over EtherCAT (SoE)

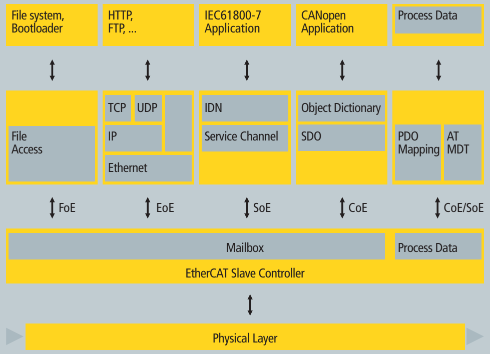
SERCOS interface™ is acknowledged and appreciated worldwide as a high-performance real-time communication interface, particularly for motion control applications. The SERCOS profile for servo drives and the communication technology are covered by the IEC 61800-7 standard. The mapping of this profile to EtherCAT is specified in part 3 [8]. The service channel, and therefore access to all parameters and functions residing in the drive, is based on the EtherCAT mailbox. Here too, the focus is on compatibility with the existing protocol (access to value, attribute, name, units, etc. of the IDNs) and expandability with regard to data length limitation. The process data, with SERCOS in the form of AT and MDT data, are transferred using EtherCAT Slave Controller mechanisms. The mapping is similar to the SERCOS mapping. The EtherCAT slave state machine can also be mapped easily to the phases of the SERCOS protocol. EtherCAT provides advanced real-time Ethernet technology for this device profile, which is particularly widespread in CNC applications. The benefits of the device profile are combined with the benefits offered by EtherCAT. Distributed clocks ensure precise network-wide synchronization. Optionally, the command position, speed or torque can be transferred. Depending on the implementation, it is even possible to continue using the same configuration tools for the drives.

Ethernet over EtherCAT (EoE)

The EtherCAT technology is not only fully Ethernet-compatible, but also characterized by particular openness “by design”: the protocol tolerates other Ethernet-based services and protocols on the same physical network – usually

■ Figure 10: EtherCAT leads to smaller Controllers

■ Figure 11: Several Device Profiles and Protocols can co-exist side by side



even with minimum loss of performance. There is no restriction on the type of Ethernet device that can be connected within the EtherCAT segment via a switchport. The Ethernet frames are tunneled via the EtherCAT protocol, which is the standard approach for internet applications (e.g. VPN, PPPoE (DSL), etc.). The EtherCAT network is fully transparent for the Ethernet device, and the real-time characteristics are not impaired (see **Fig. 12**).

The master acts like a layer 2 switch that redirects the frames to the respective devices according to the address information. All internet technologies can therefore also be used in the EtherCAT environment: integrated web server, e-mail, FTP transfer, etc.

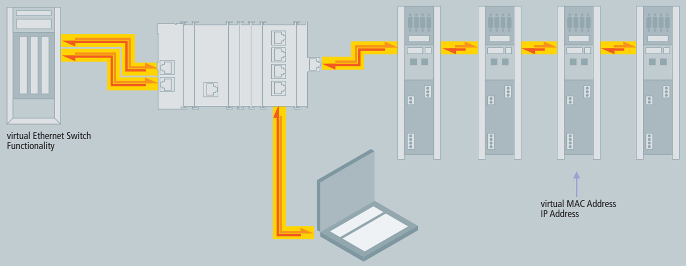
File Access over EtherCAT (FoE)

This very simple protocol similar to TFTP enables access to any data structure in the device. Standardized firmware upload to devices is therefore possible, irrespective of whether or not they support TCP/IP.

Infrastructure costs

Since no hubs and switches are required for EtherCAT, costs associated with these devices including power supply, installation, etc. are avoided. Standard Ethernet cables and standard low cost connectors are used, if the environmental conditions permit this. For environments requiring increased protection sealed connectors according to IEC standards are specified.

Figure 12: Transparent for all Ethernet Protocols



Literature

[1] EtherCAT Technology Group, http://www.ethercat.org

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[3] IEEE 802.3: Carrier Sense Multiple Access with Collision Detection (CSMA/CD) Access Method and Physical Layer Specifications.

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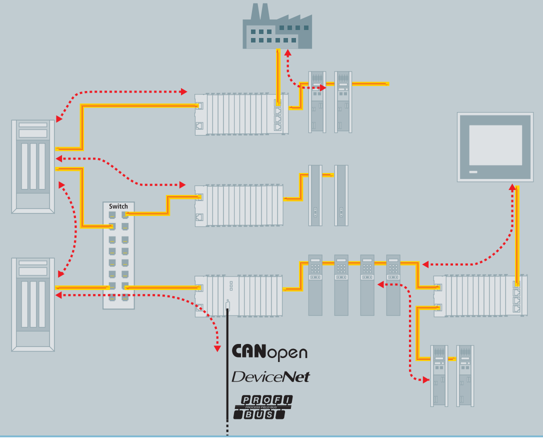
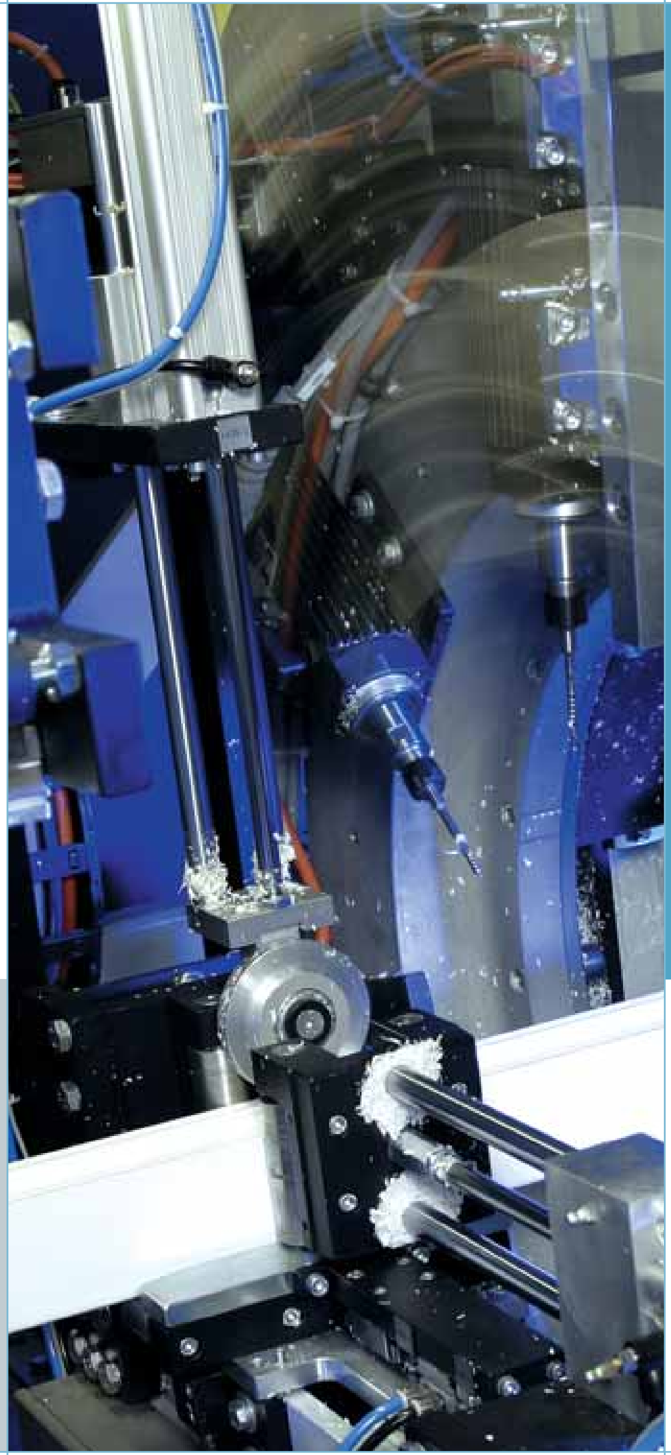
Summary

EtherCAT is characterized by outstanding performance, very simple wiring and openness for other protocols. EtherCAT sets new standards where conventional fieldbus systems reach their limits: 1,000 I/Os in 30 µs, optionally twisted pair cable or optical fiber and, thanks to Ethernet and Internet technologies, optimum vertical integration. With EtherCAT, the costly Ethernet star topology can be replaced with a simple line structure – no expensive infrastructure components are required. Optionally, EtherCAT may also be wired in the classic way using switches, in order to integrate other Ethernet devices. Where other real-time Ethernet approaches require special connections in the controller, for EtherCAT the on-board MAC or very inexpensive standard Ethernet cards (NIC) are sufficient. EtherCAT is versatile: master-to-slave, slave-to-slave and master-to-master communication is supported (see **Fig. 13**). Safety over EtherCAT is available. EtherCAT makes Ethernet down to the I/O level technically feasible and economically sensible. Full Ethernet compatibility, internet technologies even in very simple devices, maximum utilization of the large bandwidth offered by Ethernet, outstanding real-time characteristics at low costs are outstanding features of this network.

Figure 13: Versatile network architecture





Implementation Aspects

Master

The EtherCAT Technology was developed with very low cost devices in mind, like I/O terminals, sensors, and embedded controllers. EtherCAT only uses standard Ethernet frames according to IEEE 802.3. These frames are sent by the master device; the slave devices extract and/or insert data on the fly. Thus EtherCAT uses standard Ethernet MACs, where they really make sense: in the master device. And EtherCAT Slave Controllers are used, where such dedicated chips really make sense: in the slave device, where they handle the process data protocol in hardware and provide maximum real-time performance regardless of the local processing power or software quality.

■ Master requirements in a typical embedded environment

In an embedded environment an EtherCAT Master implementation has to fit some special requirements, which are often conflicting. On one hand, a specific environment restricts hard- and software properties, and on the other hand, the application requirements have to be fulfilled.

The hardware environment includes a broad variation of micro controllers (8, 16 or 32 bit) with different constraints concerning endianness and alignment limitations, which a master needs to address. There is also a broad variation of different MAC chips used where a master has to face different data access methods (DMA access, IO access, Dual Port RAM access). A special objective in an embedded environment is often the lack of a hard disk drive and of course the limited resources like Memory, CPU or bus bandwidth (when accessing the MAC). Another objective a master should meet is a broad variety of different operating systems (e.g. MicroC/OS, Windows CE, QNX, VxWorks to mention a few) or in some cases even no operating system at all. If the same master software implementation shall run on multiple of such different systems, the main requirements to the software are portability and footprint.

Besides these different environments a system designer has to consider which application requirements are to fulfill. These requirements are defined by the maximum number of slaves to be used, what kind of slaves are used with respect to the required slave protocols (e.g. EoE, CoE, FoE, SoE) and how much data has to be transferred per time period (cyclic/acyclic data volume and bus cycle rate). What also has to be considered is whether the used bus configuration is static or dynamic. When using EtherCAT as communication technology between multiple embedded systems, there is often a special operating mode used which is either the standard logical process data exchange or a point-to-point type communication, where slave stations are polled by acyclic commands and the cyclic part is only used to keep the system operational.

The main task for deciding which master solution to use is to clearly define how to face those conflicting requirements. The different options are to develop an own master solution, to adapt the master sample code to the embedded environment or to purchase a commercially available master solution.

The benefit of EtherCAT in an embedded environment is the possibility to have a scalable master by using or omitting some features or special protocols to meet the environment concerning memory and CPU. This is possible because a master stack must not be implemented in a special hardware but can be implemented in software. EtherCAT preserves space in your control unit because no additional interface devices are needed. Furthermore it reduces power consumption because only an Ethernet MAC is needed and no additional active I/O cards. On mass products the cost is always a matter of desire; here EtherCAT saves money because standard MAC hardware (consumer market) can be used, which has a very low price.

■ EtherCAT Master

EtherCAT communicates a maximum of 1,486 bytes of distributed process data with just one Ethernet frame. Unlike other solutions where the master device in each network cycle has to process, send and receive frames for each node, EtherCAT systems typically only need one or two frames per cycle for the entire communication with all nodes. Therefore EtherCAT masters do not require a dedicated communication processor. The master functionality puts hardly any load on the host CPU which can handle this task easily besides processing the application program: so EtherCAT can be implemented without special and expensive active plug-in card by just using a passive NIC card or the on-board Ethernet MAC. Implementation of an EtherCAT master can be very easy, particularly for small and medium-sized control systems and for clearly defined applications. For example a PLC with a single process image: if it does not exceed the 1,486 bytes, cyclic sending of a single Ethernet frame with the cycle time of the PLC is sufficient. Since the header does not change at run-time, all which is required is a constant header to be added to the process image and the result to be transferred to the Ethernet controller.

The process image is already sorted, since with EtherCAT mapping does not occur in the master, but in the slaves – the peripheral devices insert their data at the respective locations in the passing frame. This further unburdens the host CPU. It was found that an EtherCAT master entirely implemented in software on the host CPU uses less of its processing power than much slower fieldbus systems implemented with active plug-in cards – even servicing the DPRAM of the active card puts more load on the host.

System configuration tools – available from several manufacturers – provide the network and device parameters including the corresponding boot-up sequence in a standardized XML format.

Since EtherCAT uses standard Ethernet frames according to IEEE 802.3, any commercially available Ethernet monitoring tool can be used for monitoring EtherCAT communication. In addition, an EtherCAT parser is part of the Wireshark distribution. A Microsoft network monitor plug-in is also available for processing and displaying recorded EtherCAT data traffic.

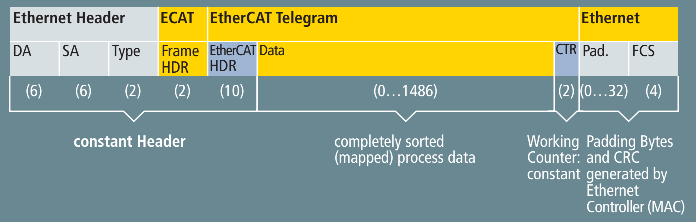
■ Master implementation services

EtherCAT masters have been implemented on a wide range of RTOS, including but not limited to: eCos, InTime, Proconos OS, Real-Time Java, RT Kernel, RT Linux, RTXC, QNX, VxWin + CeWin, VxWorks, Windows CE, Windows XP/XPE with Codesys-SP, Windows XP/XPE with TwinCAT RT extension and XENOMAI Linux. Master stacks are available as open source projects, as sample code and as commercial software. Implementation services are also available from a variety of vendors and for a variety of hardware platforms. Information about this fast growing offering can be found on the EtherCAT website [1].

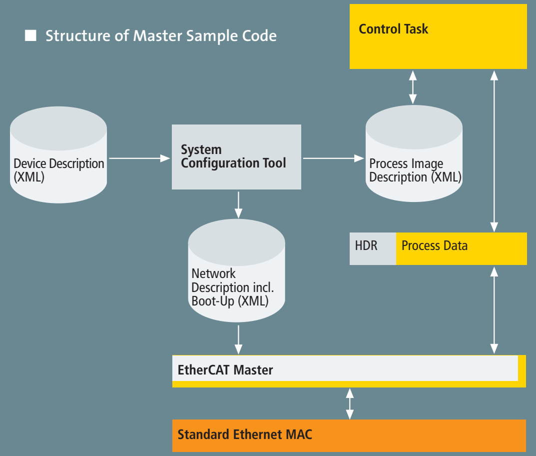
■ Master sample code

Another possibility to implement an EtherCAT master is to use sample code which is available for a nominal fee. The software is supplied as source code and comprises all EtherCAT master functions, including Ethernet over EtherCAT. All the developer has to do is adapt the code, which was created for Windows environments, to the target hardware and the RTOS used. This has been done successfully for a number of systems.

■ Master-Implementation with one Process Image



■ Structure of Master Sample Code



Slave

EtherCAT Interface with ESC20 (IDAM).

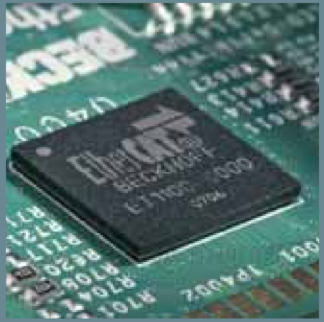
Slave Evaluation Kit (Altera/EBV)

Slave Evaluation Kit (Hilscher)

Slave Evaluation Kit (Beckhoff)

Slave architecture

A cost-effective EtherCAT slave controller is used in the slave devices. With EtherCAT the slave does not need a microcontroller at all. Simple devices that get by with an I/O interface can be implemented only with the ESC and the underlying PHY, magnetics and the RJ45 connector. The process data interface (PDI) to the slave application is a 32-bit I/O interface. This slave without configurable parameters needs no software or mailbox protocol. The EtherCAT State Machine is handled in the ESC. The boot-up information for the ESC comes out of the EEPROM that also supports the identity information of the slave. More complex slaves that are configurable have a host CPU on board. This CPU is connected to the ESC with an 8-bit or 16-bit parallel interface or via a serial connection (SPI). The performance of the host CPU is determined by the slave application – the EtherCAT protocol software can be run additionally. The EtherCAT stack manages the EtherCAT state machine and the communication protocol: This means in general the CoE protocol and for supporting firmware download FoE. Optional the EoE protocol can be implemented.

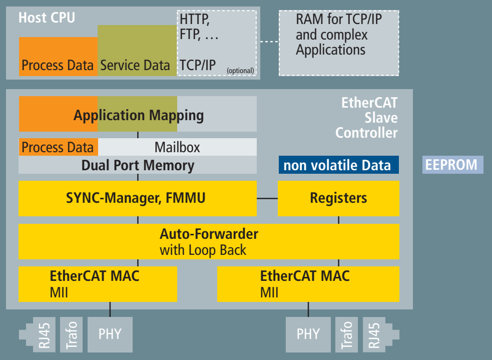


EtherCAT Slave Controller overview

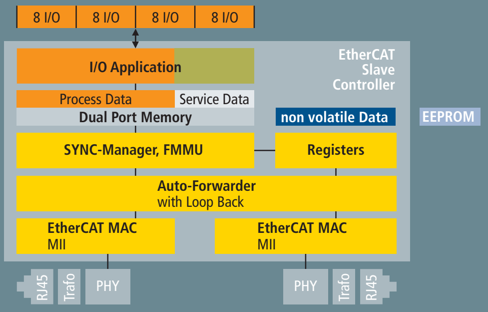
Name	ET1100	ET1200	IP-Core	netX500	netX100	netX50
Type	ASIC	ASIC	Configurable IP-Core	ASIC	ASIC	ASIC
HW-Supplier	Beckhoff	Beckhoff	Altera / Xilinx	Hilscher	Hilscher	Hilscher
Housing	BGA128, 0,8 mm Pitch	QFN48	FPGA dependent	BGA345, 1 mm Pitch	BGA256, 1 mm Pitch	PGBA 1 mm Pitch
Size	10 x 10 mm	7 x 7 mm	FPGA dependent	22 x 22 mm	22 x 22 mm	19 x 19 mm
µC-Interface	serial/parallel (8|16bit)	serial	serial/parallel (8|16bit)*	µC-Bus (internal, 32bit)	µC-Bus (internal, 32bit)	µC-Bus (internal, 32bit)
Digital I/O	32	16	32*	16 (GPIO)	16 (GPIO)	32 (GPIO)
DPRAM	8 kByte	1 kByte	1…60 kByte*	256/400 Byte (Mailbox/ Process data)	256/400 Byte (Mailbox/ Process data)	6 kByte
SyncManager Entities	8	4	0…8*	4	4	8
FMMU Entities	8	3	0…8*	3	3	8
Distributed Clock Support	yes	yes	yes*	yes	yes	yes
No of Ports	4	2 (max 1 x MII)	2 (MII)	2 (MII)	2 (MII)	2 (MII)
Specials			Buyout Licence available for Altera: Cyclone I+II+III, Stratix I+II for Xilinx: Spartan 3+3E+3A, Virtex II+II ProX ProX+4+5	Multi Protocol Support Integrated PHYs, Integrated µC (ARM9, 200 MHz)	Multi Protocol Support Integrated PHYs, Integrated µC (ARM9, 200 MHz)	Multi Protocol Support Integrated PHYs, Integrated µC (ARM9 , 200 MHz)

* Configurable

Slave Hardware: EtherCAT Slave Controller with Host CPU



Slave Hardware: EtherCAT Slave Controller with direct I/O



Slave implementation services

Several vendors offer slave implementation services including hardware and software integration. The various EtherCAT Slave Controllers are supported by corresponding evaluation kits. The Slave Evaluation Kit makes all the interfaces of the controller easily accessible. Since with EtherCAT powerful communication processors are unnecessary, the kit shown above contains an 8 bit µC which optionally can be used as host CPU. The kit comes with slave host software – the equivalent to a protocol stack – in source code, and a reference master software package. Implementation workshops are held frequently.

EtherCAT Slave Controller

Several Manufacturers provide EtherCAT Slave Controllers. Slave controller functionality can also be implemented very cost effectively on FPGAs, for which binary code as well as IP cores are available as buy-out license. The slave controllers typically feature an internal DPRAM and offer a range of interfaces for accessing this application memory:

- The serial SPI (serial peripheral interface) is intended particularly for devices with small process data quantity, such as analog I/O modules, sensors, encoders or simple drives. This interface is typically used with 8 bit µControllers, such as Microchip PIC, DSPic, Intel 80C51, etc.
- The parallel 8/16-bit microcontroller interface corresponds to conventional interfaces for fieldbus controllers with DPRAM interface. It is particularly suitable for more complex devices with larger data volume. µControllers typically using this interface are e.g. Infineon 80C16x, Intel 80x86, Hitachi SH1, ST10, ARM or TI TMS320 series.
- The 32-bit parallel I/O interface is suitable for the connection of up to 32 digital inputs/outputs, but also for simple sensors or actuators operating with 32 data bits. Such devices do not need a host CPU at all.

Latest information on the choice of EtherCAT Slave Controllers can be found on the EtherCAT website.

Migration from CANopen to EtherCAT

CAN and CANopen are used for many communication tasks in embedded systems because it can be realized simple and cost effectively. But what happens if the available data transfer rates are not sufficient? What can be done if the CANopen network has to be connected to the office level, but no money can be spent on additional Gateway components? Then the real-time Ethernet solution EtherCAT is suitable as the best alternative

With CANopen, a clearly structured bus protocol was introduced in 1994, offering a basis for the networking of embedded devices and for standard fieldbus applications. The CANopen protocol was the main reason why CAN became widely accepted as a fieldbus machine construction. Today, we have a large number of fieldbus devices covering different tasks and performance classes supporting CANopen which are available as actors and sensors in the field of machine construction for the system integrator.

No matter whether we are talking about automation devices or other CANopen devices in the embedded field: Today we have many applications for which the capacity and bandwidth of CANopen is no more sufficient as the baud rate in CAN networks inevitably decreases with increasing cable length while there are no standard repeaters available. Thus, developers and users of embedded devices are considering over and over how to extend the successful CANopen concept.

Even though different systems have entered the competition and try to be the best upgrade for CANopen since the introduction of real-time Ethernet solutions, EtherCAT is the best one for the following reasons: An EtherCAT master can be operated with standard chip sets which can normally be found in nearly every embedded device today. While integrated CAN controllers offer hardware connectivity via CPU nearly without additional costs, EtherCAT systems can directly access the Ethernet chip sets already available on board. In fact, EtherCAT can do so without having to devote further designing on additional ASICs or piggyback controller boards for the network connection.

Slaves can be connected via low-priced FPGAs or ASICs which allow an easy EtherCAT implementation. Thus, no powerful CPUs are necessary on the slave side either.

Just like for CANopen, the EtherCAT protocol is implemented as a software stack which uses the physical property of the bus with high-performance. Application parameters, functions and behavior are described in different protocols. One of them is “CANopen over EtherCAT” – which particularly facilitates the upgrade.

With “CANopen over EtherCAT”, the EtherCAT protocol supports the same specific communication mechanisms as known from CANopen:

- Object directory accessing via index and sub-index as well as access to reserved areas for different data types
- PDOs (Process Data Objects): EtherCAT manages the PDO mapping and the object directory just like CANopen. If supported by the device, more than 8 bytes per message can be exchanged and up to 64 applications can be managed.
- SDO (Service Data Objects): The user can access the CANopen object directory via EtherCAT, in the easiest case without any changes compared to CANopen. If requested, the user can up- or download more than 8 bytes per message or even all subordinated objects at once by using an extension.
- Emergency messages with the standard CANopen Emergency Frame (optionally with a broader frame)
- Comparable network management

As most of the CANopen devices’ profiles already provide reliable profiles, they can be used for EtherCAT in “CANopen over EtherCAT” and are fully compatible to the CANopen standard DS301. On proprietary systems, the upgrade from CANopen to EtherCAT can be performed very easily.

The following measures have to be taken:

- An adequate Ethernet controller must be used on the master devices.
- An Ethernet stack must be implemented on the master.
- An available EtherCAT slave or ASIC has to be applied on the slave.

For the EtherCAT stack, there is an example in the source code. Moreover, an evaluation kit providing program code in the source code facilitates this work to a great extent. Fieldbus configuration is realized by means of a generic XML configurator.

There are even available development systems that offer a very smooth way for the migration path: a CANopen stack realized as a program library and an equivalent EtherCAT stack as well. Both libraries can be referenced and used at the same time or separately in one project. For the configuration of the network and slave modules a tool which enables the configuration on the base of EDS files or XML module descriptions, can be integrated for CANopen and EtherCAT. Thus the user can decide for every application whether he wants to use CANopen or EtherCAT – or even both buses as harmonious team players.

EtherCAT provides CANopen technology on Ethernet. EtherCAT will not replace CAN based CANopen, but is an alternative whenever CAN limitations like throughput, network length or number of nodes apply. EtherCAT is so close to CANopen, that even existing protocol stacks can be reused.

Safety-over-EtherCAT (FSoE)

Embedded EtherCAT and Safety-over-EtherCAT

The Safety-over-EtherCAT (FSoE) protocol offers the possibility for an economic, consistent and scalable integration of safety functionality in the automation system.

The need for the integration of a certified safety protocol, implemented by as many manufacturers as possible with as small effort as possible, is guaranteed by the FSoE protocol. The lean, but very efficient, definition of the safety layer, with no dependencies to the underlying communication layer, allows a fast and incomplex implementation of the protocol stack. Safe FSoE master implementations integrated in the bus-master as well as stand-alone devices working decentralized in the network are already available. Also safety remote I/O and drives with integrated safety functionality can be bought of the shelf.

The conformity of the implementation to the specification can be proven accompanied by the development with an FSoE conformance test. This test will also be used as the basis of a conformance test lab. This official lab can certify the conformity and help for the assessment of the device’s integrity.

Application Examples for Embedded Systems

Contact:

EtherCAT Technology Group
Ostendstraße 196
90482 Nuremberg
Germany
Phone: +49 (0) 911 540 5620
Fax: +49 (0) 911 540 5629
info@ethercat.org

www.ethercat.org