CANopen over EtherCAT – taking a CAN technology to the next level

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CANopen is a well proven, well established and very versatile Fieldbus technology, implemented in a large variety of devices. CAN unquestionably has distinct advantages just as low connection costs per device, true multi-master capability and outstanding error detection and handling features. However, for demanding applications like motion control or applications which require large network extension CAN is increasingly challenged by the upcoming industrial Ethernet technologies.

It is shown that there is an Ethernet technology that retains CANopen to such a large extend, that even most of the CANopen communication protocol stack can be re-used. CANopen over EtherCAT features PDOs and SDOs as well as an Object Dictionary, the CANopen state machine and fully supports all CANopen device profiles. It is shown that EtherCAT provides a smooth migration path for CANopen devices towards the brave new world of Industrial Ethernet.

10 Years CANopen

In autumn 2004, the CANopen community celebrated the 10th anniversary of this technology. The first specification was published in November 1994; the development had started as early as 1992 within the ESPRIT project ASPIC. The technology was presented at the 1st International CAN Conference 1994 [1].

CANopen has been very successful, since it provides a clear architecture and meets most requirements of both standard fieldbus applications and embedded networking. Based on CAN and thus providing low cost hardware from a variety of sources and a very robust data link layer, CANopen includes a full featured but lean communication profile. The emphasis of recent developments is on the device and application profile area, where CANopen provides the most comprehensive suite of specifications.

One could expect that the adoption rate of a communication technology starts to flatten 10 years after its introduction – with CANopen, however, this is not the case. Still new industries begin to embrace this technology and sales figures of CANopen devices, CANopen technology and CAN components as such still grow with an exciting and ever increasing pace.

From CANopen to EtherCAT

So whilst CANopen is still flourishing, the next generation of communication technologies is emerging. Ethernet, which has been used above the fieldbus level for years, begins to challenge the lower parts of the networking architecture. Using internet technologies also at the device level is tempting, and the increasing performance of PLCs and controllers such as industrial PCs leads to growing appetite for network performance and further reduced cycle times.

EtherCAT – Ethernet Control Automation Technology – has superb real time behavior and claims to be the fastest solution among the Industrial Ethernet technologies. At comparable cost levels, it provides much larger network lengths than CANopen whilst allowing for most flexible topologies. And, most important for CANopen device manufacturers and users alike, it not only supports CANopen device profiles, but retains CANopen protocol technologies much more comprehensively than any other Ethernet approach.

Ethernet: the real time challenge

Unlike CAN, Ethernets original networking architecture provides pretty poor real time features. So Ethernet on the fieldbus level has to improve this behavior. There are many different approaches: for example, the CSMA/CD media access procedure is disabled via higher level protocol layers and replaced by time slicing 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 devices hard- and software 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). 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= 4.7% 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: the Ethernet packet is no longer received, then interpreted and process data then copied at every device. 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. 1). The frames are only delayed by a few nanoseconds.

Since an Ethernet frame comprises the data of many devices both in send and receive direction, the usable data rate increases to over 90%. The full-duplex features of 100BaseTX are fully utilized, so that effective data rates of > 100 Mbps (>90% of 2 x 100 Mbps) can be achieved.

The Ethernet protocol according to IEEE 802.3 remains intact right up to the individual device - and even to terminals within a modular I/O station; no sub-bus is required. In order to meet the requirements of an electronic terminal block, only the physical layer in the coupler device is converted from twisted pair or optical fiber to E-bus (alternative Ethernet physical layer: LVDS according to [4,5]). The signal type within the terminal block (E-bus) is also suitable for transfer via a twisted pair line over short distances (up to 10 m). The terminal block can thus be extended very cost-efficiently. Subsequent conversion to Ethernet 100BASE-TX physical layer is possible at any time.

EtherCAT Features: Protocol

The EtherCAT protocol is optimized for process data and is transported directly within the Ethernet frame thanks to a special Ethertype. It may consist of several sub-telegrams, each serving a particular memory area of the logical process images that can be up to 4 gigabytes in size. The data sequence is 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.

EtherCAT only uses standard frames according to [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.

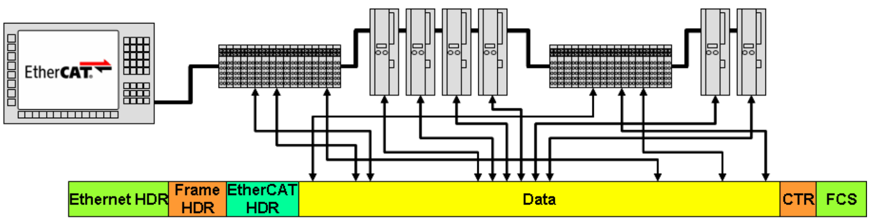

Figure 1: process data is inserted on the fly

EtherCAT Features: Topology

Line, tree or star: EtherCAT supports almost any topology (see Fig. 2). The bus or line structure known from CANopen thus also becomes available for Ethernet.

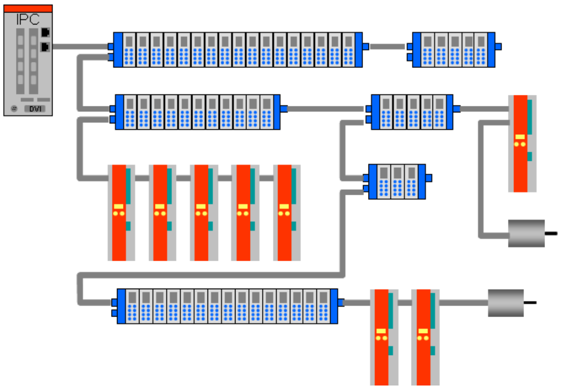

Figure 2: most flexible EtherCAT Topology

Particularly useful for system wiring is the combination of line and branches or stubs: the required interfaces exist on the couplers; no additional switches are required. Naturally, the classic switch-based Ethernet star topology can also be used.

The Ethernet physical layer (100BASE-TX) enables a cable length of 100 m between two devices; the E-bus line is intended for distances of up to 10m. For each connection, the signal variant can be selected individually. Since up to 65535 devices can be connected, the size of the network is almost unlimited.

EtherCAT Features: 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 in the new 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 vis-à-vis possible fault-related delays within the communication system.

With EtherCAT, the data exchange 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, the master clock can determine the propagation delay offset to the individual slave clocks simply and accurately - and vice versa. 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. 3). External synchronization, e.g. across the plant, is then based on IEEE 1588.

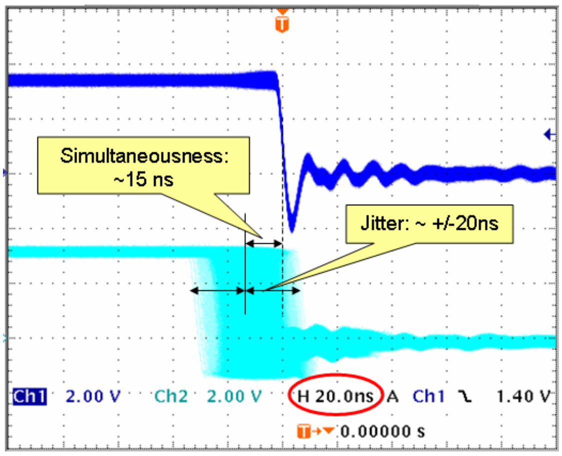

Figure 3: long term scope view of two separate devices; 300 nodes in between, 120 m cable length

EtherCAT Features: Performance

EtherCAT reaches new dimensions in network performance. Thanks to hardware integration in the slave and direct memory access to the network card 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 1000 I/Os is only 30 µs - including I/O cycle time. Up to 1486 bytes of process data can be exchanged with a single Ethernet frame - this is equivalent to almost 12000 digital inputs and outputs. The transfer of this data quantity only takes 300 µs.

The communication with 100 servo axes only takes 100 µs. During this time, 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.

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.

EtherCAT Features: Diagnostics

Experience 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 upload).

Bit faults during the transfer are reliably detected through evaluation of the CRC checksum. 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.

EtherCAT Features: Safety

Integrated functional safety is an important feature for device level communication systems. The EtherCAT safety protocol is qualified for SIL 3 applications according to IEC61508 and thus meets all factory automation safety requirements. First products implementing EtherCAT safety will be available in the second quarter 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.

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. So CANopen network segments can easily be integrated in EtherCAT environments (see Fig. 4).

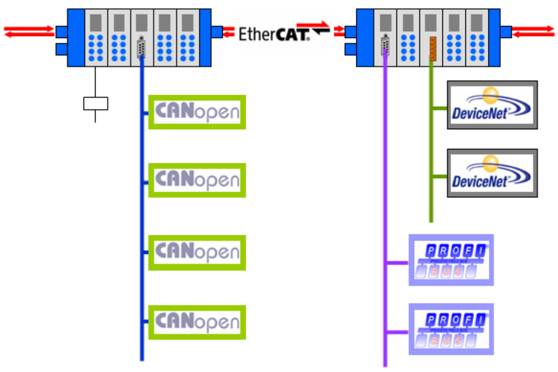

Figure 4: EtherCAT instead of PCI

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

CANopen over EtherCAT (CoE)

EtherCAT provides the same communication mechanisms as CANopen [9]: object dictionary, PDO (process data objects) and SDO (service data objects) - even the network management is comparable.

Network Management (NMT)

Like with CANopen, the EtherCAT state machine consists of four states. The only difference is the CANopen STOPPED state, which has been replaced by the EtherCAT SAFE-OPERATIONAL state. Like in STOPPED, the outputs are disabled – however, the input data may still be communicated. Thus the machine status is known before the outputs are activated.

Service Data Objects (SDO)

The CANopen SDO protocol is used with EtherCAT as well – in default mode even without any changes. If desired, one can use a protocol extension in order to allow for more than 8 bytes per message. It is also possible to up- or download all subobjects (addressed by sub-indices) of an object at once. These extensions are optional and do not have to be supported. It is even possible to re-use the CAN/ CANopen SDO protocol implementation in an EtherCAT device.

Process Data Objects (PDO)

EtherCAT organizes the process data in process data objects - just like CANopen. PDO mapping and the corresponding object dictionary entries are available. Since EtherCAT is not limited to 8 Bytes per PDO, more than 64 application objects may be mapped – if supported by the device.

Device profiles

The device profiles describe the application parameters and the functional behavior of the devices including the device class-specific state machines. For most device classes, CANopen 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, very similar interfaces for CANopen device profiles are being offered. This greatly assists users and device manufacturers alike during the migration from CANopen to EtherCAT.

IEC 61491 over EtherCAT (SoE)

Another motion control device profile is specified in IEC61491 [10]. This standard is also known as SERCOS interface™. The IEC61491 servo drive profile is supported on EtherCAT as well. The service channel, and therefore access to all parameters and functions residing in the drive, is based on the EtherCAT mailbox. The process data, here in the form of AT and MDT data, are transferred using EtherCAT slave controller mechanisms. The EtherCAT slave state machine can also be mapped easily to the phases of the IEC61491 protocol.

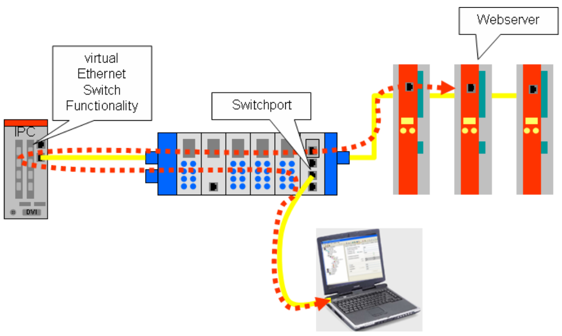

Figure 5: Ethernet over EtherCAT

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 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 switch port. 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. 5).

EtherCAT devices can additionally feature other Ethernet protocols and thus act like a standard Ethernet device. 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.

Master-Implementation

EtherCAT uses standard Ethernet controllers where real cost savings can be achieved: in the master. No communication coprocessors are required, since usually only one Ethernet frame has to be sent per cycle. EtherCAT therefore is the only Ethernet solution for demanding real-time requirements that does not require special master plug-in cards. The on-board Ethernet controller or a cost-effective standard NIC card is sufficient. The master is usually implemented as a pure software solution.

Implementation of an EtherCAT master is 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 1488 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 process data sorting does not occur in the master, but in the slaves - the peripheral devices insert their data at the respective points in the passing frame.

Master Sample Code

Master sample code for supporting a master implementation 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 user has to do is adapt the code, which was created for Windows environments, to the target hardware and the RTOS used (see Fig. 6).

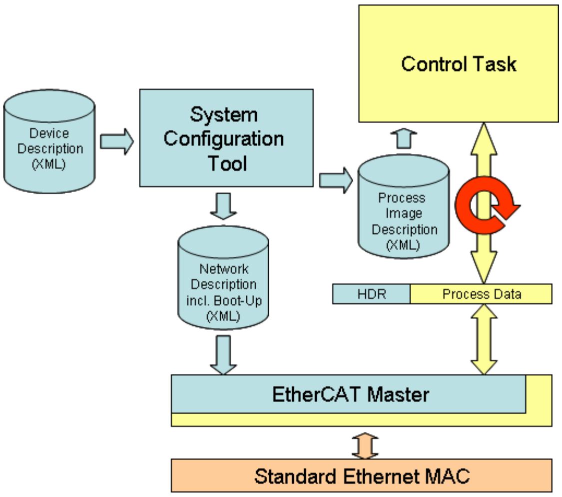

Figure 6: Master Sample Code Structure

Monitor Tools

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, free parser software for Ethereal (an open source monitoring tool) and the Microsoft network monitor is available for processing and displaying recorded EtherCAT data traffic.

Slave-Implementation

A cost-effective EtherCAT slave controller (ASIC or FPGA) is used in the slave device. For simple devices, no additional microcontroller is required. For more complex devices, EtherCAT communication performance is almost independent of the performance capability of the controller used, making the device cost-effective.

EtherCAT slave controllers are available or are in preparation from several manufacturers. The slave controllers developed by Beckhoff (available via semiconductor distribution) 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.
- 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.
- 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.

For supporting a slave implementation, an evaluation kit is available, including slave application software in source code and a test master.

Infrastructure costs

Since no hubs and switches are required for EtherCAT, costs associated with these devices including power supply, installations etc. are avoided. Standard CAT5 cables and standard connectors are used, if the environmental conditions permit this.

EtherCAT Technology Group

Everyone should be able to use and implement EtherCAT. The EtherCAT Technology Group promotes 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.

ETG was established in November 2003 and today is the largest industrial Ethernet organization, with the number of member companies currently standing at over 160. ETG has member companies from Austria, Belgium, Canada, China, Finland, France, Germany, Great Britain, India, Israel, Italy, Korea, Liechtenstein, the Netherlands, Singapore, Sweden, Switzerland, Taiwan, Turkey and the USA.

International standardization

Disclosure is not only driven from within the EtherCAT Technology Group - the international standardization of EtherCAT has also been initiated already. The IEC management board has accepted the EtherCAT Technology Group as an official liaison partner of the IEC working groups for digital communication. The EtherCAT specification was submitted to IEC in November 2004 and has already advanced to the voting process. ISO has also accepted an accelerated standardization procedure for EtherCAT, so that EtherCAT is expected to obtain the status of an official IEC and ISO specification quite soon.

Figure 7: EtherCAT Pilot Application

EtherCAT represents proven technology

EtherCAT is already used commercially: following positive experience with a pilot system, Schuler Pressen AG decided to approve EtherCAT for their Profiline press range (see Fig 7.). A Schuler representative said: “This system 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 performance problems.” Meanwhile, more than 5000 nodes have been supplied to Schuler and other customers.

In November 2004, 28 companies announced EtherCAT products at the first EtherCAT joint booth, and as of January 2005, more than 70 development kits have been sold.

Summary

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.

EtherCAT is characterized by outstanding performance, very simple wiring and openness for other protocols. Thanks to Ethernet and Internet technologies, optimum vertical integration is guaranteed. With EtherCAT, the costly Ethernet star topology can be replaced with a simple line structure - no expensive infrastructure components are required. Where other real-time-Ethernet approaches require special connections in the controller, for EtherCAT very cost-effective standard Ethernet cards (NIC) are sufficient.

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. As a high-speed drive and I/O bus for Industrial PCs or in combination with smaller control units, EtherCAT is a supplement to CAN based CANopen in a wide range of applications.

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