EtherCAT
The new standard for measurement applications
Central backbone for distributed systems

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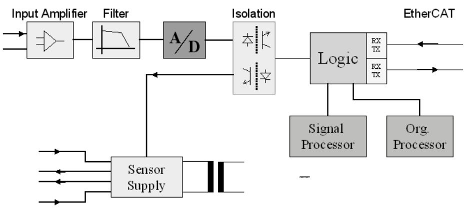
Abstract
In the past years EtherCAT has become a world wide accepted new standard in automation and control. In November 2003 the EtherCAT Technology Group (ETG) was founded and it has grown up to about 900 members from 45 countries in January, 2009. EtherCAT was designed and developed as an open high performance Ethernet-based fieldbus system. The development goal of EtherCAT was to apply Ethernet technology to automation applications which require short data update times (also called cycle times) with low communication jitter (for synchronization purposes) and low hardware costs.
Once the new standard was introduced for automation and control, it became interesting, too, to use EtherCAT also for distributed systems in measurement applications.
This paper takes a focus on the special properties of EtherCAT with respect to the usability in measurement applications. It shows the capabilities of EtherCAT as a powerful backbone, replacing classical networks based on CAN or ProfiBUS. In particular aspects of synchronisation and real-time-processing in combination with the compact data packaging are interesting for measurement applications with a big number of distributed analog channels. E.g. in applications where torque and speed of rotating parts are picked up just to measure, to detect or even to prevent oscillations, it is very important to synchronize the sampling of data at the distributed converter modules. Only this allows then to calculate exact phase information from the measured signals and evaluate and prepare the data according to the requirements of an application on top.
Although EtherCAT supports a big number of distributed devices and is known to handle about thousand digital channels in cycle rates of up to 10 kHz, it does not make sense to feed all measurement data into the context of an automation system. Usually the controlling parts of automation systems are interested and focused on real-time-signals without respect to histories. Feedback-Controllers have to use the latest values from the process to provide as quickly as possible control values to actuators. Digital information is processed in Soft-PLC modules, to provide fast reactions on certain events. However, measured signals needs different handling of the data stream. Not only filtering but also the calculation of characteristic process coefficients and real-time logging of measured signals is not a typical task for automation systems. They should receive only a subset, some few characteristics or at least reduced data streams for supervision and visualisation. This paper shows an approach to use the capabilities of EtherCAT in structured network segments, combined with multiple master/slave functionalities to fulfill the special requirements in measurement applications.

Distributed measurement systems
Testing requirements in the automotive industry often leads to the use of widely distributed sensors. Any solution which avoids overwhelming analog cabling, improves signal noise immunity, and enhances system modularity and flexibility. Hence digitization of the signals has been moved very close to the sensor and the long distant connections are based on digital, interference free data transmissions. The figure shows a typical schematic for a small, one channel acquisition module.

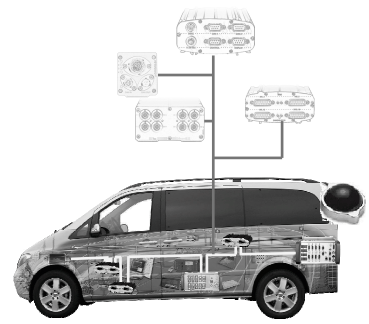


In the case of lower sample frequency (low bandwidth) signals, CAN technology has been established as communication platform. Today there's a long list of suppliers and modules, including CANSAS from imc. However, the acquisition of high bandwith (up to 25 kHz) signals as noise and vibration data requires also a high bandwidth, fast and synchronous communication media. CAN technology itself is not appropriate to fulfill the requirements in such applications. The more complex applications become and information must be carried from the sensor to the higher application levels, the more distributed real-time processing and (pre)evaluation of measured data becomes relevant to the design.

Based on a good application design, the benefits of distributed measurements are

- Reduced analog cabling and costs (cable & installation)
- Improved signal quality with reduced crosstalk, noise or distortion
- Enhanced system modularity and flexibility.

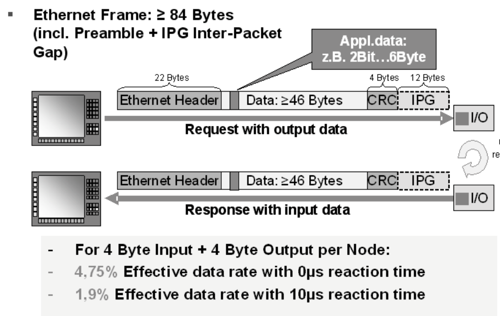
The figure gives an impression of distributed measurement in a passenger car.



Ideal Distributed Bus Connection

The bandwidth for automotive testing is determined on one hand by high channel counts, which can be found in simulation verification or type testing. If distributions of temperature or flow are measured, low sampling frequency of 100 Hz could be sufficient. But if a 3-dimensional grid is equipped with sensors (10 grid positions in each direction) the number of channels increases fast. With 1000 sensors about 100 kHz as total sample rate must be handled and transported. On the other hand high bandwidth on a few signals also increases the data throughput. To process audio signals or cylinder pressure in an internal combustion engine, a sample frequency of about 100 kHz for each individual sensor is common. Just 10 signals with this characteristic drive up the total sample rate to 1MHz. Assuming that one sample is encoded with 4 bytes (int32, float) this results in a data transfer rate of 4 MByte/s which is 40 MBit/s. But the maximum bit rate of a high speed CAN is only 1 MBit/s, Flexray supports up to 10 MBit/s and ProfiBus up to 12 MBit/s. The effective data throughput is even lower due to the communication overhead. These architectures are simply too slow and too specialized for integration with other subsystems. An ideal bus technology must at least support transfer rates above 100 MBit/s and should be increasable in future.

If signals are digitized in distributed measurement systems, it is very important to keep the sampled data synchronized precisely. Otherwise the correlation between several high bandwidth signals would be lost. Depending on the technology there's no guarantee that a frame of data is immediately transmitted. It could stick in sender due to priority conflicts on the bus (eg. CAN). This problem can be solved, if the communication to distributed slaves is controlled from one master. This master is responsible, to handle the communication (reading/writing data to any slave) and synchronize clocks in the slaves. But another problem arises, if a request-reply communication scheme is used. The figure shows the IP communication as an example. Each slave needs a small time to process incoming data and write the reply. During this time no other data transfer is allowed and the effective transfer rate is decreasing again depending upon the performance of the individual slaves. An ideal bus technology should be independent from processing power/speed in slaves or master. It must provide a synchronized and time deterministic communication.

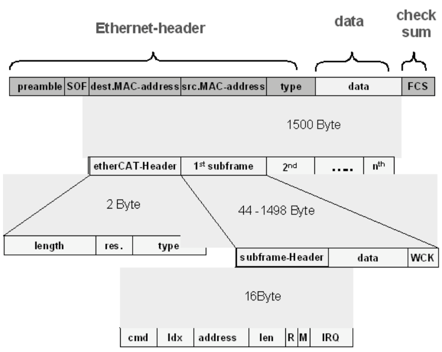


Distributed measurement systems are aimed to modularity and flexibility. Known from automotive applications, an additional measurement device must be integrated 'last minute' for the next measurement. Thus a simple wiring technology is required. As example CAN and ProfiBus need special cables, connectors and terminators placed at the right locations to fulfil the bus specifications. A simple Y-branch could be a reason for random communication failures and dropouts. Special knowledge is required to keep the configuration and network topology running. An ideal bus technology should provide robustness and redundancy, coupled with easy wiring and configuration.

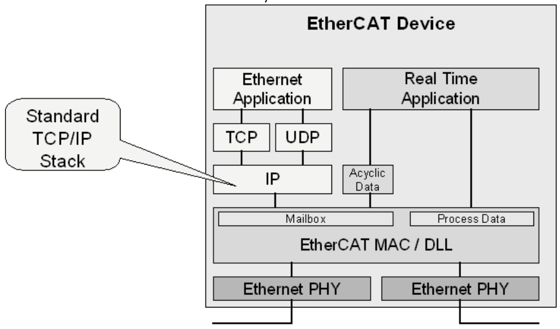
Thanks to Beckhoff, an "ideal" bus technology is available: *EtherCAT*

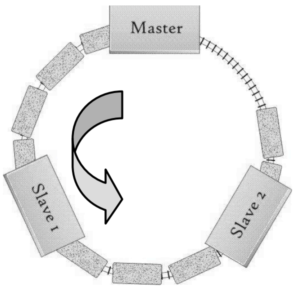
EtherCAT as backbone for distributed systems

Beckhoff invented EtherCAT in the early 21st century and granted rights to the EtherCAT Technology Group (ETG) some few years later. EtherCAT realizes a good balance of speed, determinism and synchronicity at comparable low costs for target 100 MBit/s and higher. It works as a master/slave system. The master generates specific Ethernet-frames at predetermined rate (figure). The frames are used by all participants/slaves for data transport. Since it is based on standard Ethernet technology, wiring is as easy as for a 100BaseT Of-

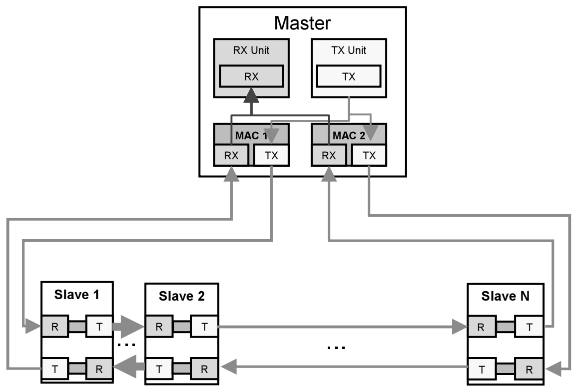


fice-Network with RJ45 plugs, there's no need to think about topology details. All standard common Ethernet protocols could still run in parallel. The EtherCAT MAC/DLL takes care, that real-time frames of EtherCAT are handled at high priority. The figure to the right shows some few ISO/OSI levels of the protocol. An EtherCAT frame itself could envelope other protocols as eg. CANopen or SERCOS.



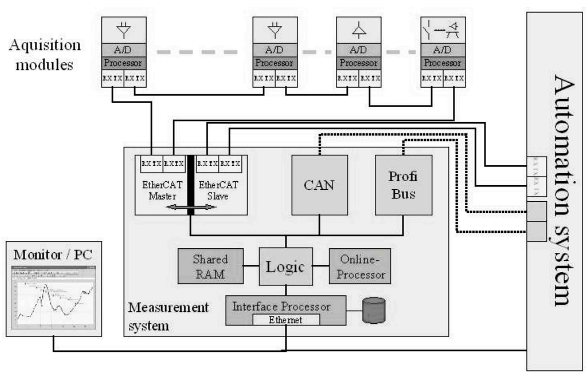


EtherCAT is very efficient in aspects of the data communication between master and slave because it is just one big frame that is used to carry the data. Comparable to a train that departs from the master-station and pulls several coaches, is passes all slave-stations without stopping there (figure to the left). The passengers (data) know, at which station to jump of the running train or into which coach and seat to jump, when the train passes the station. The trains cruising speed is limited only by an ASIC that represents the station. It refreshes the signal, exchanges the required data and forwards the train to the next station (slave). The incoming bits are delayed only by the gate times of the digital and driver circuits. The slaves may process incoming data at their own speed and provide output data, which is picked up from the next passing train. Some few micro seconds after departing, the train arrives back in the master-station, now carrying the latest data and information from all slave-stations. The total travelling time is used to determine additional offsets to synchronize the clocks at each station with a remaining jitter of less 1 µs.
The "coach and seat numbers" cover a virtual address space of 4 GByte, which can be configured to any connected slave. It's possible to build trains with individual set of coaches and configure individual cycle frequencies for them. This allows to separate low bandwidth data (temperatures, states) from high bandwidth signals or sweeps (drives, audio, noise, vibration, etc.). Additionally special trains can be started to perform auxiliary (mailbox) functions: boot a device, exchange files, etc.
Compared to classical Ethernet communication which reaches only less than 5% with polling / time-slicing (TCP), less than 30% with broadcasting (UDP), EtherCAT occupies up to 97% of the available bandwidth.
If all slaves and the master are connected to a ring structure as shown in the figure, the master is able to start two trains in parallel, running in opposite direction. Passengers can go both ways at once to minimize travel time. The redundant ways allow reconfiguration if the network is broken up at any location. The neighboured slaves will route back the trains automatically as they arrive. Additional status information allows locating the defective track.



Managing the information flood

From masters point of view all slaves are arranged in one big process image. This includes all simple low bandwidth IO, all middle bandwidth controller process and control signals and also high bandwidth measured data of audio and vibration sensors. If there's a flat structure without distributed intelligence and processing, the automation system must operate as master. It would have to handle **all** data: perform SoftPLC tasks, feedback controllers, Fourier transformations, order analysis on high bandwidth signals, characteristics extraction, including data logging and process supervision. It would require a very high performance CPU to handle all this in real-time. Using EtherCAT the bus technology is no longer the bottleneck in the applications design.
Splitting the tasks to distributed, intelligent slaves can be a solution, eg. the next generation CRONOS series from imc. These slaves provide also a master that handles all devices in an encapsulated subnetwork. This device is called Measurement system in the figure to the right.
The measurement data from the sub-network may



be routed directly to the parent network in real-time without any further processing. As a new feature, measured signals can be used now as input to any real-time calculations, which can be programmed as example using the Online-FAMOS language of the CRONOS series. This includes any kind of filtering, Fast Fourier Transformations (FFT), order analysis and tracking, classification, signal supervision or real-time feedback controlling. Results of these calculations can be routed downwards to the acquisition and output modules in the sub-network and/or to the parent network and automation system. In parallel to this, the intelligent measurement system is able to record data even from high bandwidth channels using local storage devices and display those signals in real-time on several monitoring PCs simultaneously.
By using intelligent measurement system, the network topology can be organized in several hierarchical, independent network segments with the benefit of unloading the automation system from measurement specific tasks. The robustness of the complete process increases. Each intelligent measurement system is able to manage its network segment in case of communication or functional failures in the upper network level.
The intelligent measurement system may also operate as router between classical networks (CAN or ProfiBus) and EtherCAT. This allows using older existing acquisition modules in a heterogeneous environment.
Configuration and setup of such networks can easily be done through EtherCAT or standard PC software, which may operate independently of the automation system and allows also a reconfiguration of acquisition modules during operation (as far as acceptable for the process).

Summary

EtherCAT fulfils all demands for an ideal data bus:

- Data bandwidth and bus utilisation is extremely high
- Distributed architecture over an extended geography is possible
- Data transfer is deterministic and precisely synchronized
- Allows simultaneous configuration and data transfer
- Cost effective and proven in industrial settings
- Robust by implicit redundant network cabling
- Easy setup and configuration of network cabling

As a design guide in focus to the network topology:

- Split tasks into distributed intelligent measurement systems to unload the automation system.
- Group acquisition modules into encapsulated sub-networks which becomes possible with intelligent, bridging measurement systems.