HOW TO GUARANTEE REALTIME BEHAVIOR USING ETHERNET

Jürgen Jasperneite *, **Peter Neumann** **

* *Phoenix Contact GmbH & Co. KG., R&D Department, Dringenauer Strasse 30, 31812 Bad Pyrmont, Germany, Fax:+49-5281-946212, e-mail:jjasperneite@phoenixcontact.com*

** *IFAK Institute for Automation and Communication Magdeburg, Steinfeldstr. 3, 39179 Barleben, Germany, Fax:+49-39293-81100, e-mail: peter.neumann@ifak-md.de*

Abstract: Ethernet is now conquering the field level in automation technology. Realtime behavior is a knock-out criterion therefore. This paper deals with the key concepts for guaranteed realtime behavior using Ethernet, based on the requirements of factory automation. A classification of the vendor-driven approaches that are currently under discussion for realtime Ethernet is provided.

Keywords: Realtime, Ethernet, factory automation

1. INTRODUCTION

In recent years the growing use of Ethernet in field communication has led to many discussions in automation technology. This can be attributed in part to a series of recent extensions to the relevant IEEE 802 standards for Ethernet, which suggest that it may now even be used for time-sensitive data transmission (IEEE, 1998*a*), (IEEE, 1998*b*). Most importantly, these extensions include switching technology and priority support, which make the CSMA/CD method that was previously used in Ethernet applications obsolete.

The gap between office technology and automation technology is narrowing all the time to achieve company-wide information processing (Clatha, 1998). The "connectivity gap" describes the problem, namely that highly complex programming or parameterization is required at present in order to access information from field devices through the communication pyramid (Pöschmann, 2001) . One reason for this is the lack of continuity between different, heterogeneous communication systems in the various levels of an automation solution.

At the same time, thanks to developments in microelectronics (lowering costs while increasing performance), field devices have a growing range of functions and consequently are becoming "more communicative" (Ricot, 2001). This results in an increase in throughput-oriented communication tasks in automation devices (e.g., for parameterization, archiving, and diagnostics), which in turn affects the original realtime data transmission. This is why many modern, intelligent automation devices already have an Ethernet connection, because fieldbuses do not provide sufficient data throughput. Additional interfaces for fieldbuses are required in these devices for the transmission of time-critical process data and integration into the world of programmable logic controllers.

Before a communication technology originating in the office world can make the transition to the industrial automation sector, several specific requirements must be met. The requirements range from standard industrial connectors and simple installation to a widely accepted application layer for interoperable communication. Furthermore, the question of realtime behavior must be answered, which is the aim of this paper.

The paper is organized as follows. Section 2 covers the realtime requirements in factory automation applications. Section 3 goes on to describe the factors, which influence the time response of a bridged Ethernet system. The key concepts for guaranteed realtime Ethernet are described in Section 4. The vendor-driven approaches, which are currently under discussion, can be found in Section 5. Finally, we conclude the paper in Section 6.

2. REALTIME REQUIREMENTS IN FACTORY AUTOMATION

Realtime behavior means that specific system functions are executed in a time interval $[R, D]$, which is determined by the application environment. Here, R (release)[1] denotes the earliest permissible starting time and D (deadline) the latest permissible completion time. Realtime behavior is guaranteed when the requirements for timeliness und simultaneity are met. According to (Jensen *et al.*, 1985), these requirements are best illustrated using time/utility functions (see Fig. 1). A hard realtime condition is when the utility of a data transmission abruptly drops to 0 when the deadline (D) is exceeded. Exceeding the deadline (D) may result in damage to product parts or equipment. This situation is aggravated by current developments in the transmission of safety-critical data over fieldbuses (INTERBUS, 2003), (*AS-Interface*, 2003), (PNO, 2003), (ODVA, 2003). Exceeding time limits in this case can endanger lives.

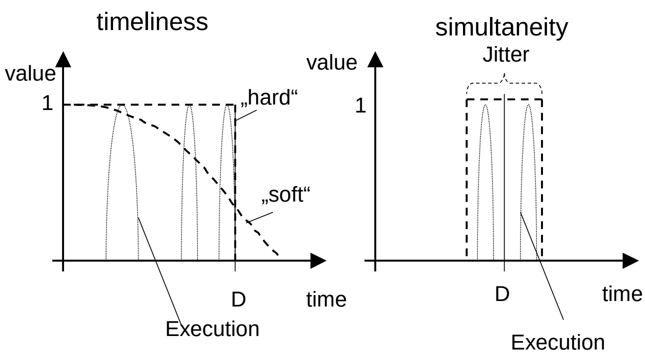

Fig. 1. Realtime criteria

A soft realtime condition is when the utility gradually falls to 0 when the deadline (D) is exceeded. In this case a violation of the deadline D is acceptable for some events.

In addition to timeliness, a realtime system must also meet the criterion of simultaneity.

Table 1. Quality of Service (QoS) requirements in field communication

QoS Class	**Application**	**QoS Latency**	**Jitter**
1	Controller-to-controller	100 ms	./.
2	Distributed I/O devices	10 ms	./.
3	Motion control	$\leq 1ms$	$\leq 1\mu s$

Here it is essential for the correct operation of a technical process that different events in a distributed system are executed quasi-simultaneously. Deviation from an ideal simultaneity is referred to as jitter. The requirements in terms of communication quality in factory automation for the area near to the process can be roughly divided into three classes (see Table 1). The definition of these rough classes is based on the experiences with existing classes of applications in the field bus technology.

3. FACTORS, WHICH INFLUENCE THE REALTIME BEHAVIOR OF A BRIDGED ETHERNET SYSTEM

Figure 2 shows a bridged Ethernet system with several connected devices. A bridged Ethernet system can be modeled as a network of queueing systems. A range of factors influence the time response and thus the realtime behavior with regard to latency and jitter. These factors have been examined in the form of a sensitivity analysis in (Jasperneite, 2002).

Starting with the devices, the properties of the packet generation process (packet sizes, burstiness, etc.) and the dwell time, which is the result of runtimes in the protocol stacks, must be considered.

The dwell time of a TCP/IP protocol stack can quickly become a multiple of the MAC runtimes in a bridged Ethernet system (Jasperneite and Neumann, 2001).

[1] Typically the value of R is determined implicitly by the instant of a function call

Another influencing factor is the scheduling strategy in the devices and the bridges. According to the IEEE standard, FCFS and non-preemptive priority queuing (PQ) can be found in a bridged Ethernet system. Furthermore, when using PQ it is still impossible to prevent high priority packets being delayed by lower priority packets, which are just served in a bridge or device. This blocks the forwarding operation of the high priority packets, which results in higher transaction times and jitter values, especially when using long chains of bridges. This property means that Ethernet cannot be used directly in time-critical synchronous applications, e.g., motion control. This is why intervention is required in the scheduling, which is part of various vendor-driven approaches.

The combination of information flow distribution and network topology also has a great influence on the realtime behavior. The more connections common subsections have along their individual paths, the greater the temporal influence of packet ordering in the relevant bridges. In addition, long chains of switches increase the achievable transaction times (Krommenacker *et al.*, 2001), (Rüping *et al.*, 1999). This is a crucial point when Ethernet has to be used to simulate the line structures of today fieldbuses.

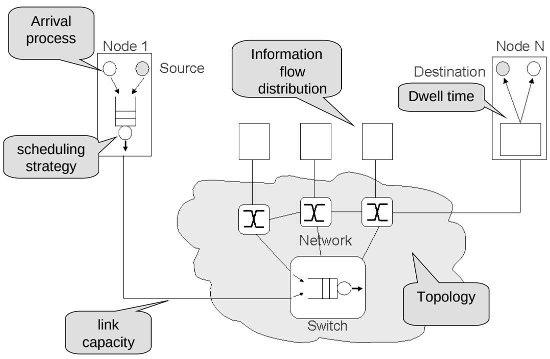

Fig. 2. The various factors, which influence the realtime behavior of a bridged Ethernet system

4. KEY CONCEPTS FOR GUARANTEED REALTIME ETHERNET

In the past, a lot of research work deals with modifications of the MAC-layer of Ethernet because of the statistical nature of the CSMA/CD procedure (Pöschmann, 1999), (Chiueh and Venkatramini, 1994), (Shimokawa and Shiobara, 1985), (Kweon *et al.*, 1999), (Bello and Mirabella, 2001). Today Realtime Ethernet is based on the exclusive use of bridging technology (IEEE, 1998*a*) and the simultaneous use of full duplex transmission (micro segmentation) (IEEE, 1997). This ensures that no more collisions can occur on the medium and therefore makes the CSMA/CD method that was previously used in Ethernet applications obsolete. Using priorities according to IEEE 802.1D/Q create an effective method for isolating time-critical and best-effort data. As mentioned above, the end-to-end delay can be reduced by factor 10 by optimizing the runtimes in the devices. These measures can be used to achieve QoS Class 2, as shown in Table 1.

For additional improvement in terms of latency and jitter, the TDMA (Time Division Multiple Access) method and time synchronization play a very important role.

4.1 TDMA method

Especially in a chain of bridges the latency and the jitter for real-time data transfer will be increased significantly. This leads to a restriction of using standard Ethernet in time-critical synchronous applications, e.g. Motion Control. To use Ethernet also for this class of applications (QoS class 3 regarding to table 1) extensions to the standard are necessary which often based on TDMA mechanism, where pre-allocated time slots are defined for the transmission of time-critical and non realtime data (cf. Fig. 3). The application of such a scheduling scheme has the advantage that the transmission times can be computed simply a priori, however the use of standard components is strongly limited. The replacement of the

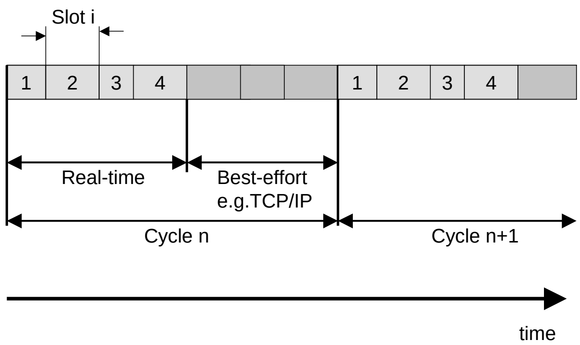

Fig. 3. TDMA method

CSMA/CD method with a token passing procedure was suggested as early as 1985 (Shimokawa and Shiobara, 1985) for the transmission of time-critical data in industrial applications. There are several ways to implement a TDMA method. The easiest option is a poll-select procedure, as is the case for Powerlink (Powerlink, 2003). Profinet IRT (IEC, 2003) uses a completely distributed TDMA method.

4.2 Time Synchronization

In order to provide isochronous conditions in a distributed system, time synchronization between the relevant devices is required. One option is to differentiate between data transfer and the execution of resulting actions. In this way, the actions in the system are only based on temporal criteria. This method is used, for example, by CIP Sync (Ethernet/IP, 2003) .

On the other hand, a distributed TDMA method such as that used in Profinet IRT, also requires appropriate time synchronization for scheduling the realtime data and best-effort data phases, as well as for packet ordering within the realtime data phase.

In both cases, the distributed clocks must be synchronized precisely. An emerging standard for this is the Precision Time Protocol (PTP) (IEEE, 2002). This standard is based on a master/slave procedure. The local clocks are adjusted using special synchronization telegrams. A defined algorithm is used to select the most accurate clock in the network as the master clock. Synchronism of $< 1\mu s$ can be achieved in a switched Ethernet network with the appropriate hardware support. For the use of PTP in chains of Bridges enhancements such as bypass clocks are suggested (Mueller and Weber, 2003). More detailed information on this standard can be found in the proceedings of the last IEEE 1588 workshop (Kang, L. and Eidson, J., 2003).

5. CLASSIFICATION OF VENDOR-DRIVEN APPROACHES UNDER DISCUSSION

The vendor-driven Real-time Ethernet approaches, which are currently under discussion, can be divided into 3 classes with regard to the used architecture (see Figure 4). The development target of these commercial approaches is to fulfill primarily the temporal requirements represented in the Table 1.

Class 1 describes the use of standard Ethernet TCP/IP as it is. In this case the different real time protocols and the best-effort protocols, like HTTP, SNMP, FTP etc., uses the services of the TCP/IP protocol suite. This includes examples such as CIP Sync (Ethernet/IP, 2003), ModBus/TCP (ModBus, 2003), and IDA (IDA, 2001). The 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 realtime data bypasses the TCP/IP stack and thus considerably reduces the dwell time in the node, and increases the achievable packet rate. The

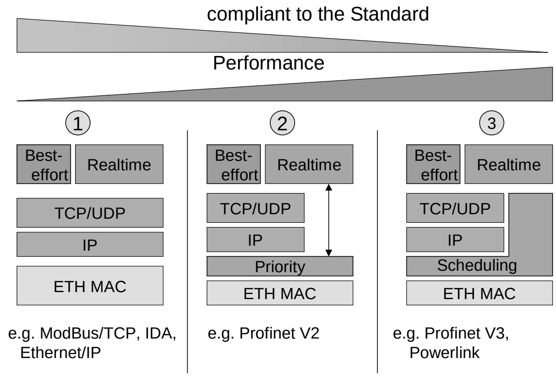

Fig. 4. Structural classification of the different vendor-driven approaches for realtime Ethernet

dwell time of the node is one of the substantial influence factors for the realtime performance and has for embedded devices typical values of $1ms$ (Jasperneite and Neumann, 2001). The soft realtime version of Profinet SRT (PNO, 2003) should be assigned to this class, for example.

In Classes 1 and 2, the priority support described in IEEE 802.1Q can also be used depending on the approach (IEEE, 1998b).

In Class 3 the scheduling on the MAC level is again modified through the introduction of a TDMA method. For example, a central poll-select procedure is used in Powerlink (Powerlink, 2003) and a procedure that is distributed in the switches is used in the Profinet IRT version. Class 3 can be used in applications that require maximum latency in the range $1ms$ and a maximum jitter of $< 1\mu s$. 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 4, conformance with the Ethernet standard decreases from left to right, while the achievable realtime performance increases in the same direction.

6. SUMMARY

Realtime behavior is guaranteed when the requirements for timeliness and simultaneity are met. Realtime Ethernet is based on the exclusive use of bridging technology and the simultaneous use of full duplex transmission (micro segmentation). This ensures that no more collisions can occur on the medium and therefore makes the CSMA/CD method that was previously used in Ethernet applications obsolete. The class of service concept according to IEEE 802.1D/Q create an effective method for isolating time-critical and best-effort applications. The end-to-end delay can be reduced by factor 10 by optimizing the runtimes in the

TCP/IP protocol stacks of the relevant devices. As a result of these standardized concepts, a MAC latency in low double figures (ms) can be achieved.

When using Ethernet in applications with latency in the range less than $1ms$ and a jitter of less than $1\mu s$, such as in motion control, intervention in the scheduling of the MAC level remains unavoidable. Here time slot methods are used in the vendor-driven approaches currently under discussion, whereby one time slot is reserved for the transmission of time-critical data and another is reserved for the transmission of TCP/IP applications, for example.

The price to pay for this improved performance is in the limited use of standard Ethernet components (chips, switches, etc.).

REFERENCES

AS-Interface (2003). http://www.as-interface.com.

Bello, L. Lo and O. Mirabella (2001). Design Issues for Ethernet in Automation. In: *Proceedings of the* 8^{th} *IEEE international Conference on Emerging Technologies and Factory Automation (ETFA'01)*. Antibes, France. pp. 213–222.

Chiueh, T. and C. Venkatramini (1994). Supporting Real-Time Traffic on ethernet. In: *Proceedings of IEEE Real-time Systems Symposium*. pp. 282–286.

Clatha, A. (1998). Automation Technologies & Strategies for the Millenium. In: *ARC Automation Technologies Forum 98*. Orlando, U.S.

Ethernet/IP (2003). *Ethernet Industrial Protocol (EtherNet/IP)*. www.ethernet-ip.org.

IDA (2001). *IDA Architecture Description and Specification V1.0*. IDA-Group. www.ida-group.org.

IEC (2003). *Digital data communications for measurement and control - Profiles for ISO/IEC 8802-3 based communication networks in real time applications MT9 / WG1*. new work item proposal.

IEEE (1997). *Specification for 802.3 Full Duplex Operation*. IEEE. New York. ANSI/IEEE Std. 802.3x.

IEEE (1998*a*). *Media Access Control (MAC) Bridges*. IEEE. New York. ANSI/IEEE Std 802.1D-1998.

IEEE (1998*b*). *Virtual Bridged Local Area Networks*. IEEE. New York. ANSI/IEEE Std 802.1Q-1998.

IEEE (2002). *IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems*. IEEE. New York. ANSI/IEEE Std 1588-2002.

INTERBUS (2003). *INTERBUS Club*. http://www.interbusclub.com.

Jasperneite, J. (2002). *Performance Evaluation of a Class-of-service based Local Area Network for using at the Field device level (only in german)*. Shaker Verlag. Aachen, Germany. ISBN 3-8322-0832-1, Dissertation.

Jasperneite, J. and P. Neumann (2001). Switched Ethernet for Factory Automation. In: *8th IEEE International Conference on Emerging Technologies and Factory Automation*. Antibes - Juan les Pins, France. pp. 205–212.

Jensen, E.D., C.D. Locke and H. Tokuda (1985). A Time-Driven Scheduling Model for Real-Time Operating Systems. In: *Real-Time Systems Symposium*. IEEE.

Kang, L. and Eidson, J., Ed.) (2003). *Workshop on IEEE-1588, Standard for a Precision Clock Synchronization Protocol for Networked Measurements and Control Systems*. National Insitute of Standards and Technology (NIST).

Krommenacker, N., E. Rondeau and T. Divoux (2001). Study of Algorithms to define the cabling plan of switched ethernet for real-time applications. In: *Proceedings of the* 8^{th} *IEEE international Conference on Emerging Technologies and Factory Automation (ETFA'01)*. Antibes, France. pp. 223–230.

Kweon, S.-K., K. G. Shin and Q. Zheng (1999). Statistical real-time communication over ethernet for manufacturing automation systems. In: *IEEE Real-Time Technology and Applications Symposium*. pp. 192–202.

ModBus (2003). *MODBUS Users Web Site:*. http://www.modbus.org.

Mueller, M. and K. Weber (2003). Impact of Switch Cascading on Time Accuracy. In: *Workshop on IEEE-1588, Standard for a Precision Clock Synchronization Protocol for Networked Measurements and Control Systems*. National Insitute of Standards and Technology (NIST).

ODVA (2003). *Open DeviceNet Vendor Association*. http://www.odva.org.

PNO (2003). *Profibus User Organization*. www.profibus.com.

Pöschmann, A. (1999). Profibus-DP-Protokoll über Ethernet. interner Projekt-Bericht. Institut für Automation und Kommunikation e.V. Magdeburg (IFAK). Barleben.

Pöschmann, A. (2001). Chancen und Nutzen von Ethernet TCP/IP in der Automation. In: *GMA-Kongress 2001: Automatisierungstechnik im Spannungsfeld neuer Technologien, VDI-Berichte Nr. 1608*. Baden-Baden. pp. 617–626.

Powerlink (2003). *Ethernet Powerlink Standardization Group*. www.ethernet-powerlink.org.

Ricot, C. (2001). Challenges and opportunities in industrial automation. In: *Invited Talk at the* 8^{th} *IEEE international Conference on Emerging Technologies and Factory Automation (ETFA'01)*. Antibes, France.

Rüping, S., E. Vonnahme and J. Jasperneite (1999). Analysis of Switched Ethernet Networks with different Topologies used in Automation Systems. In: *Field Bus Technology* (D. Diedrich, P. Neumann and H. Schweinzer, Eds.). pp. 351–358. Springer-Verlag.

Shimokawa, Y. and Y. Shiobara (1985). Realtime Ethernet for industrial applications. In: *Proceedings of the international Conference on Industrial Electronics, Control and Instrumentation (IECON'85)*. San Francisco. pp. 829–834.