INTERFERENCE CAUSED BY THE INSERTION OF AN h-BEB STATION IN STANDARD SHARED-ETHERNET NETWORKS: SIMULATION ANALYSIS[1]

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ABSTRACT

In this paper, it is presented the simulation analysis of an enhanced algorithm for the collision resolution in shared Ethernet networks. Such algorithm, referred as high priority Binary Exponential Backoff (h-BEB), provides high priority traffic separation, enabling the support of real-time communications. One of the main features of the h-BEB algorithm is to enable the coexistence in the same network segment of Ethernet standard stations with h-BEB modified stations, by imposing higher priority for the transfer of h-BEB messages (privileged traffic).

The simulation analysis shows that the proposed traffic separation guarantees a predictable and significantly smaller access delay for the h-BEB station, when compared with the access delay for standard Ethernet stations. The simulation analysis also shows that the h-BEB traffic must be tightly controlled, as it has a high interference level over the non-real-time traffic. Otherwise, if the load generated by the h-BEB station is not closely controlled, the standard Ethernet stations may experience extended access delays.

INTRODUCTION

Ethernet is the most used Local Area Network technology in the world, with million of interconnected nodes. The main reason for the success of the Ethernet networks is due to their simplicity, which derives from its MAC protocol. Nowadays, the Ethernet network appears with several advantages to be used as preferred communication protocol to suport industrial control applications (Decotignie, 2002).

In spite of a full-duplex operating mode of Ethernet networks has been introduced in the early 90s (IEEE 802.1D) (1999), using bridges (referred as Ethernet Switching Hubs) to interconnect node stations, numerous Ethernet networks still operate in heterogeneous environments, with Ethernet Switching Hubs interconnecting both independent node stations and Ethernet repeaters Hubs.

Within the traditional CSMA/CD protocol, the BEB algorithm delays the frame retransmission during a time interval (backoff delay) that is a probabilistic function of the number of previous collisions. This means that the retransmission probability does not depend on the type of traffic, but just on the state of the collision counter of each particular station.

As a consequence, within each of the collision domains, it is not possible to provide traffic separation. To separate traffic, which is a requirement to support real-time communication in unconstrained environments, there are usually two different approaches: either avoiding collisions, by controlling the medium access rights of each station (TDMA scheme, token passing, etc), or ensuring a deterministic collision resolution, by modifying the collision resolution algorithm. A third approach (that is not deterministic) is to reduce the number of occurring collisions, enhancing the network responsiveness to real-time message requests.

Several approaches and techniques have been developed to provide real-time behavior to Ethernet-supported applications. However, few of those techniques allow standard devices to coexist with enhanced stations in the same network segment. Relevant exceptions are (Sobrinho and Krishnakumar, 1998: ; Moraes and Vasques, 2005).

The proposed h-BEB algorithm (Moraes and Vasques, 2005) allows the coexistence of Ethernet standard devices together with modified devices in the same network segment. The referred algorithm imposes a higher priority for the transfer of h-BEB related traffic. As a consequence, it becomes possible the implementation of traffic separation policies, which are the foundation for the support of real-time communication in heterogeneous Ethernet environments.

One of the main particularities of the CSMA/CD protocol is the Packet Starvation Effect. (Whetten, Steinberg et al., 1994) demonstrated that, in heavily loaded networks, an older packet will have a smaller probability to be transferred than a newer one. For example: consider that 2 stations have packets ready to be transmitted (station1 and station2), which will be transmitted at approximately the same time; a collision will occur and then both stations will backoff during a randomly selected delay between 0 and 2^n-1 slot times, where n is the number of previous collisions. In the first collision resolution interval, if station1 waits 0 slot times and station2 waits 1 slot time, station1 will transmit its packet while station2 will wait. Supposing that station1 has other packets to be transferred, then, in the following collision the backoff time of station1 will be 0 or 1, and the backoff time of the station2 will be 0, 1, 2 or 3. Therefore, station1 will have a higher transmission probability. Such Packet Starvation Effect will occur whenever a station has a sequence of packets to be consecutively transferred, if the network interface adapter is able to effectively contend for the network access at the end of every transmitted frame. Otherwise, one other station will acquire the transmission medium.

The main target of this paper is to evaluate the interference caused by the insertion of an h-BEB station in a shared-Ethernet segment, by evaluating the average access delay. The results were obtained by a simulation model, which was implemented using the Network Simulator (NS-2) tool (2004).

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This paper is organized as follow: section 2 reviews the binary exponential backoff algorithm used in standard Ethernet and describes the h-BEB collision resolution algorithm (Moraes and Vasques, 2005). Section 3 shows the simulation model. The performance analyses of these protocols are presented in the section 4. In section 5 a briefly overview of work related with achieving real-time behavior in Ethernet is carried on. Followed by some conclusions and references.

THE HIGH PRIORITY BINARY EXPONENTIAL BACKOFF ALGORITHM (h-BEB)

The CSMA/CD (Carrier Sense Multiple Access with Collision Detection) protocol is the Media Access Control (MAC) protocol of Ethernet networks. Basically, the CSMA/CD protocol works as follows: when a station wants to transmit, it listens to the transmission medium. If the transmission medium is busy, the station waits until it goes idle; otherwise, it immediately transmits. If two or more stations simultaneously start to transmit, the transmitted frames will collide. Upon the collision detection, all the transmitting stations will terminate their transmission and send a jamming sequence to ensure that all the transmitting stations recognize the collision and abort the transmission. When the transmission is aborted due to a collision, it will be repeatedly retried after a randomly evaluated delay (backoff time) until it is successfully transmitted or definitely aborted (after a maximum number of 16 attempts) (1985).

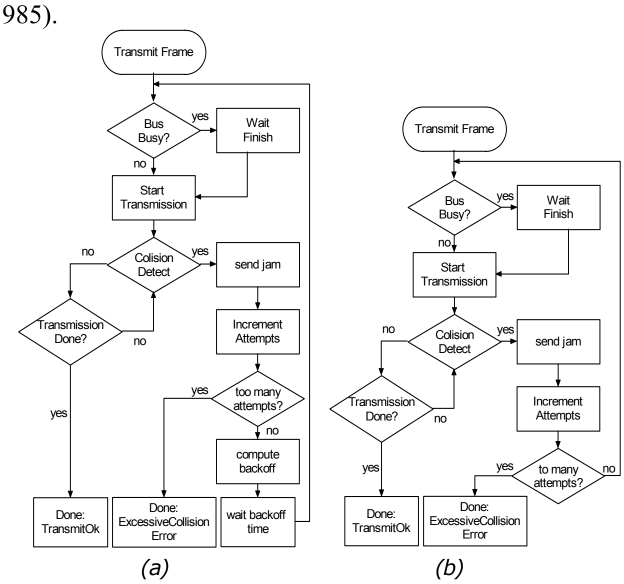

Figure 1: CSMA-CD protocol with BEB resp. h-BEB collision resolution algorithms.

A station implementing the h-BEB algorithm has the same operating behavior, except for the backoff delay, which is set to 0. In such case, an h-BEB station starts immediately to transmit after the end of the jamming sequence. This behavior guarantees the highest transmitting probability to the h-BEB station, in a shared Ethernet segment with multiple BEB stations. The h-BEB station will always try to transmit its frame in the first available slot after the jamming sequence, while all the other stations implementing the BEB algorithm will wait between 0 and 2^n-1 slot times, where n is the number of collision resolution rounds. Figures 1 (a) and (b) summarize the dynamic behavior of the CSMA/CD protocol with, respectively, the BEB and the h-BEB collision resolution algorithms.

The h-BEB collision resolution algorithm is therefore able to impose real-time traffic separation, as the traffic generated by the h-BEB station will always be transferred before the traffic generated by the other stations. Therefore, this algorithm is adequate to support real-time communications in shared Ethernet segments, as long as all the real-time traffic in the network is generate by the h-BEB station.

This behavior is highly adequate to, for instance, real-time video/voice transferring applications in legacy shared Ethernet networks. By simply plugging a notebook computer with the modified hardware to the shared Ethernet segment, it becomes possible to transfer traffic at a higher priority than the traffic generated by all the other stations.

THE SIMULATION MODEL

A simulation model was implemented using the Network Simulator (NS-2) tool (2004), which is a shareware discrete event simulator specially suited for the network performance analysis. For the BEB collision resolution algorithm, a station process implements directly the IEEE 802.3 standard, which is already available in the NS-2 tool. For the h-BEB collision resolution algorithm, a station process has been built according to the h-BEB specification described in Section 2 and in (Moraes and Vasques, 2005). The simulation model considers a shared Ethernet environment, where multiple stations are interconnected with a *special station* (Figure 2) implementing either the h-BEB (enhanced Ethernet mode) or the BEB algorithms (traditional Ethernet mode).

The target of the simulations is to analyze the behavior of the h-BEB algorithm when compared to the use of the traditional BEB collision resolution algorithm. The performance measures include: throughput, average packet delay and standard deviation (transfer jitter). The throughput is the ratio between the total duration of the successfully transferred packets and the simulated time interval, i.e., the fraction of nominal bandwidth that is used for successfully transferring data. The average packet delay is the average delay required to successfully transfer a packet, measured from the first transmission attempt to the end of the packet transfer. Discarded packets are not considered for the average packet delay evaluation, as this measure deals with just the successfully transferred packets. The standard deviation, which is related to the message transfer jitter, is given by:

$$\sigma = \sqrt{\frac{1}{N} \times \sum_{i=1}^{N} (x_i - \bar{x})^2} \qquad (1)$$

where N is the total number of simulated packets, x_i is the delay of each transferred packet and $\bar{x}$ is the evaluated average packet delay.

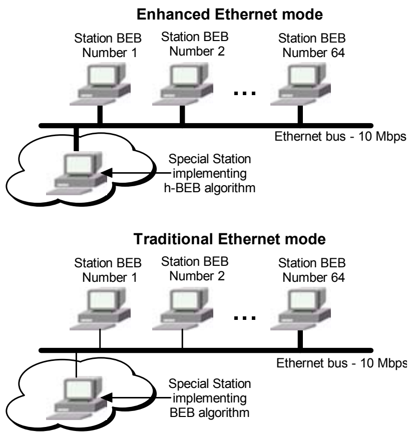

Figure 2: Shared Ethernet environment.

PERFORMANCE ANALYSIS

In a previous paper (Moraes and Vasques, 2005), the probabilistic analysis of the h-BEB algorithm has been presented. Such analysis addressed the exact analytical behavior of the h-BEB algorithm in heavily loaded network scenarios. However, it is well known that such type of exact probability analysis addresses a rarely occurring case, as it is based on the assumption that, at the start of the transmission attempt, all the network stations participate in the contention process (heavily loaded network scenario). For more realistic load scenarios (intermediate load cases), the performance analysis must be done by simulation, which enables a more comprehensive analysis of the behavior of the h-BEB algorithm but does not provide exact results. In (Moraes and Vasques, 2005) the simulation analysis of the h-BEB algorithm has been done, where both the results for the small and the large population scenarios (respectively, 5 and 65 stations in the network segment) clearly showed that, whatever the network load or the network population, the average packet delay is nearly constant for the h-BEB station in the enhanced network case scenario. Nevertheless, in that previous analysis all stations equally shared the offered load. Finally, the standard Ethernet (which uses the BEB algorithm) results were validated against previous simulation results presented by (Christensen, 1998). Such h-BEB *vs.* BEB results are briefly represented in Figures 3 and 4, which clearly demonstrate the advantage of using the h-BEB mechanism to impose traffic prioritization.

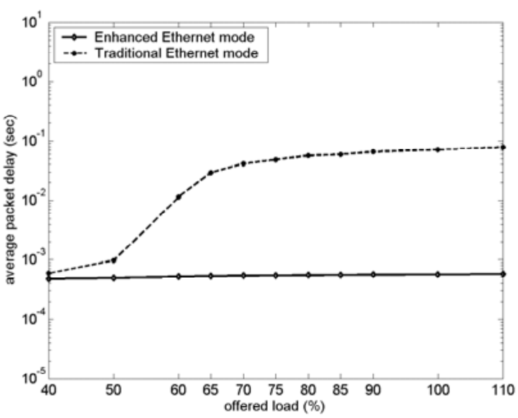

Figure 3: Average delay for the special station in a small population Ethernet segment.

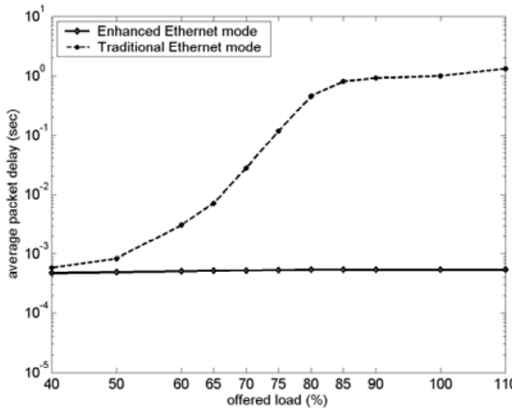

Figure 4: Average delay for the special station in a large population Ethernet segment.

The average throughput for each Ethernet mode is plotted in Figure 5 and compared with the theoretical maximum achievable throughput (i.e., without packet collisions or packets being discarded). The average throughput achievable in shared Ethernet networks decreases in the 70% to 110% load region. The difference between the maximum achievable throughput and the obtained throughput (both for the enhanced and the traditional Ethernet modes) is directly related to the lost packets. Similar results have already been shown in previous simulations made by other authors (Boggs, Mogul et al., 1995: ; Christensen, 1998). Moreover, we observed in the simulation case that the h-BEB station never discarded any packet. This is an important result for a station implementing the h-BEB collision resolution algorithm.

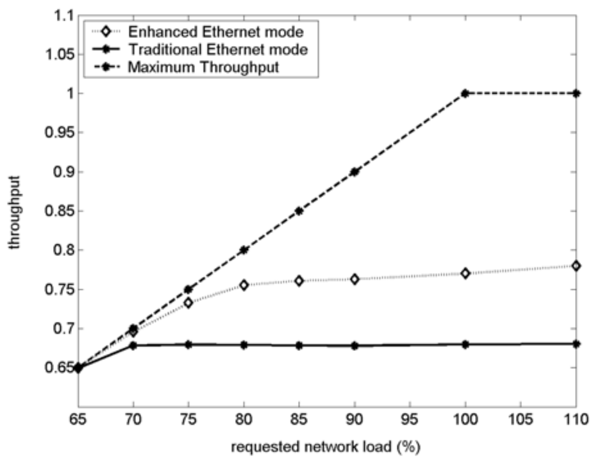

Figure 5: Throughput in the fixed load case.

The results illustrated in Figure 6 show that the special station in the enhanced Ethernet mode scenario has an average packet delay that is smaller than for the traditional Ethernet mode scenario. Such average packet delay is now slightly increasing for the simulated network load. In Figure 4 was illustrated that there is a high rate of packets loss in the network, then, it becomes clear that the sent traffic by h-BEB station should be controlled, mainly, when it is desirable that the special station has a small influence on the behavior of the other stations (Figure 7).

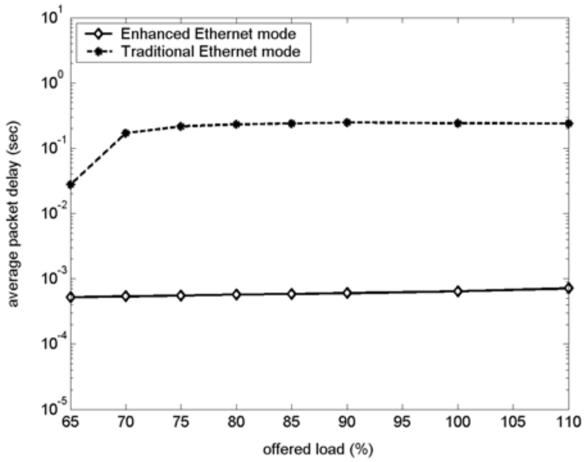

Figure 6: Average delay for special station in the fixed load case.

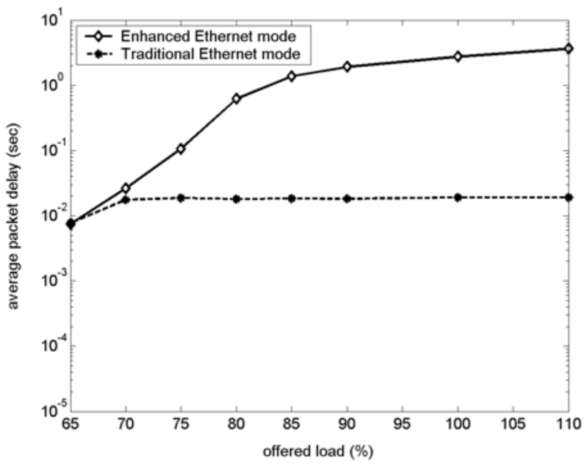

Figure 7: Average delay for other stations in the fixed load case.

Finally, the standard deviation of the average packet delay in the fixed load case is represented in Figures 8 and 9, which is directly related to the message transfer *jitter*. As in the previous cases, a significantly smaller standard deviation is observed for the case of the special station implementing the h-BEB algorithm (Figure 8) than for the case of the BEB stations.

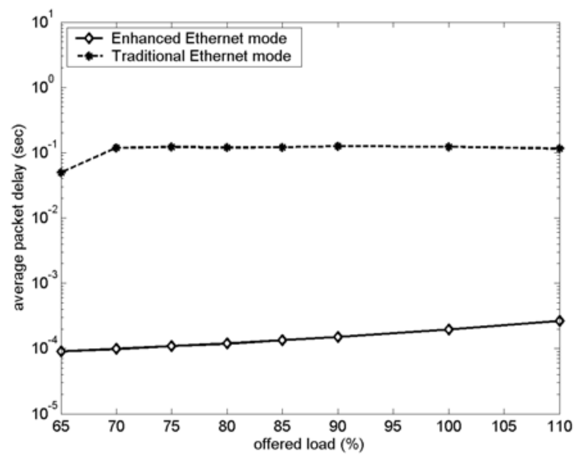

Figure 8: Standard deviation for the special station in the fixed load case.

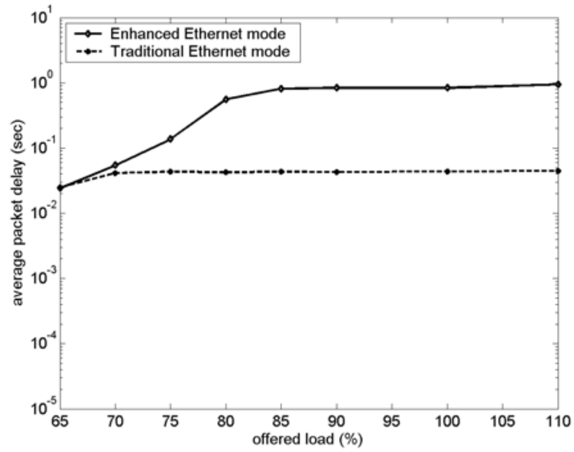

Figure 9: Standard deviation for other stations in the fixed load case.

REAL-TIME BEHAVIOR IN ETHERNET

Several approaches and techniques have been developed to provide a real-time behavior to Ethernet-supported applications. Some of these approaches are based on the Switched Ethernet technology, where the hub-based technology is replaced by switches, trying to eliminate CSMA/CD collisions by dividing "collision domains into point-to-point connections" (Jasperneite and Neumann, 2001). The Switched Ethernet standard, introduced in the early 90s (IEEE 802.1D), enables the micro-segmentation of the network by regenerating information only to the receiving port. Additionally, when using Ethernet Switching Hubs, it is possible to manage network traffic, by means of the adequate setting of data flow permissions and priorities. Also, adequate network management functionalities were specified both by the IEEE 802.1p and IEEE 802.1q VLAN standards, in order to enhance the transmission of critical data. Nevertheless, avoiding collisions does not guarantee a real-time behavior in an unconstrained environment, as the congestion/overflow of the switches may still occur.

When considering, as in this paper, the traditional shared Ethernet standard, different approaches can be identified in what concerns the support of real-time communications (Moraes and Vasques, 2005: ; Pedreiras, Almeida et al., 2005): ensuring a deterministic collision resolution, by modifying the collision resolution algorithm or avoiding collisions, by controlling the medium access rights of each station. A third approach (that is not deterministic) is to reduce the number of occurring collisions, enhancing the network responsiveness to real-time message requests.

To ensure a deterministic collision resolution scheme, it requires the modification of the network adapter of all the Ethernet stations, to guarantee that the colliding frames are serialized in an upper-bounded time interval. One of the first proposals was made by (Takagi, Yamada et al., 1983), which presented a CSMA/CD protocol with deterministic contention resolution (DCR). In the absence of collisions, the CSMA/DCR protocol implements the CSMA/CD access method. In collision situations, a binary search tree is used to sort the colliding nodes. Later, the DOD-CSMA-CD protocol (Le Lann and Rivierre, 1993) improved the CSMA-DCR protocol. The drawback of such approaches is the need for MAC modifications in all the network stations.

For controlling the medium access right many approaches have been proposed. One of the first was the one by (Chen and Lu, 1990) based on the TDMA (Time Division Multiple Access) paradigm, where each station has a pre-allocated transmission time interval. Another approach was proposed by (Pritty, Malone et al., 1995), based on the use of the Timed Packet Release principle, where a monitor node periodically transmits a slot pulse to synchronize the medium access. Some recent solutions use master-slave techniques, where a special node, the Master, instructs the other nodes, the slaves, to transmit in specific instants. Collisions are thus avoided. (Pedreiras, Almeida et al., 2001) proposed a master-multi slave technique called FTT-Ethernet to schedule communications in a shared Ethernet network.

Another way to provide a deterministic collision-free environment is to use an explicit token passing procedure, where each station is allowed to access the medium only during the token holding intervals. (Venkatramani and Chiueh, 1994) proposed the RETHER (real-time Ethernet) protocol, where the network operates in the CSMA mode until a real-time request arrives, passing then to the RETHER mode, where all nodes operate according to a token passing protocol. (Lee, Moon et al., 1998), proposed the use of the IEEE 802.4 Token-Passing Bus Access method directly on top of the Ethernet Physical Layer.

Concerning solutions that allows standard devices to coexist with enhanced modified stations in the same network segment, imposing higher priority to privileged traffic, there are not many works to report. Besides the h-BEB algorithm proposed by (Moraes and Vasques, 2005) and described in section 2, one can identify the EquB protocol proposed by (Sobrinho and Krishnakumar, 1998). It enables a privileged access to real-time traffic with a FCFS (First-Come-First-Served) discipline. The collision resolution mechanism for real-time sources requires the disabling of the exponential back-off mechanism and the transmission of jamming sequences with durations dependent on the contention periods experienced by the real-time traffic.

The third approach to support real-time communications in shared Ethernet environments is to reduce the number of occurring collisions, enhancing the network responsiveness to real-time message requests. Note that these solutions are non-deterministic, as collisions are still solved in a probabilistic way. (Molle and Kleinrock, 1985) proposed a CSMA algorithm, called Virtual Time CSMA (VTCSMA). It uses a probabilistic approach combined with specific timing parameters (arrival time, laxity, deadline, length) for the collision resolution, enabling different scheduling policies. (Zhao and Ramamritham, 1987) presented a performance analysis of the four VTCSMA protocols. Another relevant modification proposed to the CSMA/CD protocol is the Window Protocol (Kurose, Schwartz et al., 1984: ; Kurose, Schwartz et al., 1988: ; Zhao, Stankovic et al., 1990), which implements a dynamic time window to reduce the number of occurring collisions. In (Jan and Yeh, 1993) is presented the Dynamic pi persistent CSMA/CD protocol, where the transmission probability depends on the laxity of the ready packet. (Molle, 1994) proposed a BEB compatible algorithm, the Binary Logarithmic Arbitration Method (BLAM), with a modified collision counter policy. According to (Christensen, 1996), following to a successful transmission, all the stations will have an equal access probability to the medium. Therefore, it eliminates the packet starvation effect (Whetten, Steinberg et al., 1994). The Capture Avoidance Binary Exponential Backoff (CABEB) algorithm proposed by (Ramakrishnan and Yang, 1994) addresses also the packet starvation effect.

Finally, another approach is to use traffic smoothing mechanisms, introduced by (Kweon, Shin et al., 1999: ; Kweon, Shin et al., 2000), where the packet generation rate (from the upper layers) is kept below a defined threshold, the network-wide input limit. In (Carpenzano, Caponetto et al., 2002) the smoothing actions are performed by a fuzzy controller, where the network load is observed along determined time intervals, via the throughput measurement and the number of occurring collisions.

CONCLUSIONS

This paper analysis the interference caused by a station implementing a traffic separation procedure in a shared-Ethernet network segment, by means of the high priority Binary Exponential Backoff (h-BEB) algorithm.

The simulation analysis shows that the proposed traffic separation guarantees a predictable and significantly smaller access delay for the h-BEB station, when compared with the access delay for standard Ethernet stations. The simulation analysis also shows that the h-BEB traffic must be tightly controlled, as it has a high interference level over the non-real-time traffic. Otherwise, if the load generated by the h-BEB station is not closely controlled, the standard Ethernet stations may experience extended access delays.

REFERENCES

(1985). IEEE standards for local area networks: carrier sense multiple access with collision detection (CSMA/CD) access method and physical layer specifications. ANSI/IEEE Std 802.3-1985.

(1999). IEEE standards for local and metropolitan area networks: virtual bridged local area networks. IEEE Std 802.1Q-1998.

(2004). ns-2 Network Simulator.

Boggs, D. R., J. C. Mogul, et al. (1995). "Measured capacity of an ethernet: myths and reality." Computer Communication Review **25**(1): 123-136.

Carpenzano, A., R. Caponetto, et al. (2002). Fuzzy traffic smoothing: an approach for real-time communication over Ethernet networks. Proceedings 4th IEEE International Workshop on Factory Communication Systems, 28-30 Aug. 2002, Vasteras, Sweden, IEEE.

Chen, W.-H. and C.-C. Lu (1990). CSMA/CD/TDMA: A dynamic combination for voice and data integration. Proceedings of IEEE INFOCOM '90: Ninth Annual Joint Conference of the IEEE Computer and Communications Societies, Jun 3-4 1990, San Francisco, CA, USA, Publ by IEEE, Piscataway, NJ, USA.

Christensen, K. J. (1996). Performance evaluation of the binary logarithmic arbitration method (BLAM). Proceedings of LCN - 21st Annual Conference on Local Computer Networks, 13-16 Oct. 1996, Minneapolis, MN, USA, IEEE Comput. Soc. Press.

Christensen, K. J. (1998). "A simulation study of enhanced arbitration methods for improving Ethernet performance." Computer Communications **21**(1): 24-36.

Decotignie, J.-D. (2002). A perspective on Ethernet-TCP/IP as a fieldbus. Proceedings of LORIA. 4th International Conference on Fieldbus Systems and their Applications, 15-16 Nov. 2001, Nancy, France, Elsevier Sci.

Jan, R.-H. and Y.-J. Yeh (1993). "CSMA/CD protocol for time-constrained communication on bus networks." IEE Proceedings I (Communications, Speech and Vision) **140**(3): 197-202.

Jasperneite, E. and P. Neumann (2001). Switched Ethernet for factory communication. ETFA 2001. 2001 8th International Conference on Emerging Technologies and Factory Automation. Proceedings, 15-18 Oct. 2001, Antibes-Juan les Pins, France, IEEE.

Kurose, J. F., M. Schwartz, et al. (1984). "Multiple-access protocols and time-constrained communication." ACM Comput. Surv. **16**(1): 43-70.

Kurose, J. F., M. Schwartz, et al. (1988). "Controlling window protocols for time-constrained communication in multiple access networks." Communications, IEEE Transactions on **36**(1): 41-49.

Kweon, S.-K., K. G. Shin, et al. (2000). Achieving real-time communication over Ethernet with adaptive traffic smoothing. RTAS 2000: 6th IEEE Real-Time Technology and Applications Symposium, May 31-Jun 2 2000, Washington, DC, USA, Institute of Electrical and Electronics Engineers Computer Society, Los Alamitos, CA, USA.

Kweon, S.-K., K. G. Shin, et al. (1999). Statistical real-time communication over Ethernet for manufacturing automation systems. Proceedings of RTAS'99: Fifth IEEE Real-Time Technology and Applications Symposium, 2-4 June 1999, Vancouver, BC, Canada, IEEE Comput. Soc.

Le Lann, G. and N. Rivierre (1993). Real-Time Communications over Broadcast Networks: the CSMA-DCR and the DOD-CSMA-CD Protocols, INRIA.

Lee, J.-Y., H.-J. Moon, et al. (1998). Token Passing Bus Access Method on the IEEE 802.3 Physicl Layer for Distributed Control Networks. Proceedings of the 15th IFAC Workshop on Distributed Computer Control Systems, Italy.

Molle, M. and L. Kleinrock (1985). "Virtual Time CSMA: Why Two Clocks Are Better than One." IEEE Transactions on Communications **COM-33**(9): 919-933.

Molle, M. L. (1994). A New Binary Logarithmic Arbitration Method for Ethernet. Toronto Canadá, Computers Research Institute, University of Toronto.

Moraes, R. and F. Vasques (2005). A Probabilistic Analysis of Traffic Separation in Shared Ethernet Systems Using the h-BEB Collision Resolution Algorithm. 13th International Conference on Real-Time Systems - RTS'2005, Paris - France.

Moraes, R. and F. Vasques (2005). Real-Time Traffic Separation in Shared Ethernet Networks: Simulation Analysis of the h-BEB Collision Resolution Algorithm. 11th IEEE International Conference on Embedded and Real-Time Computing Systems and Applications, Hong Kong - China.

Pedreiras, P., L. Almeida, et al. (2005). The Quest for Real-Time Behavior in Ethernet. Handbook of Industrial Information Technology. R. Zurawski, CRC Press**:** 48-1, 48-14.

Pedreiras, P., L. Almeida, et al. (2001). The FTT-Ethernet protocol: Merging Flexibility, Timeliness and Efficiency. Proceedings of the 14th Euromicro Conference on Real-Time Systems, Austria.

Pritty, D. W., J. R. Malone, et al. (1995). A real-time upgrade for Ethernet based factory networking. Proceedings of IECON '95 - 21st Annual Conference on IEEE Industrial Electronics, 6-10 Nov. 1995, Orlando, FL, USA, IEEE.

Ramakrishnan, K. K. and H. Yang (1994). Ethernet capture effect: Analysis and solution. Proceedings of the 19th Conference on Local Computer Networks, Oct 2-5 1994, Minneapolis, MN, USA.

Sobrinho, J. L. and A. S. Krishnakumar (1998). EQuB - Ethernet quality of service using black bursts. 23rd Conference on Local Computer Networks, Boston, MA, USA, IEEE, Piscataway, NJ, USA.

Takagi, A., S. Yamada, et al. (1983). "CSMA/CD with Deterministic Contention Resolution." Selected Areas in Communications, IEEE Journal on **1**(5): 877-884.

Venkatramani, C. and T.-c. Chiueh (1994). Supporting real-time traffic on Ethernet. Proceedings Real-Time Systems Symposium, 7-9 Dec. 1994, San Juan, Puerto Rico, IEEE Comput. Soc. Press.

Whetten, B., S. Steinberg, et al. (1994). The packet starvation effect in CSMA/CD LANs and a solution. Proceedings of 19th Conference on Local Computer Networks, 2-5 Oct. 1994, Minneapolis, MN, USA, IEEE Comput. Soc. Press.

Zhao, W. and K. Ramamritham (1987). "Virtual time CSMA protocols for hard real-time communication." IEEE Transactions on Software Engineering **SE-13**(8): 938-952.

Zhao, W., J. A. Stankovic, et al. (1990). "A window protocol for transmission of time-constrained messages." Computers, IEEE Transactions on **39**(9): 1186-1203.

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