Analysis of Switched Ethernet Networks with different Topologies used in Automation Systems

S. Rüping[1], E. Vonnahme[1], J. Jasperneite[2]

[1]Heinz Nixdorf Institut
University of Paderborn
System and Circuit Technology
Paderborn, Germany

[2]Phoenix Contact GmbH
Concept Development
Blomberg, Germany

Abstract. Ethernet is the most famous type of communication network used for office applications. Currently, networks used on field level and on office level are different due to their specific requirements. Especially for real-time systems, the deterministic behavior of the network is very important. Now Switched Ethernet seems to be applicable also on field level, because collisions can be avoided and priorities can be used. In this paper Switched Ethernet networks with different topologies are analyzed concerning the transmission delays. Therefore a typical master-slave scenario of an automation system is investigated.

1 Introduction

Today nearly every computer is connected to a network. The most famous type used for local area networks (LAN) is Ethernet [2]. Since 1975, when Ethernet was introduced by Xerox, a steady development has been done up to the newest Gigabit Ethernet. At the moment research is carried out for Terabit Ethernet.

The large number of Ethernet networks worldwide leads to the following consequences. First, many hard- and software components are available. Second, the components are inexpensive due to the high number of sold units. And third, there are many people, that have high knowledge about Ethernet. These consequences combined with the fact, that the transmission rates become higher and higher, make it sensible to think about Ethernet in automation systems even at field level.

One of the main problems of applying Ethernet to field level is based on the medium access control protocol CSMA/CD (Carrier Sense Multiple Access / Collision Detection), which cannot guarantee a maximum delay time for data transmission. A solution for this seems to be the Switched Ethernet technology [1, 3, 6]. In this paper a theoretical analysis of Switched Ethernet networks applied to field level tasks is presented. The main point of interest is the analysis of different topologies, which can be used to build these networks.

2 Switched Ethernet Networks

Ethernet networks based on twisted pair connections usually have a star topology with a central Hub. A Hub is a multiport repeater that forwards the data received by a port to all other ports. If the network is enlarged, up to 2 Hubs can be added. But nevertheless, the whole network is a so-called shared medium, which means only a single node can send data at a time. If the number of nodes becomes too high, a router or a bridge can be used to split the network into different collision domains [4]. The problems with router or bridges are, that they are relatively expensive and often have only a few ports.

A Switch is an intelligent Hub, that can read and process the destination address of the incoming data and send it only to the required out-ports. Figure 1 shows the difference between a network based on Hubs and on Switches.

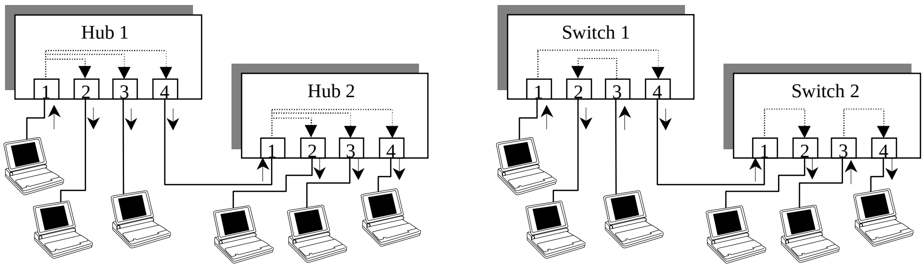

Fig. 1. Difference between Hub and Switch technology

In the Hub network the data, which is sent by a node, is received by all other nodes. In the Switch network, the data is sent only to the destination nodes, which means several nodes can send data at a time.

3 Requirements of Automation Systems

The requirements of automation networks are different to the requirements of computer LANs. On field level data packets are often small (only a few Bits or Bytes), and the latency and overall delay time must be very short. Especially for real time systems the network has to guarantee a deterministic behavior [5].

In order to investigate the suitability of Switched Ethernet in automation applications, the following system will be analyzed.

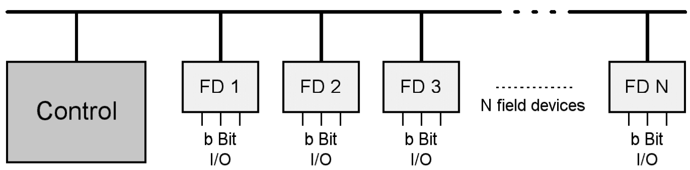

Fig. 2. Example of an Automation System

The master of the system is the node “Control” (e.g. a CNC or PC node). Besides this there are N field devices, which are connected to the master by a network. Each field device has b bits input/output data. The system runs cyclic. A cycle begins with transmitting individual data from each field device to the master (sensor data). After that the master calculates new actuator data for all field devices and transmits it. It is important, that the network has a small and deterministic latency and delay time in order to guarantee the defined cycle time.

4 Calculations for different Topologies

With Switched Ethernet systems can be built, that realize a completely deterministic behavior. In order to do so, two things are important. First, each device in the network must have it’s own switch. Second, the switches must work in the so-called Store-and-Forward mode. This mode makes it possible, that a switch, which receives multiple data for just one output-port, can store the data and send it one after the other. If now every device has it’s own switch, there are only point-to-point connections in the system. Therefore no collisions on the medium can occur. By using priorities or other mechanisms to order the sequence of packets in the switches, the system will be deterministic [6].

Figure 3 shows three different topologies, that can be used to connect the nodes of the example system. Each connection between two nodes enables full duplex communication. For all following calculations Fast Ethernet with 100 Mbits/sec is used. The transmission of data from the master to the field devices can be done on two different ways. The first is, to build a large packet, in which the data for all devices is included, and to send it as a multicast. Therefore each field device has to know, at which position in the packet the right data is. In the following, this is called the multicast-solution. The second is, to send individual packets to each field device. This will be called the unicast-solution.

All calculations have been done for simple protocols only, which are SNAP (Subnetwork Access Protocol) or SNAP with UDP (User Datagram Protocol) [1]. Based on the rules, how packets for these protocols have to look like, the theoretical minimum cycle times depending on the number of field devices and the number of input/output bits per device are calculated. This is done for the three presented topologies. The time, that is needed to process the data in the control unit and the field devices is assumed to be zero.

For the unicast solution the following formulas can be given. The time that is necessary to transmit a packet is:

$$t_f = \max\{h + b; 512\} \cdot t_b + t_g \qquad (1)$$

h is the number of header bits, b is the number of data bits. A frame is not allowed to be smaller than 512 bits, therefore the maximum must be taken. t_b is the bit time, t_g is the interframe gap time.

For the line topology a minimum cycle time t_c can be calculated as:

$$t_c = 2(N+1)t_S + 2(N+2)t_f \qquad (2)$$

N is the number of field devices, t_s is the switch delay time.

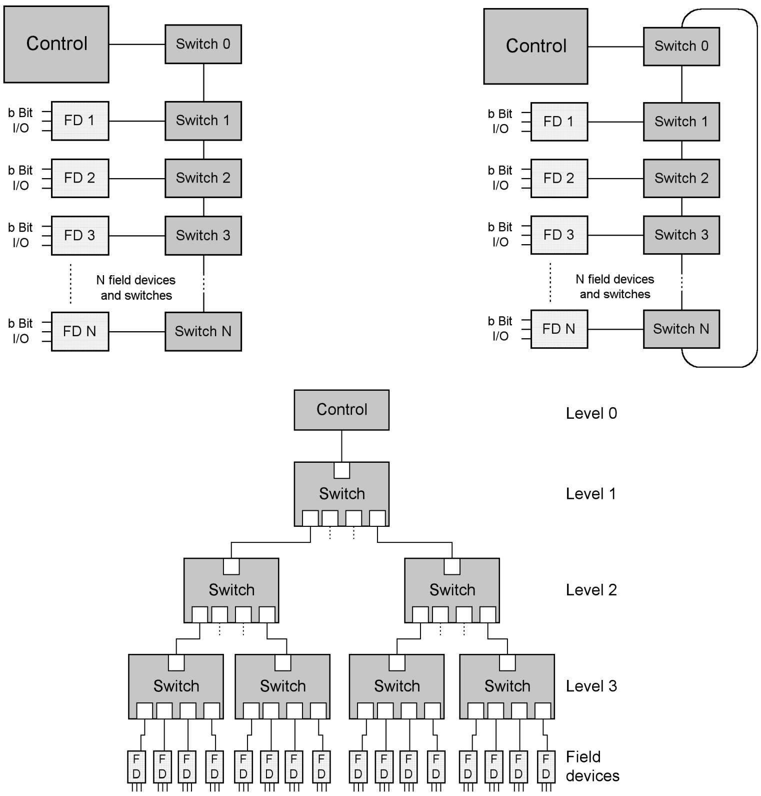

Fig. 3. Line Topology (top left), Ring Topology (top right) and Tree Topology (bottom)

For the ring topology the minimum cycle time is:

$$t_c = (N+3)t_S + 2(N+2)t_f \qquad (3)$$

And the same for the tree topology, where E is the number of switch levels:

$$t_c = 2\,E\,t_S + (2\,E + N + 1)t_f \qquad (4)$$

For the multicast solution, the packet that is sent from the master to the field devices has the following transmission time:

$$t_{fm} = \max\{h + N\,b; 512\} \cdot t_b + t_g \qquad (5)$$

The answers from the field devices still need the same time as before:

$$t_{fa} = \max\{h + b; 512\} \cdot t_b + t_g \quad (6)$$

Again the minimum cycle time for the topologies are calculated:

Minimum cycle time for the line topology:

$$t_c = 2(N+1)t_S + (N+2)(t_{fm} + t_{fa}) \quad (7)$$

Minimum cycle time for the ring topology:

$$t_c = \max\{t_1 + (N+1)t_S + (N+2)t_{fa}; (N+1)t_S + (N+2)t_{fm} + t_S + 2t_{fa}\} + (N-1)t_{fa} \quad (8)$$

Minimum cycle time for the tree topology

$$t_c = 2Et_S + (E+1)t_{fm} + (E+N)t_{fa} \quad (9)$$

5 Presentation of the results

In order to present the calculated results, the following figures show plots of a comparison between the topologies. For the number of field devices the minimum cycle times are calculated and shown as a graph.

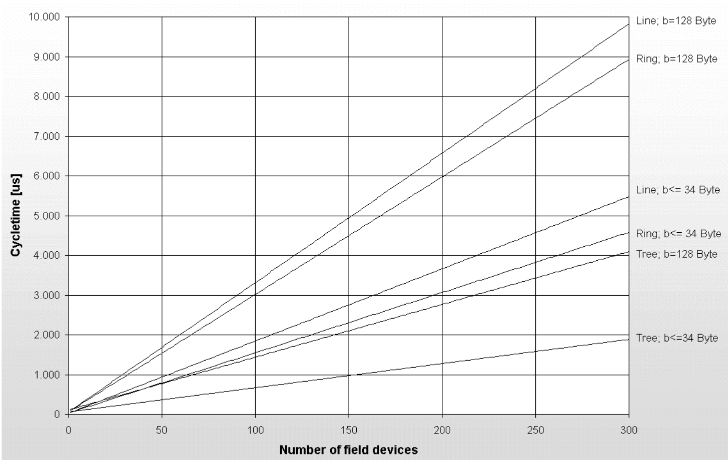

Fig. 4. Comparison of the topologies for the unicast solution

Figure 4 and 5 show the results of the topology comparison, when the unicast-solution is used (figure 4) and when the multicast-solution is chosen (figure 5). It can be seen, that the usage of unicasts is much faster (e.g. line topology, 300 devices, b=32: about 5.400 µs) than the multicast solution (about 34.000 µs for the same parameters). This is a result that has not been expected at the beginning. The main reason for it is the usage of store-and-forward switches. A packet has to be received completely before it can be transmitted to the next switch. If the packet is large and the number of switches is high, the system becomes slow. Optimization of the longest data-path by reordering the packets cannot be untertaken when using the multicast-solution.

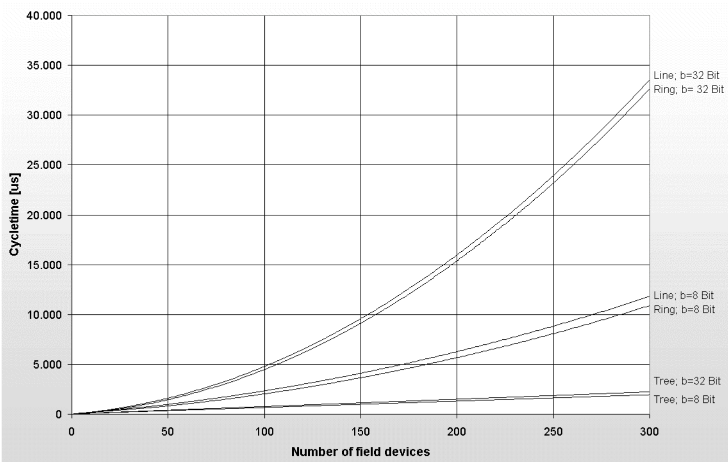

Fig. 5. Comparison of the topologies for the multicast solution

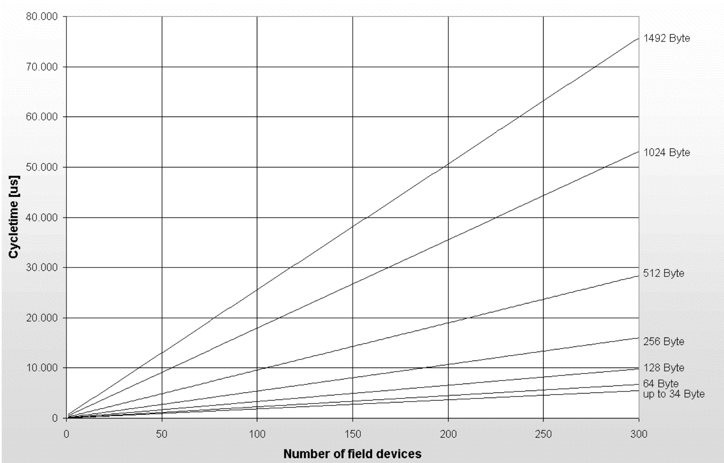

Fig. 6. Influence of the number of bits per device (line topology)

As another example for visualized results, the figures 6, 7 and 8 present the minimum cycle time for the line topology when the number of data bits per device (figure 6), the type of protocol (figure 7) and the switch delay is a parameter. All numbers are based on the unicast-solution.

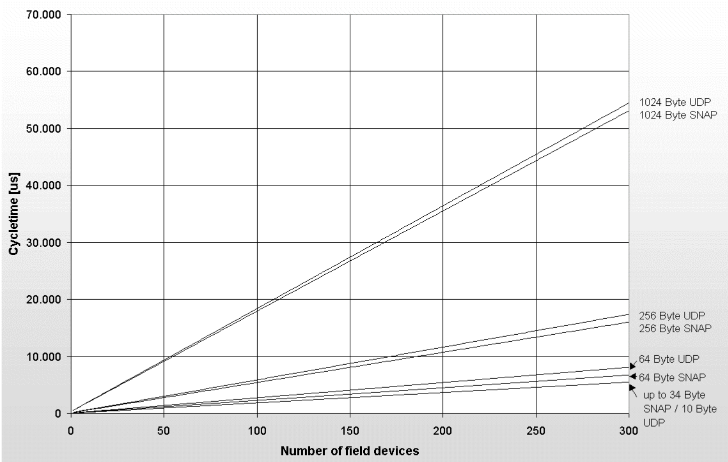

Fig. 7. Influence of the protocol (line topology)

The cycle time increases linearity with the I/O data size of the field devices, but if the size is smaller than 34 Bytes with SNAP, the frame must be padded to be at least 64 Bytes long. The type of the analyzed protocols has only little effect on the cycle time, connection oriented protocols like TCP would have a greater influence.

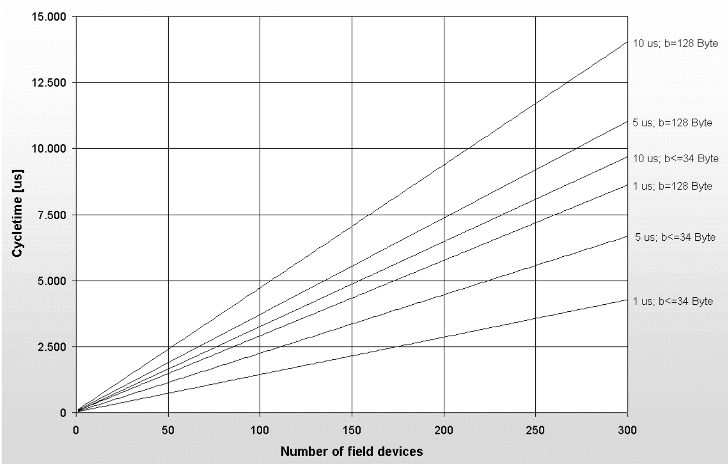

Fig. 8. Influence of the switch delay (line topology)

6 Conclusions

In this paper different topologies of Switched Ethernet networks applied to automation systems are analyzed. The theoretical minimum cycle time for a simple master-slave communication model is calculated based on line, ring and tree topology. Further parameters are the switch delay, the protocol type, the number of field devices and the I/O data size. Concerning the data transmission from the master to the field devices, two different concepts are investigated: the unicast- and the multicast-solution.

The results show, that the unicast-solution performs better than the multicast-solution. The tree topology achieves shorter cycle times, than line and ring topology. Another advantage of the tree topology is, that the number of required switches is smaller.

The ring topology performs better than the line topology. Especially the redundancy in case of an error is important for many applications. The problem is, that a special routing strategy and redundancy management is necessary.

Contact: rueping@hni.uni-paderborn.de

References

1. Held, G., “Ethernet Networks: Design, Implementation, Operation, Management”, Wiley, New York, 1996

2. IEEE Standard 802.3, “Carrier Sense Multiple Access with Collision Detection (CSMA/CD) Access Method and Physical Layer Specifications”, 1998

3. Johnson, H., “Fast Ethernet: Dawn of a new Network”, Prentice Hall, New Jersey, 1996

4. Perlman, R., “Interconnections: Bridges und Routers”, Addison Wesley, Bonn, 1993

5. Schnell, G., “Bussysteme in der Automatisierungstechnik”, Vieweg, Braunschweig, 1996

6. IEEE Standard 802.1