Why Ethernet?

Due to the worldwide deployment of Ethernet in office environments, there is increasing demand for using this technology for networking time-critical embedded applications, too. Seamless transparent communication from within the application to the outside world, based on one single standard, device availability and familiarity with this technology are the main advantages. However, there are some technical issues to be solved in order to use Ethernet for real-time applications.

Convincing Speed

Current Ethernet standards promise transfer speeds of 100Mbit/s (Fast Ethernet) and more (e.g. Gbit Ethernet). This is significantly faster than most of the established fieldbus systems and embedded networks. Therefore Ethernet also seems to be a good choice for connecting industrial devices with hard real-time requirements. However, deterministic behaviour of data transfer is more crucial than the network bandwidth. With Ethernet in particular, data communication can be delayed unpredictably. This is not acceptable for dynamic industrial control applications.

The reason for Ethernet being non-deterministic is its stochastic media access mechanism CSMA/CD (Carrier Sense Multiple Access /Collision Detect). With this method, all ready-to-send devices on a network segment first check if any other data is currently being transmitted on the network. If this is not the case, one or more devices start sending their data. If there is more than one device trying to gain access, a collision occurs. Thus the data telegrams are not valid anymore and the devices involved interrupt their transmission. After a randomly calculated delay, each device starts checking the network again for free access.

The random delay should reduce the probability of further collisions. If subsequent collisions occur, delays for the involved nodes will be incremented respectively. It is obvious that this method is not suitable for dynamic industrial control applications.

Switched Ethernet for better real-time?

To achieve predictable timing on Ethernet networks, collisions need to be avoided. Moving from shared Ethernet (many devices on one network segment) to (fully) switched Ethernet (only two devices on a network segment) seems to be a promising solution. Just like with switches in a telephone network, data packages are only being forwarded to a specific network segment if the target address matches with a device connected to that particular segment.

Since there are only two ports per network segment (switch port and device port), the forward and backward channel of the segment can be used simultaneously. This full-duplex operation theoretically
doubles the bandwidth of the network. With switched Ethernet, collisions no longer occur in any of the network segments. However, the network is still not suitable for real-time operations for the following reason:

The bottleneck point of switched Ethernet is the switch itself. All data streams arriving simultaneously at the switch ports need to be buffered and bundled by the switch and sent out sequentially on the output port. The timing for multiplexing and buffering depends on the respective switch implementation and varies with the network load.

By reducing the amount of data to be transferred on a particular network, timing delays and deviations can be somewhat limited. An exact calculation of the timing is still not possible.

In many industrial applications, it is necessary to send data from one device to various other devices simultaneously (broadcast, publish/subscribe relationship). Switched Ethernet is better suited for point-to-point data relationship. Broadcast or multicast messages load many switch ports simultaneously leading to exactly those timing delays and deviations mentioned above.

Another aspect to be considered when using switched Ethernet is the wiring topology of such networks. Point-to-point connections unavoidably lead to a tree topology. There is limited space in embedded systems, therefore machines and control equipment require the wiring topology to be adapted to the needs of the system and not vice versa.

**Clock Synchronisation with IEEE 1588**

A specific solution for handling real-time data, not only via Ethernet, is described in the IEEE 1588 standard. It defines methods to synchronise distributed clocks in a network and time-tagging data. All distributed clocks are calibrated regularly using synchronisation telegrams. Each piece of data is tagged with time information stating when it has been captured or when a certain activity has to be initiated. The receiver processes the time tag accordingly i.e. sets a certain output or samples an input at the specific time. These clocks can be implemented in hardware or software depending on the necessary precision. This method allows precise synchronisation down to the µs range.

Advantages of this method are that it is based solely on standard IEEE protocols and it is transparent across multiple network systems. Disadvantages are the effort necessary to compensate for inevitable switching delays and the additional load on the network through regular sync-messages. Infrastructure components like switches and routers need to be equipped with integrated boundary clocks to guarantee timing precision. This method only achieves synchronisation of devices, it does not guarantee that data will arrive at the addressee in time. There is still the possibility that the time tag has already expired when the data arrives. Additional measures have to be implemented for timely delivery.

**Time Slicing**

The methods mentioned earlier have limitations fulfilling the needs of critical real-time applications. Time slicing seems to be a better method to guarantee predictable data communication via Ethernet with very short cycle times and precise timing, and to reserve additional bandwidth for less time-critical data. It has been implemented with ETHERNET Powerlink, an open real-time protocol standard managed by the EPSG (ETHERNET Powerlink Standardization Group), an association comprised of leading...
companies in the automation and embedded industry. With this method, even highly dynamic drives systems can be synchronised. Until now, this was only possible with dedicated motion bus systems.

This method organises data transmission on the network chronologically. Thus it guarantees that there are no collisions on the network and that the bandwidth is ideally utilized. Each node on the network has its dedicated time window to send data. Management of time allocation is handled by one dedicated node, the managing node. Communication is organised in regular basic cycles which are divided into specific phases:

- **Start Phase:** All networked nodes synchronise themselves to the managing node’s clock.
- **Isochronous Phase:** The managing node assigns a fixed time window to each node to transfer time-critical data. All other nodes can always listen to the traffic during this phase. (publish/subscribe)
- **Asynchronous Phase:** The managing node grants the right to send ad-hoc data to one particular node. Standard IP-based protocols and addressing are used during this period.
- **Idle Period:** Remaining time until the start of the next basic cycle.

Durations of the isochronous and the asynchronous phase can be configured. The precision of the cycle time is always better than 1µs in typical ETHERNET Powerlink implementations. Basic cycle times down to 200µs have been achieved in industrial implementations with that protocol.

In addition to transferring isochronous data during each cycle, data during that period can be multiplexed for better bandwidth utilisation. Less important time-critical data can be transferred in larger cycles than the basic cycle. Assigning the time slots during each cycle is at the discretion of the managing node.

The method complies with standard Ethernet according to IEEE 802.3 and can be implemented on any standard Ethernet chip or interface card. All IP-based protocols on higher layers, like TCP or UDP, can be further used without modifications. Besides transferring data in real-time on standard Ethernet, the ETHERNET Powerlink implementation complies with the following standards:

- IEEE 802.3 Fast Ethernet
- IP-based protocols (TCP, UDP,..)
- IEEE 1588 clock synchronisation for distributed real-time domains
- Standard device profiles according to CANopen EN50325-4 for automation
- Can be implemented on any Ethernet hardware – no ASICs necessary

**Other Approaches**

Besides methods for real-time Ethernet that comply with the standard like those described above, several other approaches were introduced recently. These methods only leverage parts of Ethernet technology in
one way or the other. However, those are so far away from the standard that the most compelling benefits of using Ethernet in an industrial environment—transparency, standard protocols and chips, available equipment etc.—are lost. Here is a brief list of those methods:

* **Other access mechanisms on Ethernet physics.** Only the physical layer of Ethernet is in use. Everything else above is proprietary.

* **Special switch mechanisms.** Special switches are used to switch between a real-time phase on the network and a standard phase. During the real-time phase, direct paths between real-time devices are opened. All other traffic is handled during the standard phase.

* **Bit-stream decoding:** All real-time data is sent in one Ethernet frame. Special chips in all nodes extract its relevant output data from the stream and stuff in relevant input data on the fly.

* **Crippled Ethernet frames:** The standard Ethernet frame format is not being used, instead it is reduced in several segments.

**ETHERNET Powerlink Security**

One of the main reasons for using Industrial Ethernet is the transparency achieved when transferring data to standard applications such as data bases, process control systems, ERP systems, etc. System accessibility over the Internet also offers new possibilities for maintenance and service. However, this transparency also offers potential drawbacks.

For this reason, ETHERNET Powerlink provides clear dividing lines and access controls on the machine level from the very beginning. While it is important to guarantee external access to the machine network for authorized persons, the timing of the real-time domain must not be influenced by malicious attacks on the higher-level network. Separation between real-time and non-real-time domains in ETHERNET Powerlink ensures security in all aspects.

**ETHERNET Powerlink in Safety-related Applications**

Safety related systems are needed when it is requested to protect personnel from potential severe injuries through automated machines and processes. These systems have to guarantee that even erroneous interactions will not cause any damage or harm and, the machine will be switched over to a specific safe operation mode. In the past, this has been realized by using discrete wired electromechanical circuits. With the deployment of fieldbusses for networking automation components, this has to be done electronically.

The EPSG’s safety working group has recently introduced EPLsafety, the safety related extension of ETHERNET Powerlink. EPLsafety will become the first open an independent Ethernet based safety bus which will support cycle times down to 100μs. EPLsafety will cover applications in all areas like machine automation, process control and transport systems. There is even the potential in this system to satisfy reliability and availability demands of category SIL 4 according to IEC 61508. EPLsafety’s concept certification is planned for end of 2004.

**Real-time Ethernet in Real-Life**

Real-time Ethernet is not theory anymore. Even true real-time requirements in the μs-range can be met today. For more than two years, over 25,000 Ethernet Powerlink nodes are being deployed successfully in series machines and embedded systems. Those nodes are running reliably in rough environments, for example injection moulding machines or packaging machines all over the world. Typical installations are comprised of 20-50 axes with controllers and a few hundred I/O peripherals running with 200μs to 2ms cycle times. An interesting benchmark application in the packaging industry is built with 50 axes and 2000 I/O points which are synchronised in 2.4ms. At the same time the video stream for a web camera is transmitted via the same real-time network.

Many industrial vendors are working on Ethernet Powerlink compliant solutions. Ethernet as a well known networking technology and its worldwide acceptance are reducing the risk of using this new real-time standard. Inexpensive tools are available and long-term availability of Ethernet is guaranteed.
Ethernet is by far the most common networking technology in the world, thus Ethernet Powerlink will displace many proprietary real-time systems which are in use today.

Ethernet Powerlink is managed by the open vendor and end-user association EPSG (Ethernet Powerlink Standardization Group). Leading companies, like ABB, Altera, Tetra Pak, Baldor, National Instruments, Lenze or Hirschmann are working on further development and deployment. Together with the IAONA, the EPSG is submitting this method to the IEC for standardisation. Further information about ETHERNET Powerlink, the technology, applications and the group can be found at www.ethernet-powerlink.org.