On the performance of the IEC 61158 Fieldbus

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Luca Durante [a,1] and Adriano Valenzano [b,2]

[a] *Dipartimento di Automatica e Informatica Politecnico di Torino, Corso Duca degli Abruzzi 24, I-10129 Torino, Italy*

[b] *Centro per l'Elaborazione Numerale dei Segnali Politecnico di Torino, Corso Duca degli Abruzzi 24, I-10129 Torino, Italy*

Abstract

The IEC 61158 fieldbus protocol merges two well-established medium access control techniques based respectively on a centralized arbitration method and on a token-passing distributed scheme. The first method is used to handle real-time (cyclic) traffic, while the second one allows to share out fairly the bandwidth left free by the cyclic traffic. This paper analyzes the behaviour of an IEC 61158 network to study how the acyclic message exchanges are affected by the selection of some relevant protocol parameters. In particular two working conditions are considered in the paper: first case a steady state situation is analyzed where the asynchronous requests for the system bandwidth are equally shared among the different nodes. Second a transient condition is considered where the asynchronous message queues are temporarily overloaded and the offered load is higher than the available system bandwidth.

Key words: fieldbus, factory communications, real-time protocols

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[1] tel: +39 011 564 7078 fax: +39 011 564 7099 e-mail:durante@polito.it
[2] tel: +39 011 564 7061 fax: +39 011 564 7099 e-mail:valenzano@polito.it

Preprint submitted to Elsevier Preprint

1 Introduction

The IEC 61158 project [1–4] is an attempt to define a world-wide international standard for fieldbus communications started jointly by IEC and ISA at the beginning of the 80's. As is probably well known, since then the works of the technical committees were stalled and delayed by an endless stream of debates and contrasts among different groups representing opposite industrial interests and moved by their own economical and marketing reasons. At present the 61158 proposal is still being promoted by IEC and ISA and is facing a critical situation. In fact, the physical layer of the communication profile was approved as an international standard in 1993 [1] while an agreement is still far from being reached about the data-link and application layers [2–4]. The two more recent votes about those documents have led to opposite results: in the November 1997 ballot the data-link and application layers were accepted as draft international standards (DIS), while the September 1998 vote was negative and the DIS proposals did not become final draft international standard (FDIS). The future of the project is, to several extents, unclear, nevertheless it is important to study and analyze the peculiar characteristics of the 61158 protocol suite in order to achieve a deeper understanding of the behaviour of this kind of systems. This will enable the designer to predict and tune the network performances when (and if !) components and devices will be designed and made available according to some globally accepted version of the standard specification. From a technical point of view the IEC 61158 protocol tries to merge two well-established medium access control techniques based respectively on a centralized arbitration method similar to the one used in the Cenelec EN50170 Vol. 3 fieldbus (WorldFIP) [5] and on a token-passing distributed scheme similar, to some extent, to those adopted in the IEEE 802.4 token bus [7], FDDI [8] and Cenelec EN50170 Vol. 1 (Profibus) [6] solutions. Even though a lot of studies can be found in the literature concerning the behaviour and performance of both token-based networks [9,10] and FIP-like arbitration schemes [11], a lot of work has still to be done when considering systems where the two mechanisms are used together inside the same network as in the IEC Fieldbus. This paper investigates on some aspects concerning the current 61158 specification [3] and analyzes the performance of the network in some significant working conditions. In particular, since the proposed standard provides supports for both periodic and aperiodic information exchanges, we are interested in those system situations where a constant (asynchronous) load is offered by all the nodes connected to the system, besides a given cyclic traffic managed by the network. We will show how the selection of some network parameters such as the target token rotation time ($TTRT$) and the token holding time ($DTHT$) affects the overall system performance. The results presented in this paper have been obtained by running a software simulator of the IEC 61158 developed "ad hoc" in a number of different situations and for (simulated) network working times considerably long.

The paper is structured as follows: section 2 summarizes the main features of the 61158 protocol and outlines those characteristics that are of particular interest for our analysis while section 3 deals with the model used for carrying out the simulation experiments and section 4 reports on the results obtained for different network configurations and load conditions.

2 Some characteristics of the IEC 61158 fieldbus

As most fieldbuses the IEC 61158 (also known as IEC Fieldbus or simply Fieldbus) has a reduced protocol stack consisting of only three layers (namely physical, data link and application) and offers services at both the data-link and application layer users. Data-link services are claimed to be compatible with those offered to the OSI network layer even though the Fielbus is not OSI-compliant. In the following we will focus on those characteristics of the first two layers that are useful for understanding the work described in this paper.

The mechanism for allocating and managing the shared medium bandwidth is centralized and a single station (called link active scheduler or LAS) for each network segment is needed for arbitrating the rights to ask for bandwidth and send data between the other data link entities (DLEs). The IEC fieldbus supports both periodic and aperiodic data traffic. The LAS provides to schedule all the periodic data exchanges according to their timing requirements and then, if some residual transmission time remains, it enables the network DLEs to share out the (unused) bandwidth in a fair way. The LAS activities can be dynamically reorganized at any time according to any new request that comes from the other DLEs.

The Fieldbus physical specification is an international standard since 1993. Different media can be used for implementing the network such as copper wire, optical fiber and radio channels. In addition, remote powering can be adopted in conjunction with the copper wire links.

A 61158 system can consist of several subnetworks (local links) based on a shared bus topology and interconnected by means of bridges. Bridges can also be used to connect those stations which are not able to satisfy the timing requirements imposed by communication rules. In this case the bridges works as suitable interfaces to the network.

The physical layer offers the data link layer a set of services which are in practice the same as the most popular fieldbus solutions such as WorldFIP [5] and Profibus [6]. Only one service is completely new and is used at the startup of the network to notify the data-link layer about some characteristics of the underlying physical subsystem such as the data rate and the number of (control) bits added to each message for the transmission by the physical layer. This information is needed by the data-link entity to evaluate in advance the time needed to complete any data exchange transaction.

At the data link layer the system bandwidth is controlled by the link active scheduler which gives each station the right to transmit on the shared medium by means of a special message (token).

In practice three kinds of token can circulate (in different times) on the network:

- the *scheduler token* is always owned by the station acting as the current LAS. When this token is sent to another DLE (link master - LM) the receiver becomes the new LAS. Only one LAS can be active in each local link at any given time. Link masters are conventional stations which are able to behave as a LAS.
- the *delegated token* is created by the current LAS and sent to a (requesting) DLE in the same network segment. Since the delegated token represents the right to transmit messages, it specifies also the maximum amount of time it can be hold by the receiving station. The latter must return the token to the active LAS before the "delegated time" elapses completely.
- the *reply token* is used by the (temporary) owner of a delegated token to invoke an immediate answer from another DLE. The reply token is then returned to the requestor together with the immediate reply. Also in this case the immediate transmission from the polled DLE must be completed before the expiration of the (delegated) token.

Each cyclic data transmission over the network corresponds to an information exchange transaction scheduled by the LAS. The scheduler token represents the right to start scheduled transactions. A scheduled transaction can then be carried out by either the LAS itself (by means of a reply token sent to another DLE) or some other station which receives a delegated token from the LAS and so the right to manage the communication until the delegated token expires.

The time elapsing between two subsequent scheduled transactions can be used by LAS to distribute the local time (i.e. to synchronize the station clocks), to perform several link maintenance activities such as the probing of DLEs wishing to enter the network or to circulate a delegated token between the active DLEs.

The token circulation activity consists in periodically sending the delegated token to each active station in the network according to a round-robin strategy and allows DLEs to send acyclic data. Each DLE is allowed to obtain a certain amount of delegated time (i.e. system bandwidth) during each token “rotation”. When the token time (which can be shorter than the DLE delegated time) expires the delegated DLE is forced to return the token to the LAS but, if its activity has still to be completed, it can request further delegated time to the link scheduler. It is worth noting that if such a further request does not exceed the remaining delegated time, the LAS is compelled to satisfy it before the end of the current cycle of token circulation. When each DLE has no more pending requests or the remaining requests exceed the delegated time, the LAS resets the delegated time count for each DLE and starts a new cycle of token circulation.

The LAS continuously monitors the time needed to complete a token rotation cycle, called *actual token rotation time* ($ATRT$) and compares it to the *target token rotation time* ($TTRT$) representing the expected upper bound for $ATRT$. If the actual $ATRT$ exceeds the $TTRT$ value, the LAS increases, if possible, the priority of the acyclic exchanges for the next cycle. By contrast, when $ATRT$ is less than $TTRT$ the LAS decreases the token rotation priority.

Delegated tokens, in fact, can be assigned three different priority values that is urgent, normal and time-available; in practice the higher the priority the shorter the maximum length that is allowed for the transmitted message. For instance, urgent messages must have a data field shorter than 64 bytes, normal messages must be shorter than 128 bytes while time-available frames can carry up to 256 bytes of data. When a DLE obtains a delegated token with a given priority value it is constrained to send messages with that priority or higher.

By changing the token priority the LAS tries to affect the $ATRT$ and to keep its value below the expected $TTRT$. This mechanism, however, is not sufficient to control or bound the $ATRT$; in fact a key role is also played by the amount of delegated time ($DTHT$) a DLE can ask for each token rotation cycle. For instance, under heavy load conditions, when all the N active DLEs in the system require and use a whole $DTHT$ period for each token cycle, $ATRT$ is constrained by the product $N * DTHT$, irrespective of $TTRT$.

A control of the token rotation time simply based on the priority adjustment is too weak to keep $ATRT$ close to $TTRT$ and, in those networks where only urgent messages are used, it is useless in practice. In the IEC 61158 the $TTRT$ is completely different when compared to other token based protocols [6–8] where the target rotation times can be used to set an upper bound to the $ATRT$ [9,10].

In our case LAS owns a data structure to store a different value of $DTHT$ for each DLE interested in token circulation, but no mechanism based on the effective $ATRT$ is provided to set up or to change dynamically those values.

3 The model

The purpose of our work is to investigate on the behaviour of a Fielbus network physically containing the LAS and a number N of DLEs connected to a (single segment) shared bus. Both cyclic and acyclic data exchanges are used in the modelled system.

Each cyclic transmission has its own duration Tdc_i and should occur at a given rate $Rc_i = \frac{1}{Tpc_i}$ (where Tpc_i is the periodicity of such a cyclic exchange). This condition is less restrictive than the hypotheses on the cyclic traffic used in other performance analysis appeared in the literature such as [12].

Acyclic exchanges are asynchronous in their nature and are characterized by a duration Tda_i and a priority Pa_i.

The LAS activities considered in our model are those foreseen in the IEC DIS document [3] that is: schedule the transactions concerning the cyclic traffic, manage the acyclic traffic by circulating the delegated token, distribute the time to the different DLEs and perform the link maintenance operations.

In the following we will assume that the cyclic traffic is initiated by the LAS itself by means of special enquiries (compel data frames) sent to the DLEs acting as data producers at the correct (scheduled) times. When a compel data frame is received the producer immediately returns the LAS the requested information by means of a data message.

The acyclic traffic is managed directly by the DLEs according to a round-robin policy: when the time of the next scheduled transaction is far enough to come, the LAS sends the delegated token the next DLE in the token circulation list. The receiving DLE scans its data queues starting with the highest priority and continues to transmit data until one of the two following events occurs:

(1) all the queues become empty (as allowed by the token priority)
(2) the token duration time expires.

The time distribution activity is periodic and driven by the LAS to supply the global time to all the DLEs in the network. When the time distribution period (TDP) has elapsed, the LAS broadcasts a time distribution frame over the network.

Furthermore, several link maintenance operations can be performed by the LAS in order to probe DLEs waiting for entering the network or to convey updated schedule information to other link masters and so on. In our analysis, in accordance with the IEC proposal, it is assumed that the amount of system bandwidth devoted to the link maintenance during each “rotation” of the delegated token be constrained by a maximum link maintenance token holding time ($LTHT$).

Because of the number and kind of assumptions listed above the development of an analytical model for predicting the network performance in terms of transmission delays and throughput for acyclic data exchanges should be very difficult and probably would lead to quite inaccurate results caused by the approximations introduced in the model itself. For this reason we decided to develop an "ad hoc" software simulator which is able to take in account all the relevant characteristics of the medium access technique adopted in the IEC Fieldbus.

In particular we are interested in two different working conditions of the simulated system:

(1) in a first set of experiments a steady state condition of the network is considered where a part of the system bandwidth is devoted to deliver cyclic traffic under the LAS responsibility, while all the other DLEs generate acyclic data exchange requests for the three different priority levels. In this situation it is important to study how the $TTRT$ and $DTHT$ affect the system responsiveness and throughput, since the values of these parameters have to be selected by the designer when tuning the network for supporting the distributed applications.
(2) a second set of experiments concerns the same kind of network which it is temporarily overloaded with a significant amount of acyclic traffic for a predefined period of time. In this case it is interesting to evaluate the effect of the most significant parameters on the evolution of the transient condition.

In fact, an increase of the priority level in the token circulation cycle is not sufficient to guarantee "a priori" that $ATRT$ be less or equal to $TTRT$. Each DLEs can obtain the delegated token for a time period equal to $DTHT$ on each virtual rotation of the token, thus the time needed to complete the delegated token circulation (that is $ATRT$) is obviously constrained by $DTHT$ to some extent.

In a time period as long as $ATRT$, the maximum system bandwidth devoted to the acyclic exchanges can be as high as the percentage of the nominal bandwidth which is not used for the cyclic exchanges, the time distribution and the link maintenance operations. In practice, however, a certain amount of transmission time gets lost because of the scheduling of the various exchanges by the LAS which can generate a number of time intervals that are too short to drive any data exchange even if the system has data to send. Consider, for instance, the time period between two subsequent scheduled transactions: when that time is too short to manage any activity, it simply elapses and can not be used in any way. Then, given a value of $ATRT$, use of the system bandwidth can be described by means of the following equation:

$$acycl_{ATRT} = \left(1 - \alpha - \beta - \frac{TD\_DLPDU}{TDP}\right) \cdot ATRT - LTHT \qquad (1)$$

where $acycl_{ATRT}$ is the time devoted to the acyclic exchanges, α is the fraction of $ATRT$ devoted to the cyclic exchanges and $\beta \in [0, 1)$ is a (stochastic) coefficient that takes into account the lost time as a fraction of $ATRT$. In other words β represents the *external fragmentation* of the system bandwidth. $LTHT$ is the time globally devoted to the link maintenance activities during a single token circulation while the term $\frac{TD\_DLPDU}{TDP}$ represents the fraction of $ATRT$ devoted to the time distribution. In fact, TD_DLPDU is the time needed to send a time distribution frame and $\frac{1}{TDP}$ is the rate of such an activity.

If the network consists of N identical DLEs, $\frac{acycl_{ATRT}}{N}$ is an estimated value for the delegated time used by each DLE, except for the time needed by the LAS to delegate the token. If *dto* (delegating token overhead) is the time needed by LAS to delegate the token, we have:

$$\delta \cdot DTHT + \gamma \cdot dto = \frac{acycl_{ATRT}}{N} \qquad (2)$$

where $\delta \in [0, 1]$ represents the fraction of $DTHT$ (i.e. the delegated time) really used by each DLE and depends on the acyclic offered load, while $\gamma \in \left[\left\lceil \frac{\delta \cdot DTHT}{Tacycl_{MAX} - dto} \right\rceil, \left\lfloor \frac{\delta \cdot DTHT}{min_{PDU}} \right\rfloor\right]$ takes into account the number of times the LAS has to delegate the token to a DLE so that the latter is assigned all the delegated time it needs; γ depends on the external fragmentation. $Tacycl_{MAX}$ is the longest "uninterrupted" time between two consequent cyclic exchanges allowed in the network and min_{PDU} is the time needed by a DLE to send a frame with the minimum allowed size.

From (1) and (2) we obtain:

$$ATRT = \frac{N \cdot (\delta \cdot DTHT + \gamma \cdot dto) + LTHT}{1 - \alpha - \beta - \frac{TD\_DLPDU}{TDP}} \qquad (3)$$

Both β and γ depend on the external fragmentation and contribute to decrease the efficiency in the use of the bandwidth by means of a non-minimal delegation token overhead and lost time. Thus it is useful to try to minimize their influence in order to increase the network performance in terms of both responsiveness and throughput.

It is simple to see that external fragmentation is mainly affected by those cyclic exchanges occurring at the highest rate $Rc_{MAX} = max\{Rc_i\}$, in fact the longest and uninterrupted token delegation must occur between two subsequent cyclic exchanges at the highest rate. By defining Tpc_{min} as $\frac{1}{Rc_{MAX}}$, it can be easily proven that:

$$Tacycl_{MAX} \geq Tpc_{min} \cdot (1 - \alpha) \tag{4}$$

By using $Tpc_{min} \cdot (1 - \alpha)$ as a safe estimation (lower bound) for $Tacycl_{MAX}$, the external fragmentation can be dramatically reduced if $Tpc_{min} \cdot (1 - \alpha)$ can be divided exactly by $(DTHT + dto)$: in this case, in fact, each DLE receives a whole $DTHT$ within a single token delegation ($\gamma = 1$). This constraint can be written as:

$$M \cdot (DTHT + dto) = Tpc_{min} \cdot (1 - \alpha) \tag{5}$$

The choice of M is constrained by $DTHT$ as follows:

(1) $DTHT$ shall allow a DLE to send at least one time-available PDU;
(2) a larger $DTHT$ increases the throughput and reduces the internal fragmentation, but it affects the responsiveness accordingly;
(3) the choice of $DTHT$ should reduce the *internal fragmentation* (i.e. it is possible that the overall size of the messages sent during each $DTHT$ period does not fit in exactly and a fraction of $DTHT$ could not be used).

Let us assume that $DTHT$ has been selected by means of (5) to minimize the token delegation overhead and both external and internal fragmentation, then we expect that $\beta \to 0$ and $\gamma \to 1$, thus equation (3) becomes:

$$ATRT = \frac{N \cdot (\delta \cdot DTHT + dto) + LTHT}{1 - \alpha - \frac{TD\_DLPDU}{TDP}} \tag{6}$$

In order to prevent $ATRT$ from being always greater or always lower than $TTRT$ irrespective of the network load, it could be useful to set up $TTRT$ so that, when the network load increases and all DLEs use their whole $DTHT$ ($\delta \to 1$), the average $ATRT$ is kept close to $TTRT$. With such an hypothesis, $TTRT$ can be computed by means of (6) so that:

$$TTRT = \frac{N \cdot (DTHT + dto) + LTHT}{1 - \alpha - \frac{TD\_DLPDU}{TDP}} \tag{7}$$

4 Simulation results

Simulation experiments have been oriented to evaluate the average response time (Ddl) and the throughput (Tdl) for acyclic data exchanges in networks containing 8, 32 and 255 DLEs respectively.

For our purposes Ddl is the time elapsing between the user request which is issued to the data link layer to send a message and the reception of the last bit of the message itself by the data link entity of the destination DLE. Thus Ddl also includes the time spent by the message in the queues of the sending DLE.

Cyclic traffics corresponding to 10%, 30% and 50% of the overall system bandwidth have been taken into account (the α parameter in the above formulas). Then each condition has been studied by using three different values for the shortest period of cyclic exchanges, that is 500, 1000 and 2000 octets respectively, and different load partitioning schemes among the three priority queues have been adopted. The arrival process of frames in each queue is a Poisson process.

All the simulations give the same kind of results. Figs. 1, 2 and 3, for instance, shows the outputs obtained for a network containing 32 DLEs, with a cyclic load equal to 30% ($\alpha = 0.3$) of the whole bandwidth and the shortest period of cyclic exchanges (Tpc_{min}) set to 1000 octets. The acyclic load is equally distributed among the three priority queues (that is 33.33%, 33.33% and 33.34% for the urgent, normal and time-available queue respectively).

In all the experiments a suitable value was selected for $DTHT$ and then $TTRT$ was computed by using (7).

Fig. 1 shows the throughput obtained for each priority queue, plotted for five values of $DTHT$: the diagram marked "1.000" has been obtained for the value of $DTHT$ which satisfies (5) with $M = 1$, while the other curves concern values of $DTHT$ obtained by scaling the "optimal" value by a suitable factor.

All the queues exhibit a better throughput with a larger $DTHT$, in particular quite similar behaviours are obtained by those $DTHTs$ that are equal to or larger than the optimal case.

Fig. 1 also shows that after a threshold value has been reached, the throughput of both the time-available and normal queues decreases. This happens since the priority control mechanism progressively affects the lower priority queues when the offered load increases. When a queue is stopped completely, the percentage of the load offered by that queue no longer contributes to the network traffic which is totally caused by the remaining (high priority) queues.

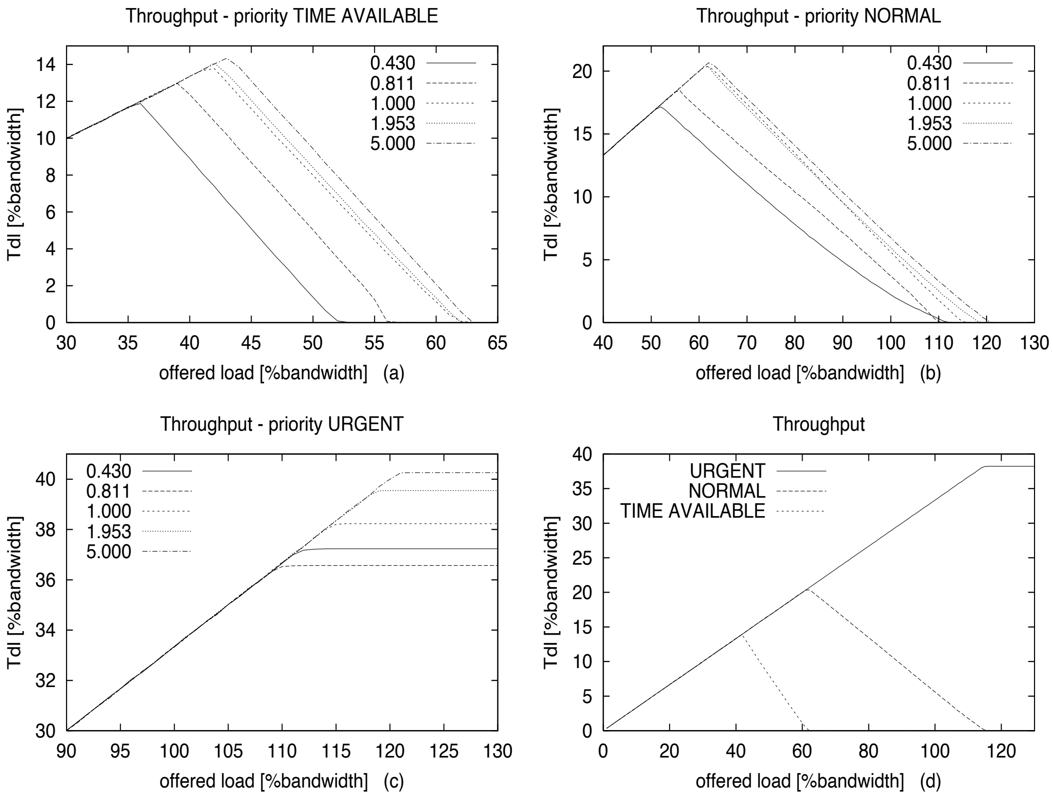

Fig. 1. Tdl vs acyclic offered load for time-available (a), normal (b) and urgent (c) messages. Tdl for the three priority queues combined (d)

This behaviour can be observed in Fig. 1 (c) where the throughput of the urgent queue becomes quite constant when the offered load exceeds the 120% of the total bandwidth, in fact in this condition only the 33% of the offered load generates real acyclic network traffic.

Fig. 1 (d) combines the throughput plots for the three queues in a single picture where a single DTHT value is used. When the offered load falls between 0 and 40% the three queues reach the same throughput (in fact the offered load is equally partitioned among them).

When the offered load is 40%, the system bandwidth is fully used and beyond such a threshold the priority mechanism starts to inhibit the time-available queue. The lowest priority queue is stopped when the offered load is 60% of the system bandwidth corresponding to a network traffic equal to $0.6666 * 60\% = 40\%$. When the offered load reaches the 120%, also the normal queue is blocked. At this point only the high priority traffic is handled which, in this case, consists of the 33% of the whole offered load.

Fig. 2 depicts the medium access delay Ddl for each queue: $DTHT$ values corresponding to the "1.000" diagram or greater offer undoubtedly better per-

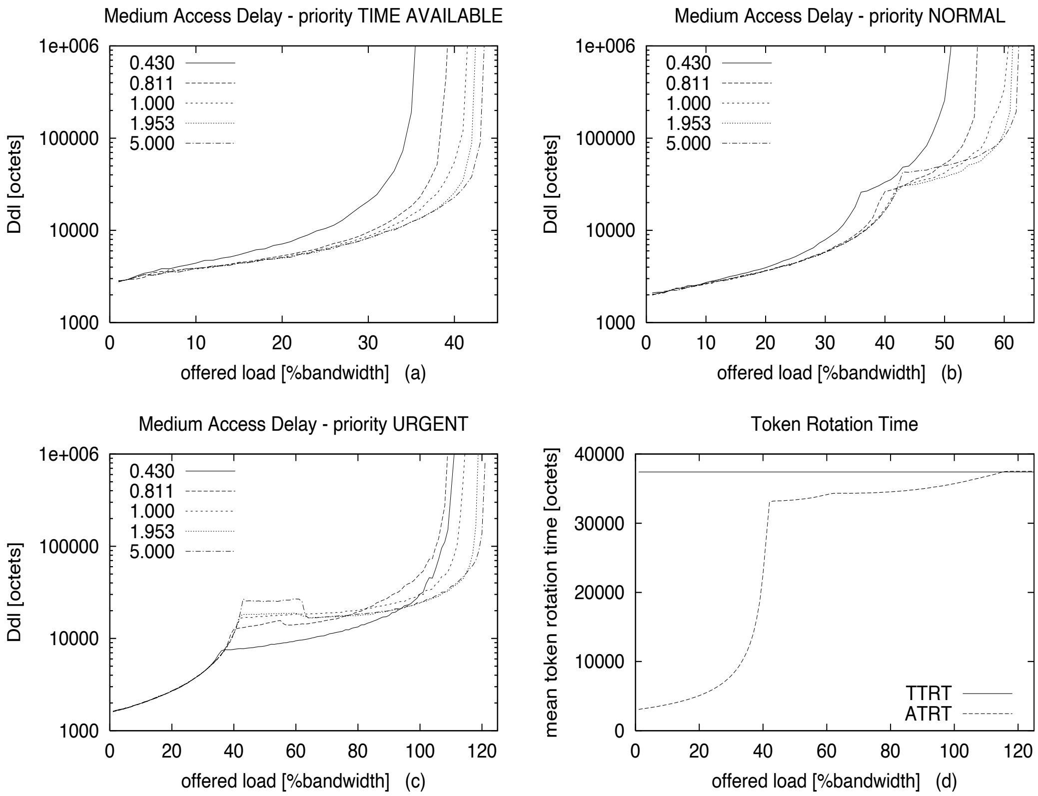

Fig. 2. Ddl for time-available (a), normal (b) and urgent (c) queues and ATRT (d) vs acyclic offered load

formance for the time-available and normal queues. On the other hand, when the offered load is between 40% and 60%, the largest $DTHT$ value leads nearly to double the Ddl value for urgent queue (Fig. 2 (c)).

The best choice for $DTHT$ in this case should be greater or equal to the optimal delegation time but lower than twice that value.

Fig. 2 (d) confirms that the value of $TTRT$ computed by means of (6) matches the value of $ATRT$ when the network bandwidth is fully used.

Finally Fig. 3 shows the Ddl for each queue when a peak of traffic is temporarily offered to the urgent queue. In particular, starting from a steady condition where the offered load is 20% (i.e. the 50% of the acyclic bandwidth), a peak of 80% (i.e. 200% of acyclic bandwidth) of traffic is offered to the urgent queue of each DLE for a period of 500000 octets then the initial value equal to 20% is restored.

Figgs. 3 (a), (b) and (c) show that the best choice of $DTHT$ is that obtained by (5) with $M = 1$, in fact such a value allows the network to get through the peak of traffic in a shorter time with a minimal delay affecting queues.

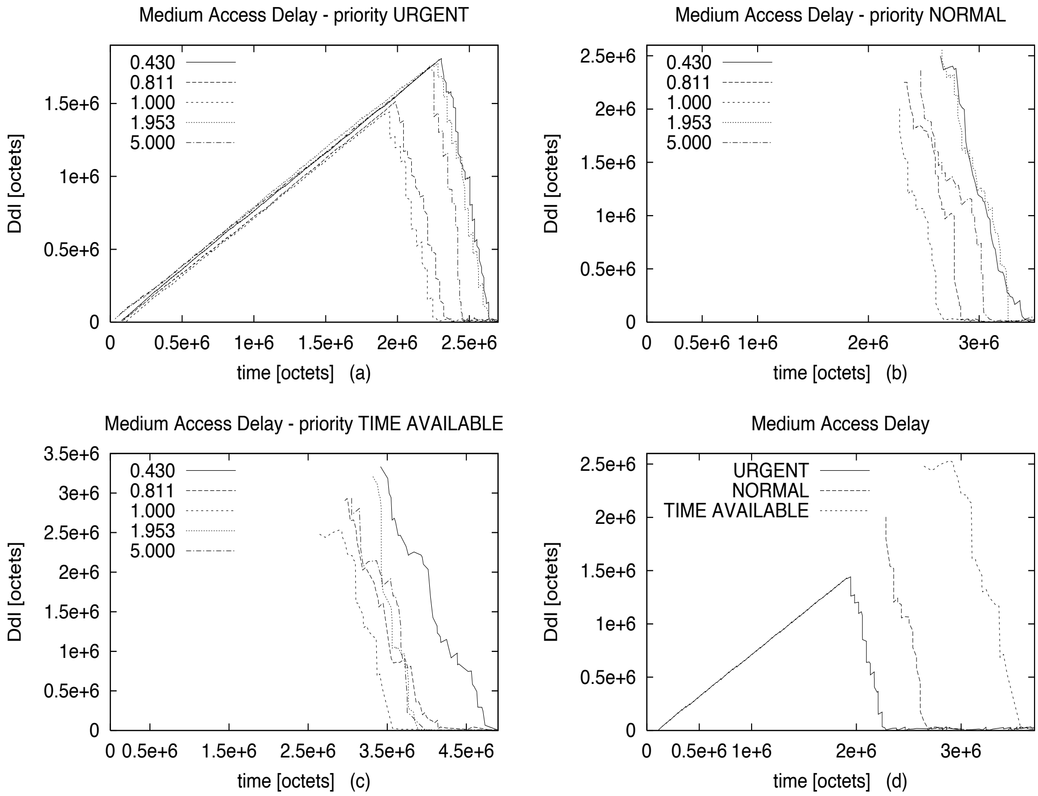

Fig. 3. Ddl vs time when a peak of load is offered to the urgent queue

In particular Fig. 3 (d) depicts the behaviour of the three queues when the optimal value of $DTHT$ is adopted: first the priority mechanism allows all the urgent frames to be delivered. When the highest priority queue returns to the steady condition, the normal queue is enabled to send the frames queued in the meantime. Finally the time-available transmission are resumed and carried out until the steady state is reached.

5 Conclusions

In this paper several features of the IEC 61158 fieldbus protocol have been addressed. The two related mechanisms of token delegation and bandwidth allocation have been studied to help the designer to tune the most critical parameters of the protocol (i.e. $DTHT$ and $TTRT$) for obtaining better performance in terms of throughput and delays for acyclic data exchanges. The analysis has been carried out by taking into account all the features of both cyclic and acyclic traffic and is based on the knowledge of few network parameters such as the percentage of the bandwidth devoted to the cyclic exchanges, the highest rate of the cyclic exchanges and the number of DLEs in the network.

The results have been confirmed by a number of experiments where the network behaviour was simulated for very long times (i.e. each point in Figgs. 1 and 2 has been obtained by simulating 45 minutes of network behaviour). Steady state and transient traffic conditions have been investigated and in both cases it has been possible to find some conditions that can be used to set the protocol parameters and obtain very high performances.

Acknowledgements

The authors wish to thank Dr. Robert Patzke for his valuable help in improving the readability of this paper.

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