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Ethernet for Real-time Applications

ABSTRACT

This contribution points out which techniques can be considered in order to enable real-time transfer of audio-visual data over Ethernet infrastructures in a Television (TV) production environment. Therefore applications from industrial automation domain are checked for applicability because there Ethernet is also replacing a traditional technology (field bus) to some extent.

INTRODUCTION

The network technology Ethernet has been developed more than three decades ago and achieved a broad spreading in particular with the expansion of the Internet. Thus today not only the prices for hardware and installation of Ethernet are affordable, but also the knowledge of application and maintenance of such networks is very common. Benefited by a star topology, which is enabled by the application of switches, and particularly by increasing data transmission rates the Ethernet technology enters into areas, within which other network technologies lose their supremacy. A current example is the area of the production of audio-visual media in the professional TV production studio, where affordable Ethernet could be a partial solution to the rising cost pressure of broadcasting stations.

IT BASED TV PRODUCTION

Within TV production a changeover from tape-based to file-based approaches takes place. In the past very special and therefore expensive equipment was used to record, transport and edit audio-visual information based on magnetic tapes. Nowadays a strengthened application of standard (commodity) IT hardware can be noticed. This tendency affects not only pieces of equipment but also interfaces in-between: Real-time streaming interfaces get replaced by IT network structures too.

There are some general requirements to be considered when handling content data in a TV production studio. First of all the transmission has to be fail-safe. Not a single piece of data should get lost at any time (very low ***error rate***). It is not acceptable if audio or video frames arrive not or after a defined time at a processing device. Secondly the transport mechanism should be scalable in terms of e.g. the number of clients or bandwidth. Finally yet importantly a new transport system has to be affordable.

Especially for production of live TV program material there are enhanced requirements for the transmission of A/V data. Transfers should happen in real-time, meaning that the ***delay*** time - coming into existence because of transfer time - is underneath a determined limit. For live TV production purposes the delay over all transmissions and calculations should be less than 40 or 20 milliseconds – depending on used production frame rate. In addition, the variation of delay – so-called ***jitter*** - should be constant and predictable.

High quality material, which is handled within TV production, requires a certain ***bandwidth*** for transmission. Compared to audio video signals need an about two dimensions higher throughput capability. For an uncompressed serial component video signal (SDI, ITU-R.BT601, 10-Bit quantization) a bandwidth of approximately 270 Mbps is needed. About the same bandwidth is necessary for compressed high definition (HD) video material. When handling uncompressed HDTV signals for high quality purposes more than four times this bandwidth is required - over 1.000 Mbps.

REFERENCE MODELS

To minimize design complexity, modern networks tend to use a layered architecture in which each layer is a logical entity that performs certain functions. Each layer provides services for the next layer above and shields the details of how the services are carried out from this higher layer. When users located at different network nodes communicate, the corresponding layers at each node also communicate. A well-defined set of rules for this communication in networks is called *protocol* [4].

With the aim of standardizing network architectures and protocols the International Organization for Standardization (ISO) has developed the so-called Reference Model of Open Systems Interconnection (OSI), which divides into seven layers (see Figure 1). The *physical layer* is concerned with the transmission of each bit in a bit stream over a direct physical connection (e.g. Ethernet). The *data-link layer* ensures the reliable transmission of data blocks or frames by detecting and if necessary correcting errors that occur in the raw bit stream (e.g. CSMA/CD). The *network layer* provides the services to set up and maintain the flow of messages (e.g. Internet Protocol IP). A basic function of the *transport layer* is the segmentation of messages into smaller units, if this is necessary, and to ensure that these smaller units are properly transmitted to their destination. This layer can also set up and maintain a specified type of service using the resources of the network (e.g. User Datagram Protocol UDP or Transmission Control Protocol TCP). The *session layer* sets up and maintains a connection between application processes and therefore serves as the users interface to the network. Examples of the services provided by the *presentation layer* are code conversion and text compression. The composition and functionality of the final *application layer* are almost totally application-dependent [4]. A detailed discussion of the different layers and their functionality can be found in [12].

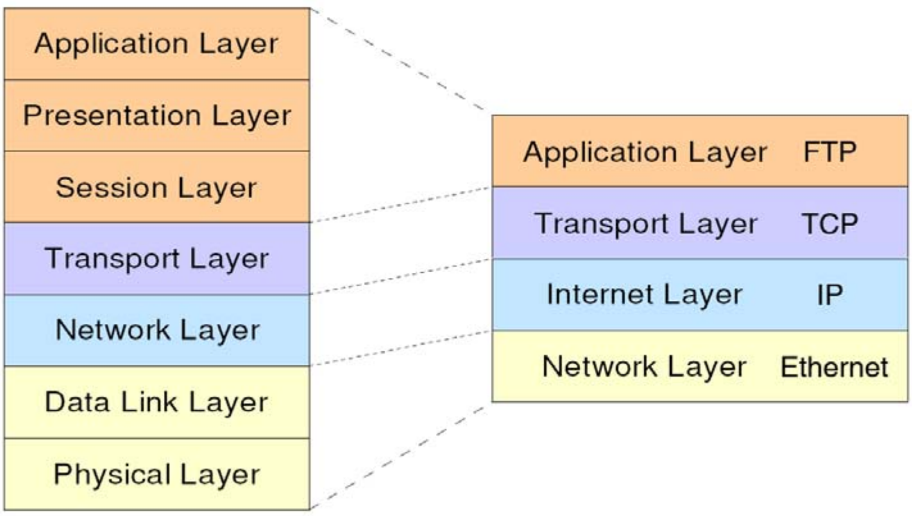

Figure 1: Comparison of ISO/OSI (left) and TCP/IP (right) reference model based on [5] including example protocols

The Internet or TCP/IP reference model only consists of four different layers that can totally be mapped to the seven layers of ISO/OSI (see Figure 1).

ETHERNET

In the end of the 1970s the American company XEROX introduced the innovative concept of “Ethernet” which allowed a communication of more than 100 network clients at transfer speeds of 3 Mbps over 1000 meter long coaxial cable. Versatile refinements led to a consistent and powerful network technology, which achieved a huge spread all over the world. In the 1990s Ethernet advanced in three fields: Higher transfer speeds (Fast/Gigabit/10-Gigabit-Ethernet), more transmission media (twisted pair copper, optic fibre) and new network topologies. The latter includes switched Ethernet whose introduction had positive effects on the temporal behaviour of data communication [3].

Ethernet clients are independent from each other. They are synchronized neither by a network master nor by a token. Originally an Ethernet client first verifies if another communication process is going on (*carrier sense*). In case of a free transmission medium (“ether”) the client starts to send. If the ether is not free the client waits to reattempt after a random amount of time. Because of transmission time collisions between messages of different clients are possible. Therefore the client observes the ether while sending (*collision detection*). In case of a collision the client again resends the message after a random amount of time. This regulation of usage of a shared communication medium is *called carrier-sense multiple access with collision detection* (CSMA/CD).

With the introduction of switched Ethernet the network topology changed from a bus to a star. Collisions of messages were not possible anymore – within a star topology based on a central switch every client possesses a one-to-one connection to other clients. Therefore CSMA/CD regulation is not necessary in switched Ethernet structures. However, still a guaranteed delay and jitter for transmission is not possible – mainly because of temporal performance of switches and because of flexibility in routing through the network.

IP NETWORKS

Usually Ethernet in layer 1 provides a basis for TCP/IP protocol stack in layers above. IP Networks may cause packets to be dropped. The most common reason for this is buffer overflows at routers or switches because of congestion in the networks. To recover these losses there are in principle two possibilities: Backward error correction (BEC) means resending the message while Forward Error Correction (FEC) involves sending redundant information such that the losses can be recovered from the received data. Since real-time applications have strict deadlines FEC is preferable to retransmission [1]. It is to be kept in mind that FEC also increases bandwidth requirements.

The variable delay (jitter) mainly is caused by buffering delay at switches and routers. Real-time data has to be played out in a regular manner, so that jitter commonly is “smoothed out” by the application of buffers. The larger the jitter introduced by the network the larger the buffer size required by the receiver, which has the negative effect of increased end-to-end latency [1]. The end-to-end latency is composed of switching latency (destination port look-up, etc.), frame-forwarding time (depends on the frame-forwarding mode – cut-through or store and forward) and buffering delay when a frame is queued [11].

$$t_{total} = t_L + (n+1)\cdot t_p + (n-1)\cdot t_{gap}$$

Equation 1: Delay calculation of a switch (t_L – product-specific latency, t_p - duration of a packet, t_{gap} – gap between packets) [10]

REAL-TIME APPROACHES IN INDUSTRIAL AUTOMATION

The term "industrial automation" comprises control and monitoring of technical processes by computers or better software [3]. Therefore a sophisticated, reliable and preferable standardized infrastructure is needed to transmit the required control and status information. In the past a so-called field bus technology has been developed which mainly resulted in proprietary products. In order to use the advantages of the Internet technology and protocols (like HTTP for using Web servers for device engineering or FTP for up- and downloading files to field devices), the latest trend is to make possible real-time communication on Ethernet structures [2].

There are several requirements to be met by Ethernet structures to substitute field bus successfully [2], [3] mainly:

- fail-safe transmission (built-in error recognition and correction)
- integrity of operation (reliable functionality even after massive breakdowns and under extreme conditions, redundancy recovery time)
- defined quality of service (guaranteed response/delivery time: less than 1 ms to 100 ms, time synchronization accuracy/jitter: down until not more than 1 µs)
- message length (in general short control messages only, therefore small bandwidth necessary)
- installation issues (often bus topology, number of end nodes)

In principle there are two main approaches of synchronous real-time communication. The common one is the guaranteed, accurately timed transmission of data. The second one describes the handling of data not arriving synchronously at a receiver. Acquisition or play-out of this data then takes place at definite sampling instances based on time stamps within data stream and synchronous clocks in all devices (see Figure 2) [10].

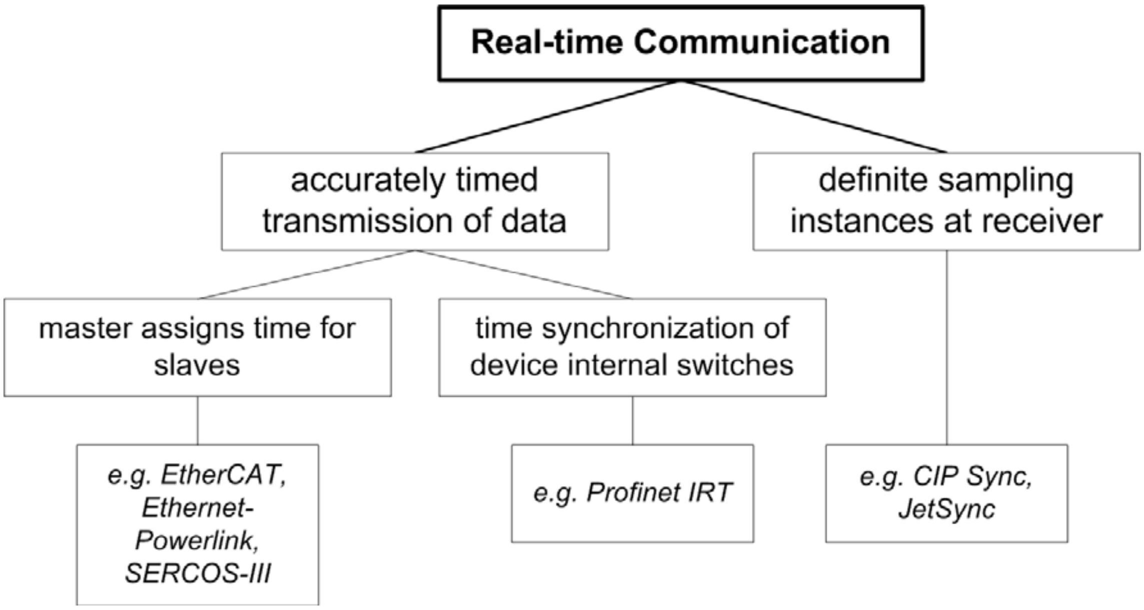

Figure 2: Approaches in real-time communication [10]

Concerning real-time communication in a switched Ethernet the function of a switch has to be kept in mind. In IEEE 802.1D (MAC bridging/spanning tree) no difference is made between packet with high priority (real-time data) and packets with low priority (non-real-time data). For a 100-Mbps network therefore a dwell time of up to 122 µs per switch can come into existence. As solutions to this problem two main key principles are applied: TDMA (Time Division Multiple Access) and Synchronization. TDMA segments the available bandwidth into exclusive time-critical blocks for real-time data and blocks for non-real-time data. An interaction of both data classes is thereby avoided. The synchronization of involved devices can be realized with the help of PTP (Precision Time Protocol, IEEE 1588) [6].

Jasperneite distinguishes between three classes of real-time approaches for industrial automation (see Figure 3) [8]. Felser [2] proposes a similar classification. Class 1 describes the use of standard Ethernet TCP/IP without any change. In this case the different real-time protocols and the best-effort protocols, like HTTP, SNMP, FTP etc., use the services of the TCP/IP protocol suite. Class 1 has the largest conformity to the Ethernet TCP/IP standard and can thereby use standard hardware and software components. Class 2 introduces optimizations, whereby the real-time data bypasses the TCP/IP stack and thus considerably reduces the dwell time in a node and increases the achievable packet rate. The dwell time of the node is one of the substantial influence factors for the real-time performance [8].

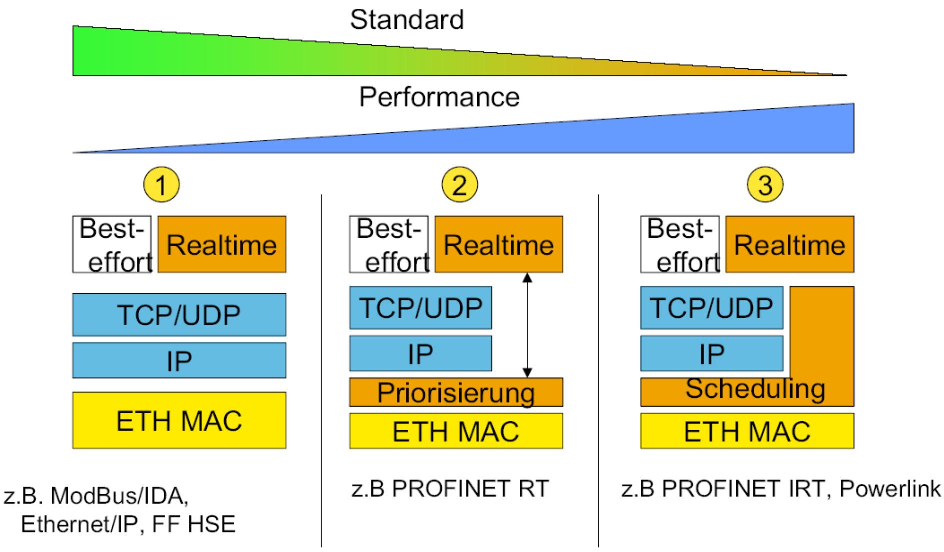

Figure 3: Classification of approaches for real-time Ethernet [4]

In Class 3 the scheduling on the MAC level is again modified through the introduction of a TDMA method. Therefore central poll-select procedures (Powerlink) or procedures that are distributed in the switches (Profinet IRT) can be used. Class 3 can be used in applications that require maximum latency in the range 1ms and a maximum jitter of < 1µs. In this class there are strong restrictions for the use of standard components or the necessity for special components, like switches. As shown in Figure 3, conformance with the Ethernet standard decreases from left to right, while the achievable real-time performance increases in the same direction [8].

CONCLUSION

Coming back to the starting question of which real-time Ethernet solution in automation seems to be fulfilling the requirements of transmission of high-rate A/V data within a TV studio it is no surprise that neither of the candidates can be “reused” without any changes. The main reason is the available bandwidth, which is limited to 100 Mbps in general – due to the requirements in industrial automation. It has to be further investigated if presented approaches can be widened to higher throughput capabilities. Therefore TDMA methods and synchronization with the help of Precision Time Protocol seem to be promising approaches.

Especially the latency of switches in Ethernet structures have to be taken account of if applied in TV Studio, although latency is already been introduced with the increased application of digital signal processing. Switches have a throughput latency of at least one to 20 µs. In case of congestions this latency can grow much bigger. IP switches therefore are classed as asynchronous devices whereas traditional SDI routers are isochronous in nature with perfectly timed (fixed latency, very small jitter, bit accurate timing) I/O ports. Live audio/video (A/V) signals need to be timed within the size of nanoseconds. Features of SDI routing which need to be duplicated by network switches are [9]:

- low latency (few nanoseconds)
- horizontal/vertical (H/V) timing during routing
- point to multipoint (splitting of an input signal to one or more output signals)

Because of switching latency it is very likely that high-rate real-time communication will be based on definite sampling instances in all devices rather than on guaranteed, accurately timed transmission of data (see Figure 2).

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Abbreviations:

A/V – audio-visual
BEC – Backward Error Correction
CSMA/CD – Carrier-Sense Multiple Access with Collision Detection
FEC – Forward Error Correction
FTP – File Transfer Protocol
H/V – horizontal/vertical
HD(TV) – High Definition (Television)
HTTP – Hypertext Transfer Protocol
I/O – Input/Output
IP – Internet Protocol
IT – Information Technology
ISO/OSI – Reference Model of Open Systems Interconnection developed by the Organization for Standardization
IEEE – Institute of Electrical and Electronics Engineers
ITU – International Telecommunication Union
MAC – Media Access Control
Mbps – Megabits per second
PTP – Precision Time Protocol
SDI – Serial Digital Interface
SNMP – Simple Network Management Protocol
TCP – Transport Control Protocol
TDMA – Time Division Multiple Access
TV – Television
UDP – User Data Protocol

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