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Properties of BuST and Timed-Token Protocols in Managing Hard Real-Time traffic

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Abstract

Token passing channel access mechanisms are used in several communication networks. An important class of token passing approaches are the so-called timed token protocols, which are able to manage both real-time traffic and non real-time traffic. Recently, a new token passing protocol, called Budget Sharing Token protocol (BuST), was proposed to improve the existing timed token approaches in terms of real-time bandwidth guarantee.

This paper analyzes the ability of BuST to manage real-time and non real-time traffic under three different budget allocation schemes, and compares the performance of BuST with the original timed-token protocol (FDDI) and its modified version (FDDI-M). It is shown that BuST provides an higher guaranteed bandwidth for real-time traffic than FDDI, and improves the service for non real-time traffic with respect to FDDI-M. Moreover, new properties of the analyzed budget allocation schemes are provided for BuST, FDDI and FDDI-M. Finally, a set of simulation results are carried out to assess the performance of the three considered protocols.

1 Introduction

Modern control systems are often implemented as interconnected intelligent embedded components (nodes), forming large distributed systems. Since such systems must often interact with the environment for sensing and/or actuation, a key requirement is to operate in real-time. To satisfy such a requirement, a timely computation is needed in each component and, since common information might be shared among different nodes, an adequate performance is not possible without the support of a real-time communication network.

There exist several MAC protocols designed for achieving a real-time communication, mainly in the fieldbus domain. One of the most effective solutions is represented by the token passing approach. These protocols provide features that make them attractive for real applications. For instance, they do not require clocks synchronization among the nodes. Furthermore, the token passing mechanism achieves an implicit bandwidth reclaiming, such that the bandwidth not used by a node can be exploited by the next ones. Another important feature is that, by using time budgets to bound the transmission of each node, there are no transmissions overrun due to misbehaving of message streams (e.g., messages with length greater than expected). The main drawbacks of token passing disciplines comprise: a high overhead when the network traffic is low, a high jitter on messages ending transmission time, and the token loss problem, which both requires dedicated strategies to be solved and decreases the available network bandwidth.

Examples of network standards adopting a token passing discipline are PROFIBUS [3], Foundation Fieldbus [1], P-NET [2], FDDI [6] and FDDI-M [19].

In particular, among token passing protocols, one of the most popular solution is the timed token approach. Timed token protocols are token passing disciplines in which each node receives a guaranteed share of the network bandwidth. A token travels between nodes in a circular fashion and each node can transmit only when it possesses the token; this guarantees a collision-free medium access.

Token passing disciplines are used in different application domains. For instance, a timed token policy called Wireless Timed Token Protocol (WTTP) [11] has been proposed as a scheduling mechanism for the IEEE 802.11e Hybrid Coordination Function (HCF) Controlled Channel Access (HCCA). WTTP is used to provide a minimum rate for those streams with QoS requirements and to fairly share the unused bandwidth among the best-effort streams.

In real-time communication systems, messages can be grouped in two classes: synchronous and asynchronous. The former class is primarily used for real-time messages with periodic arrival pattern, whereas the latter is used for non real-time aperiodic messages with unknown arrival time.

In timed token approaches, an important parameter is the so-called Target Token Rotation Time ($TTRT$), which represents the expected time needed by the token to complete an entire round-trip of the network. Each node i has an associated time budget H_i; whenever a node receives the token, it can transmit its synchronous messages for a time no greater than H_i. It can then transmit its asynchronous messages if the time elapsed since the previous token arrival to the same node is less than the value of $TTRT$, that is, only if the token arrives earlier than expected. To assign the budget H_i to each node, several allocation rules have been proposed during the past years. These rules are named Synchronous Budget Allocation (SBA) schemes.

In this paper, the timed token protocol used in the MAC level of the FDDI standard and its modification named Modified FDDI (FDDI-M) [19] are considered for a comparison with BuST [13].

BuST is a token passing protocol recently introduced to improve the communication service provided by classic token passing protocols employed in FDDI and FDDI-M networks. The BuST protocol differs from FDDI and FDDI-M in how each node exploits the bandwidth saved during the token round-trip, if any, to deliver asynchronous traffic. The transmission of asynchronous traffic occurs within the spare budget unused by synchronous traffic, even when the token is not early. In other words, the budget of a node is shared between real-time and non real-time traffic.

For evaluating and comparing the performance of different SBA schemes in a timed-token network, several metrics have been proposed. One of the most widely adopted is the Worst Case Achievable Utilization (WCAU)

[15, 20]. The WCAU of an SBA scheme represents the largest utilization of the network such that, for any real-time message set whose total network utilization is less than or equal to WCAU, the SBA scheme can guarantee the timeliness of each single real-time message.

Evaluation of WCAU is useful to guarantee the feasibility of a real-time message set when only an estimation of the amount of real-time traffic is known (i.e., the maximum time required to send a message) without requiring a detailed characterization of each single real-time message.

1.1 Contributions and summary

In this paper, the time properties of BuST, FDDI and FDDI-M are analyzed and compared. Three different SBA schemes will be considered: the Equal Partition Allocation (EPA) scheme, the Local Allocation (LA) scheme and Modified Local Allocation (MLA) scheme.

The WCAU for the EPA scheme, under both FDDI and FDDI-M, can be found in literature. This paper shows that, the WCAU of the EPA scheme, under BuST, is equal to that under FDDI-M, which is greater than that for FDDI.

The LA scheme has been studied only for FDDI. This paper shows that the results, concerning the WCAU provided for FDDI, are valid also for both FDDI-M and BuST. However, by simulation experiments, it is shown that the performance offered by both FDDI-M and BuST are better than that offered by FDDI.

The MLA scheme has been proposed for FDDI-M, and its time properties have been studied marginally in the literature. This paper provides the WCAU for the MLA scheme under FDDI, FDDI-M and BuST. Moreover, it is shown that the WCAU depends on the choice of $TTRT$. Furthermore, methods on selecting a suitable $TTRT$ value that can guarantee a given real-time message set are also provided.

Finally, the performance of BuST, FDDI and FDDI-M under the considered SBA schemes are analyzed by simulation.

The rest of the paper is organized as follows: Section 2 presents the communication model; Section 3 describes the BuST protocol; Section 4 introduces the SBA schemes considered in the analysis, and provides theoretical results for the discussed protocols; Section 5 shows the simulation results and finally, Section 6 states the conclusions and the future work.

2 Communication model

The communication system is composed by a set of n communicating nodes. Each node i is associated with a synchronous message stream S_i, which is described by three parameters (C_i, T_i, D_i), where:

- C_i is the maximum amount of time required to transmit a stream message. This includes the time required to transmit both the payload data and message headers.
- T_i is the inter-arrival period between consecutive messages in stream S_i. If the first message of node i is put in the transmission queue at time $t_{i,1}$, then the j-th message in stream S_i will arrive in transmission queue at time $t_{i,j} = t_{i,1} + (j-1)T_i$, where $j \geq 1$.
- D_i is the relative deadline associated with messages in stream S_i, that is, the maximum amount of time that can elapse between a message arrival and the completion of its transmission. Thus, the transmission of the j-th message in stream S_i that arrives at $t_{i,j}$ must be completed not later than $d_i = t_{i,j} + D_i$, which is the message's absolute deadline.

Without loss of generality, only one synchronous stream per node is assumed. In fact, as proved in [5], a timed token network with more than one stream per node can be transformed into a logically equivalent network with one synchronous stream per (logical) node.

Notice that, in order to guarantee the deadlines of asynchronous real-time messages, if any, a dedicated budget for this kind of messages can be assigned using the same stream model, as proposed in [18].

The channel utilization of each message in the stream S_i is

$$U_i^S = \frac{C_i}{min(T_i, D_i)}.$$

The total effective channel utilization, U^S, of a periodic message set is then

$$U^S = \sum_{i=1}^{n} U_i^S$$

which measures the total channel bandwidth required by the whole periodic message set.

The parameters described above are crucial for guaranteeing the timely delivery of periodic messages. Before discussing how to select the communication parameters, the following definitions are introduced:

Definition 1 τ *is the time needed to transmit the token between nodes during a full token rotation, including the overhead introduced by the protocol.*

The value of τ clearly depends on the number of nodes.

Any choice of the communication parameters must satisfy the following two constraints:

Definition 2 ***(Protocol Constraint)*** *The total bandwidth allocated to the nodes must be less than the available network bandwidth, that is,*

$$\frac{\sum_{i=1}^{n} H_i}{TTRT} \leq 1 - \frac{\tau}{TTRT}.$$

The Protocol Constraint is necessary to ensure a stable operation of the timed token protocol.

Definition 3 ***(Deadline Constraint)*** *If $s_{i,j}$ is the time at which the transmission of the j-th message in stream S_i is completed, the deadline constraint requires that for $i = 1, \ldots, n$ and $j = 1, 2, \ldots$,*

$$s_{i,j} \leq t_{i,j} + D_i$$

where $t_{i,j}$ is the message arrival time and D_i is its relative deadline.

The Deadline Constraint ensures that every periodic message is transmitted before its absolute deadline. Note that in the above inequality, while $t_{i,j}$ and D_i are defined by the application, $s_{i,j}$ depends on the synchronous bandwidth allocation and on the $TTRT$ value.

3 BuST protocol overview

The BuST protocol has been developed to improve the performance of existing timed token protocols like FDDI and FDDI-M. Due to space limitations, the details of FDDI and FDDI-M are not presented. More information can be found in [13, 12].

The main drawback of FDDI is the worst-case token rotation time, which is bounded by $2TTRT$. Because of this,

Allocation scheme	Assignment rule
Equal Partition Allocation (EPA)	$H_i = \frac{TTRT-\tau}{n}$
Local Allocation (LA)	$H_i = \frac{C_i}{\lfloor \frac{T_i}{TTRT} - 1 \rfloor}$
Modified Local Allocation (MLA)	$H_i = \frac{C_i}{\lfloor \frac{T_i}{TTRT} \rfloor}$

Table 1. The Synchronous Budget Allocation schemes considered in this paper.

FDDI can only guarantee up to one half of the total available bandwidth for the real-time traffic. On the other hand, as it will be stated in Section 4.3, FDDI-M cannot deliver non real-time traffic under the EPA scheme. For a complete overview on problems related to FDDI and FDDI-M see [13, 12].

Using BuST, the worst-case token rotation time is limited so that it can not exceed the $TTRT$, which improves FDDI, and allows a node to deliver non real-time traffic in those cases where FDDI-M fails.

Like in the traditional timed token policy, the BuST protocol assigns each node a time budget H_i for transmitting the associated real-time traffic. When a node receives the token, it can transmit its real-time traffic no longer than the corresponding budget. The main difference with respect to FDDI and FDDI-M concerns the non real-time message service. Using FDDI, when the token arrives early, the node can transmit asynchronous traffic for a time up to $T_A = TTRT - \tau - T_{LRT}$, where T_{LRT} is the time spent in the last round-trip of the token. Using FDDI-M a node does the same but with $T_A = TTRT - \sum_{i=1}^{n} H_i - \tau$. Using BuST, a node can deliver non real-time traffic each time it gets the token, early or not, using the spare budget left by real-time messages. If H_i^{cons} is the budget consumed by node i to deliver synchronous traffic, then it can send asynchronous traffic for a time equal to $T_{A_i} = H_i - H_i^{cons}$, even if the token is not early. Observe that FDDI and FDDI-M can deliver asynchronous traffic only when the token is early, that is, when $T_{LRT} < TTRT - \tau$.

In BuST, node i can use its budget H_i for delivering both real-time and non real-time messages. Therefore, the worst-case token rotation time can not exceed $TTRT$. With respect to FDDI, BuST improves (as FDDI-M) the bandwidth available for real-time messages. For more detail on BuST see [13, 12].

Finally, it is worth remembering that the protocol standard rules assume that $TTRT \leq \min(D_i)/2$ for FDDI, and $TTRT \leq \min(D_i)$ for both BuST and FDDI-M.

4 Time properties

The real-time guarantee of the stream set highly depends on the SBA scheme adopted. In this paper, the Equal Proportional Allocation (EPA) [5], the Local Allocation (LA) [4], and the Modified Local Allocation (MLA) [8] schemes are considered. Time properties of such schemes have been analyzed for FDDI and (partially) for FDDI-M, thus the time properties derived for BuST can be compared with the results available in literature. The budget H_i is allocated to each node i using the equations showed in Table 4.

Looking at the assignment rules reported in Table 4, it can be observed that both LA and MLA schemes are based on local information, i.e., the budget H_i referred to the i-th stream is calculated using the parameters of S_i only, while the EPA uses global information, that is, the number of streams in the network.

Notice that, even though it is assumed $D_i = T_i$ for all streams, since $U_i^S = \frac{C_i}{\min(D_i, T_i)}$, the same results can be derived for the case where $D_i < T_i$ by simply substituting D_i to T_i.

To make the paper self-contained, Lemmas 1, 2 and 3 are reported from [13] without proofs, since they represent the starting point from which the results of this paper have been derived. They calculate the bound on the maximum transmission time for real-time messages when BuST, FDDI-M and FDDI are respectively used. Such results are valid for all possible SBA schemes.

Lemma 1 *Under the BuST protocol, for all SBA schemes, if $T_i \geq TTRT$, $i = 1, \ldots, n$, it holds*

$$\forall i, j : s_{i,j} \leq t_{i,j} + \left\lceil \frac{C_i}{H_i} \right\rceil \left(\sum_{r=1}^{n} H_r + \tau \right).$$

Lemma 2 *Under the FDDI-M protocol, for all SBA schemes, if $T_i \geq TTRT$, $i = 1, \ldots, n$, it holds*

$$\forall i, j : s_{i,j} \leq t_{i,j} + \left\lceil \frac{C_i}{H_i} \right\rceil TTRT + C_i - \left\lceil \frac{C_i}{H_i} \right\rceil H_i.$$

Lemma 3 *Under the FDDI protocol, for all SBA schemes, if $T_i \geq 2TTRT$, $i = 1, \ldots, n$, it holds*

$$\forall i, j : s_{i,j} \leq t_{i,j} + \left(\left\lceil \frac{C_i}{H_i} \right\rceil + 1 \right) TTRT + C_i - \left\lceil \frac{C_i}{H_i} \right\rceil H_i.$$

In the rest of the section, due to the lack of space, some proofs of the provided results are not reported. Such proofs can be found in [12, 14].

For the sake of clarity, when not differently specified, the terms $\beta_i = \frac{T_i}{TTRT}$ and $\alpha = \frac{\tau}{TTRT}$ will be used. Parameter α represents the bandwidth loss due to the protocol overhead.

4.1 Equal Partition Allocation

When the EPA scheme is used, WCAU is equal to $\frac{1-\alpha}{3n-(1-\alpha)}$ under FDDI [5], and is equal to $\frac{1-\alpha}{2n-(1-\alpha)}$ under FDDI-M [10]. Since the maximum token rotation time for BuST [12] is $TTRT$, as for FDDI-M, it is possible to adopt the same methodology used in [10] to prove that BuST also achieves a WCAU equal to $\frac{1-\alpha}{2n-(1-\alpha)}$. See cited references for further details.

In this paper, two additional schedulability tests for the EPA scheme under BuST, FDDI-M and FDDI are provided. The first one is based on the utilizations U_i^S of each stream S_i.

Theorem 1 provides an upper bound on the utilization U_i^S of each stream S_i, such that if this bound is satisfied the stream set can be scheduled.

Theorem 1 *Using the EPA scheme, if $\forall i$: $U_i^S \leq \frac{1-\alpha}{2n}$, then a stream set $M = \{S_1, \ldots, S_n\}$ is schedulable with BuST and FDDI-M. If $\forall i$: $U_i^S \leq \frac{1-\alpha}{3n}$, then M is schedulable using FDDI.*

Proof. The Protocol Constraint it satisfied independently of U_i^S, since

$$\frac{1}{TTRT} \sum_{i=1}^{n} H_i = \frac{1}{TTRT} \sum_{i=1}^{n} \frac{(TTRT - \tau)}{n} =$$

$$\frac{TTRT - \tau}{TTRT} = 1 - \frac{\tau}{TTRT}.$$

Under BuST and FDDI-M, being $C_i = U_i^S T_i$, from Lemma 1 and Lemma 2 the Deadline Constraint is satisfied if for any i:

$$\left\lceil \frac{nU_i^S \beta_i}{(1-\alpha)} \right\rceil \leq \beta_i. \quad (1)$$

From Lemma 4 (see Appendix 6), the Inequality 1 is met for all i if $\frac{nU_i^S}{1-\alpha} \leq \frac{1}{2}$, that is, if $U_i^S \leq \frac{1-\alpha}{2n}$.

For FDDI, from Lemma 3, the Deadline Constraint is satisfied if

$$\left\lceil \frac{nU_i^S \beta_i}{(1-\alpha)} \right\rceil \leq \beta_i - 1. \quad (2)$$

It is not difficult to prove that, since $\beta_i \geq 2$, if $\forall i$: $\frac{nU_i^S}{1-\alpha} \leq \frac{1}{3}$, that is, if $U_i^S \leq \frac{1-\alpha}{3n}$ the Inequality 2 is met, thus Deadline Constraint is met. □

In the conditions of Theorem 1, if $\forall i$: $U_i^S \leq \frac{(1-\alpha)}{2n}$ then summing up for each i the maximum utilization U^S guaranteed for both BuST and FDDI-M results to be $\frac{(1-\alpha)}{2}$, under the EPA scheme. Similarly, if $\forall i$: $U_i^S \leq \frac{(1-\alpha)}{3n}$ then summing up for each i the maximum utilization guaranteed for FDDI is equal to $\frac{(1-\alpha)}{3}$. Notice that, if the proposed test on the U_i^S is met then it is possible to guarantee a greater channel utilization than that guaranteed by the WCAUs provided in [5], [10].

The following corollary shows how to properly choose $TTRT$ in order to increase the upper bound on the stream utilizations U_i^S provided by the previous theorem.

Corollary 1 *If $TTRT = GCD_i(T_i)$, if $\forall i$: $U_i^S \leq \frac{1-\alpha}{n}$, then a stream set $M = \{S_1, \ldots, S_n\}$ is schedulable with BuST and FDDI-M under the EPA scheme. Under FDDI, if $TTRT = 0.5 \cdot GCD_i(T_i)$, if $\forall i$: $U_i^S \leq \frac{1-\alpha}{2n}$, then M is schedulable under the EPA scheme.*

Proof. Following the same methodology used to prove Theorem 1, the Deadline Constraint is met, under BuST and FDDI-M, if

$$\left\lceil \frac{nU_i \beta_i}{(1-\alpha)} \right\rceil \leq \beta_i$$

It is easy to see that, being $\beta_i = \frac{T_i}{GCD_i(T_i)} \in \mathbb{N}$, the Deadline Constraint is met if $U_i^S \leq \frac{1-\alpha}{n}$.

For FDDI, the Deadline Constraint is met if

$$\left\lceil \frac{nU_i \beta_i}{(1-\alpha)} \right\rceil \leq \beta_i - 1$$

Being $\beta_i = \frac{T_i}{0.5 \cdot GCD_i(T_i)} \geq 2$ an integer, the Deadline Constraint is met if $U_i^S \leq \frac{1-\alpha}{2n}$. □

Considering BuST and FDDI-M, if $TTRT$ is chosen as in Corollary 1 and for all i, $U_i^S \leq \frac{1-\alpha}{n}$ then the bandwidth guaranteed for real-time traffic is equal to the total available bandwidth $1-\alpha$. To verify this last statement, it sufficient to note that by the corollary hypotheses $\sum_{i=0}^{n} U_i^S \leq \sum_{i=0}^{n} \frac{1-\alpha}{n} = 1-\alpha$. Furthermore, under the conditions of Corollary 1, the maximum bandwidth $(1-\alpha)/2$ [19], achievable for real-time traffic under FDDI, can be guaranteed.

4.2 Local Allocation schemes

In this section the performance of BuST, FDDI-M and FDDI in managing real-time traffic is analyzed under two local allocation schemes.

4.2.1 The LA scheme

The Local Allocation (LA) scheme is a local SBA scheme proposed for the first time in [4]. By this last, budgets H_i are assigned using Equation 3.

$$H_i = \frac{C_i}{\lfloor \beta_i - 1 \rfloor} \quad (3)$$

As it can be noted, $\beta_i = 1$ for a stream S_i with $T_i = min(T_i) = TTRT$; this means that the denominator of the last equation is equal to zero. It follows that, when $TTRT$ is assigned by the standard rules of both BuST and FDDI-M, the LA scheme can not be used. However, if the $TTRT$ is set equal to half of the minimum period (deadline) in the system, the LA scheme can be used also with both BuST and FDDI-M.

Under FDDI, the WCAU of the LA scheme is equal to $(1-\alpha)/3$ [4]. Theorem 2 shows that, with both BuST and FDDI-M, the WCAU of the LA scheme is the same as for FDDI.

Theorem 2 *If for $i = 1, \ldots, n$, let $\beta_i \geq 2$ then the WCAU factor of the LA scheme ($H_i = C_i / \lfloor \beta_i - 1 \rfloor$) is equal to $\frac{1-\alpha}{3}$.*

Proof. The proof can be found in [14]. □

Corollary 2 extends the WCAU provided by the last theorem. In particular it shows that the WCAU depends on the minimum value of β_i ($\beta_{min} = min(T_i)/TTRT$), i.e, it depends on $TTRT$. This result is valid also for FDDI [17].

Corollary 2 *For $i = 1, \ldots, n$, let be $\beta_i \geq 2$, if $U^S \leq \frac{\lfloor \beta_{min} - 1 \rfloor}{\lfloor \beta_{min} + 1 \rfloor}(1-\alpha)$ then the stream set $M = \{S_1, \ldots, S_n\}$ is schedulable under the LA scheme.*

Proof. The proof can be found in [14]. □

Corollary 2 provides a method to select $TTRT$ such that, a timely delivery can be guaranteed for synchronous stream set with $U^S > (1-\alpha)/3$.

As an example, consider a stream set with $U^S = 0.5$, an overhead $\tau = 0.2$ msec, and a minimum period $T_{min} = \min_i(T_i) = 10$ msec. Since $U^S = 0.5 > (1-\alpha)/3 \simeq 0.33$, the stream set schedulability is not guaranteed by the test on WCAU. However, a value of $TTRT$ that achieves the schedulability can be found using Corollary 2. It is sufficient to find a value of $TTRT$ such that $\frac{\lfloor \beta_{min} - 1 \rfloor}{\lfloor \beta_{min} + 1 \rfloor}(1-\alpha) \geq 0.5$. For instance, with $TTRT = 2.5$ the schedulability condition of Corollary is satisfied, hence the stream set is schedulable.

4.2.2 The MLA scheme

The Modified Local Allocation (MLA) SBA scheme has been proposed for FDDI-M [8]. In this last, the budgets H_i are assigned using Equation 4.

$$H_i = \frac{C_i}{\lfloor \beta_i \rfloor} \quad (4)$$

Differently from the LA scheme, under MLA the case of $\beta_i = 1$ is not a problem. Unfortunately, as highlighted in [8], with FDDI under MLA the Deadline Constraint can not be satisfied. It follows that in this case the WCAU of FDDI is equal to zero. Moreover, in [8] the authors do not provide the WCAU of this scheme under FDDI-M. Theorem 3 provides the WCAU of the MLA scheme both for BuST and for FDDI-M.

Theorem 3 *The WCAU factor of the MLA scheme (where $H_i = C_i / \lfloor \beta_i \rfloor$), with BuST and FDDI-M is equal to $\frac{1-\alpha}{2}$.*

Proof. For both BuST and FDDI-M, the Protocol Constraint requires that:

$$\sum_{i=1}^{n} \frac{C_i}{\lfloor \beta_i \rfloor} \leq TTRT - \tau$$

Since $\forall i$, $1/\lfloor \beta_i \rfloor \leq 2/\beta_i$ [14]:

$$\sum_{i=1}^{n} \frac{C_i}{\lfloor \beta_i \rfloor} \leq \sum_{i=1}^{n} 2\frac{C_i}{\beta_i} = 2TTRTU^S$$

Hence, it is possible to derive the WCAU that satisfied the Protocol Constraint:

$$2TTRTU^S \leq TTRT - \tau$$
$$U^S \leq \frac{1-\alpha}{2}$$

It has been just proved that if $U^S \leq \frac{1-\alpha}{2}$ the Protocol Constraint is satisfied, that is, $\sum_{i=1}^{n} H_i \leq TTRT$. To complete this first part, it remains to show that for any given $\epsilon > 0$, there exist a message stream set with $U^S = \frac{1-\alpha}{2} + \epsilon$ such that the Protocol Constraint will be violated. Due to the lack of space, this last claim is not proven here; an interested reader can see [14].

To complete the proof, it is shown that the Deadline constraint is satisfied independently from the value of U^S.

Assuming that the Protocol Constraint is satisfied, using Lemma 1 and observing that $\lceil \lfloor \frac{C_i}{H_i} \rfloor \rceil = \lceil \lfloor \beta_i \rfloor \rceil = \lfloor \beta_i \rfloor$, it results that for BuST:

$$s_{i,j} \leq t_{i,j} + \left\lceil \frac{C_i}{H_i} \right\rceil \left(\sum_{r=1}^{n} H_r + \tau \right) \leq$$
$$t_{i,j} + \left\lceil \frac{C_i}{H_i} \right\rceil TTRT = t_{i,j} + \lfloor \beta_i \rfloor TTRT$$

It follows that the Deadline constraint requires that $\forall i$: $\lfloor \beta_i \rfloor TTRT \leq T_i$, that is, $\lfloor \beta_i \rfloor \leq \beta_i$, which is always true. In the same way, it is possible to proof that the Deadline Constraint is met also for FDDI-M. It sufficient to use Lemma 2 instead of Lemma 1. □

Next results extend the one provided by Theorem 3. In particular, Corollary 3 shows that WCAU depends on the minimum value of β_i, i.e, it depends on both the value of $TTRT$ and the minimum period $\min(T_i)$.

Corollary 3 *For $i = 1, \ldots, n$, let be $\beta_i \geq 1$, if $U^S \leq \frac{\lfloor \beta_{min} \rfloor}{\lfloor \beta_{min} + 1 \rfloor}(1-\alpha)$ then the stream set $M = \{S_1, \ldots, S_n\}$ is schedulable under the MLA scheme.*

Proof. The proof can be found in [14]. □

This last result is similar to that provided by Corollary 2 under the LA scheme, the same example provided at the end of Section 4.2.1 could be used to show its usage.

Corollary 4 shows that, by properly setting $TTRT$, the WCAU can be equal to the total available bandwidth for BuST and for FDDI-M.

Corollary 4 *If $TTRT = GCD_i(T_i)$, under BuST and $FDDI-M$, the WCAU factor of the MLA scheme is equal to the total available bandwidth, i.e., $1-\alpha$.*

Proof. Observe that, if $TTRT = GCD_i(T_i)$ then β_i is an integer. Hence, it results that $H_i = C_i / \lfloor \beta_i \rfloor = C_i / \beta_i = TTRTU_i^S$. From these last observations it is straightforward to verify that both the Protocol and the Deadline Constraints are met. □

Notice that, setting $TTRT$ like in Corollary 4, since in the worst case $GCD_i(T_i) = 1$, then the total available bandwidth could be very small, since in this case $1-\alpha = 1-\tau$. It follows that, the WCAU provided by last corollary may gets worse with respect to the WCAU provided by Theorem 3.

4.3 Non real-time service

So far, real-time stream service have been extensively analyzed. This section briefly describes the non real-time service of the BuST protocol and its improvements with respect to FDDI-M.

As showed in Section 3, under FDDI-M the maximum time a node can exploit to deliver non real-time traffic is $T_A = TTRT - \sum_{i=1}^{n} H_i - \tau$. When the EPA scheme is used, FDDI-M can not deliver non real-time traffic, as proved by:

$$T_A = TTRT - \sum_{i=1}^{n} \frac{TTRT - \tau}{n} - \tau$$
$$= TTRT - (TTRT - \tau) - \tau = 0$$

To analyze the worst-case scenario for non real-time service with BuST, it is assumed that each node receiving the token has an infinite amount of non real-time traffic to deliver. In this case, the total channel utilization of the network, including both real-time and non real-time traffic, is equal to $1-\alpha$. Theorem 4 provides the minimum bandwidth that a node i can exploit to deliver non real-time traffic with BuST under the EPA scheme.

Theorem 4 *Using BuST, under the EPA scheme a node i can guarantee a minimum bandwidth of U_i^{NRT} for non real-time traffic given by*

$$U_i^{NRT} = \frac{1-\alpha}{n} - U_i^S.$$

Proof. For a node i, the maximum bandwidth available to deliver both real-time and non real-time traffic is $U_i^{TOT} = \frac{H_i}{\sum_{j=1}^{n} H_j + \tau}$. It follows that, being U_i^S the utilization of the real-time messages at node i, the minimum bandwidth available for non real-time messages at the same node results to be $U_i^{NRT} = U_i^{TOT} - U_i^S$. Considering the EPA scheme, where $H_i = \frac{TTRT-\tau}{n}$, it follows that:

$$U_i^{TOT} = \frac{H_i}{\sum_{j=1}^{n} H_j + \tau} = \frac{\frac{TTRT-\tau}{n}}{TTRT - \tau + \tau} = \frac{1-\alpha}{n}$$
$$U_i^{NRT} = U_i^{TOT} - U_i^S = \frac{1-\alpha}{n} - U_i^S$$

□

Theorem 4 shows that, using BuST with the EPA scheme, a minimum bandwidth is guaranteed for non real-time traffic at each node. In addition, it is worth observing that, when not all nodes have to send non real-time traffic during the token round trip, the value of U_i^{NRT} can further increase, and thus a better performance can be obtained.

SBA scheme	FDDI	FDDI-M	BuST
EPA	$\frac{1-\alpha}{3n-(1-\alpha)}$	$\frac{1-\alpha}{2n-(1-\alpha)}$	$\frac{1-\alpha}{2n-(1-\alpha)}$
LA	$\frac{1-\alpha}{3}$	$\frac{1-\alpha}{3}$	$\frac{1-\alpha}{3}$
MLA	0	$\frac{1-\alpha}{2}$	$\frac{1-\alpha}{2}$

Table 2. Comparison among the WCAU of the considered schemes.

4.4 Discussion of theoretic results

Table 2 shows the WCAU of each SBA scheme analyzed in this paper. For the EPA scheme, the WCAU for both FDDI-M and BuST is greater than the WCAU for FDDI.

For the EPA scheme, there exists an upper bound on the stream utilizations U_i^S that guarantees the stream set schedulability. This upper bound is provided for BuST, FDDI, and FDDI-M. The bound for BuST and FDDI-M is the same and equal to $\frac{1-\alpha}{2n}$, whereas for FDDI is equal to $\frac{1-\alpha}{3n}$ (see Theorem 1). When $TTRT$ is selected as in Corollary 1, the upper bound for the stream utilizations U_i^S can be improved, in particular it becomes equal to $\frac{1-\alpha}{n}$ for FDDI-M and BuST, and equal to $\frac{1-\alpha}{2n}$ for FDDI.

As far as the non real-time service is concerned, under the EPA scheme, FDDI-M can not deliver non real-time traffic. Section 4.3 shows that, under BuST, this drawback is removed.

For the LA scheme, in Section 4.2.1 it is shown that the WCAU and other time properties provided under FDDI do not change under both BuST and FDDI. This is mainly due to the fact that these properties are related to the satisfaction of the Protocol Constraint, and the properties of the three protocols with respect to this last constraint are the same.

Under the MLA scheme, in Section 4.2.2 it is highlighted that FDDI can not satisfies the Deadline Constraint, hence the WCAU of FDDI is equal to zero. FDDI-M and BuST have the same time properties under MLA; in particular they have a WCAU equal to $\frac{1-\alpha}{2}$. Moreover, Corollary 3 shows that the WCAU depends on the value of β_{min}, namely $TTRT$, and the minimum stream period, hence it can be greater than $\frac{1-\alpha}{2}$ if $TTRT < \min(T_i)$.

5 Simulation results

In this section the performance of the discussed protocols is compared by simulation. Two kind of experiments have been performed. A first set of result simulates the protocols to get the Maximum Deadline Miss Ratio when the total streams channel utilization U^S is changed. A second set of experiments consists on the generation of a certain number of stream set with a total utilization $U^S \in [0.1, 1]$. For each value of U^S, the ratio of the stream sets that satisfy the Protocol Constraint to the total number of stream sets generated is calculated.

5.1 Maximum Deadline Miss Ratio

The simulations consider a network composed by 10 nodes. Each node has a periodic stream with a relative deadline ranging from $10msec$ to $100msec$. An infinite amount of non real-time traffic is assumed; this means that, every time a node receives the token it has some non real-time traffic to deliver. Notice that, in this case the total channel utilization $U^{TOT} = U_i^{NRT} + U^S$ is equal to the total available bandwidth $1-\alpha$. Node budgets are assigned

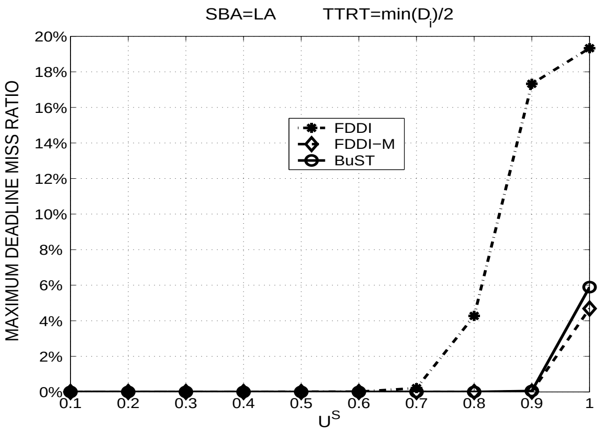

Figure 1. Maximum Deadline Miss Ratio for the LA scheme.

using the LA and MLA schemes. The Maximum Deadline Miss Ratio (MDMR) is measured as a function of the real-time channel utilization U^S, ranging from 0.1 to 1.0 with a step of 0.1. For each value of U^S, up to 500 simulation runs are performed, and the Maximum Deadline Miss Ratio is considered among the runs. A different stream set is generated for each run. In particular, for each stream set the utilizations U_i^S have been generated randomly with a uniform distribution using the method proposed in [7]. For each value of U_i^S, a relative deadline D_i is generated randomly with a uniform distribution in the interval $[10, 100]$ msec. Periods are assumed equal to deadlines. The message lengths C_i have been computed as $C_i = U_i^s D_i$. The overhead τ is assumed equal to 20μsec.

To guarantee a stable operation of the protocols, the Protocol Constraint has to be guaranteed. Moreover, for both the LA and the MLA schemes, whenever the Protocol Constraint is satisfied the Deadline Constraint is satisfied as well. In order to guarantee a stable operation also when the Protocol Constraint is not satisfied, in the simulations, the ring recovery process is removed [9, 16]. In this case, the token is considered as never lost and the maximum delay between two consecutive token visits at the same node may be greater than $2TTRT$ for FDDI, and greater than $TTRT$ for both BuST and FDDI-M.

Figure 1 shows the Maximum Deadline Miss Ratio when the LA scheme is used to assign the node budgets, and $TTRT = min(D_i)/2$. As long as $U^S \leq 0.8$, FDDI-M and BuST present a null Maximum Deadline Miss Ratio. For $U^S = 0.9$ they present an MDMR not appreciable in the figure, which is less than 0.05% for both protocols. FDDI presents a null MDMR as long as $U^S \leq 0.4$, and a MDMR less than 0.3% for $U^S \leq 0.7$. For $U^S > 0.7$, FDDI presents a MDMR significantly greater than BuST and FDDI-M.

Figure 2 shows the MDMS under the MLA scheme when $TTRT = min(D_i)/2$. For BuST and FDDI-M, as long as $U^S \leq 0.8$ the MDMS is null. When $U^S = 0.9$, the MDMS is not greater than 0.3%, hence is not appreciable in the figure. It is worth noticing that when the channel is overloaded, i.e. $U^S = 1$, the MDMS is not greater than 9%. For FDDI, the MDMS is non-null for all values of U^S. This is due to the fact that, as stated in Section 4.2.2, the Deadline Constraint can not be satisfied when the MLA scheme is used under FDDI.

Notice that, although under the MLA scheme $TTRT$ could be set equal to $min(D_i)$, to compare the LA and the MLA schemes under the same conditions, simula-

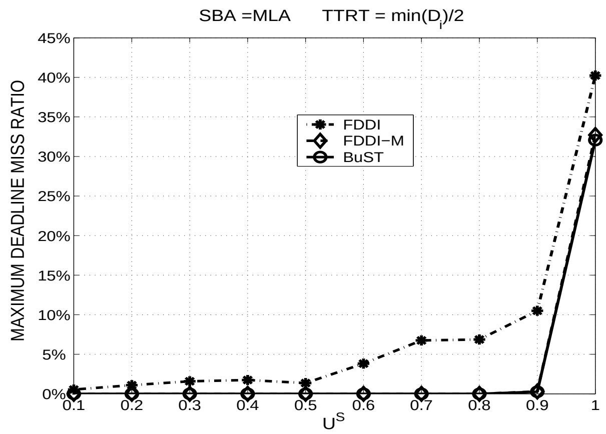

Figure 2. Maximum Deadline Miss Ratio for the MLA scheme.

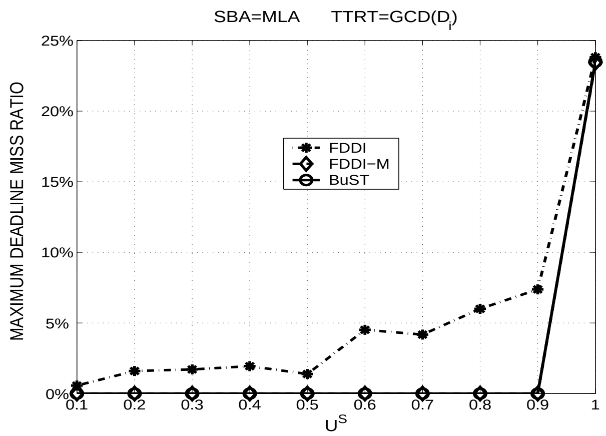

Figure 3. Maximum Deadline Miss Ratio for the MLA scheme when $TTRT = GCD_i(D_i)$.

tions have been performed using the same $TTRT$ for both schemes.

Figure 3 shows the simulation results for the MLA scheme when $TTRT$ is selected as stated in Corollary 4. Under this condition, as predicted by the theory, as long as $U^S < 1$ both FDDI-M and BuST present a null MDMR. As before, since FDDI can not guarantee the Deadline Constraint under MLA scheme, it presents a non-null MDMR for all values of U^S.

In general, the simulations show that BuST and FDDI-M present a similar performance, and outperform FDDI under both the LA and the MLA scheme.

5.2 Protocol Constraint Miss Ratio

This second set of experiments also considers a network of 10 nodes. The Protocol Constraint Miss Ratio (PCMR) is measured as a function of the real-time channel utilization U^S, ranging from 0.1 to 1.0 with a step of 0.1. For each value of U^S, 10^5 stream set has been generated; the PCMR is obtained by assigning the stream budgets with either the LA scheme or the MLA scheme, and by calculating the ratio of the number of stream set that satisfy the Protocol Constraint to the total number of stream set. The stream parameters are generated as in Section 5.1. $TTRT$ is set equal to $min(D_i)/2$ when the LA scheme is considered, and equal to $min(D_i)$ for the MLA scheme. The overhead τ is assumed negligible, i.e $\tau = 0$.

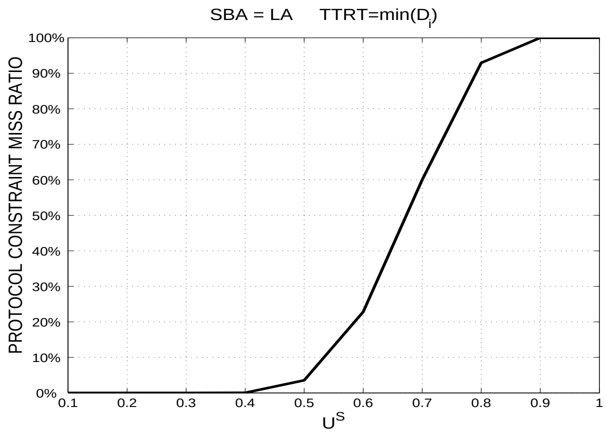

Figure 4. Protocol Constraint Miss Ratio for the LA scheme.

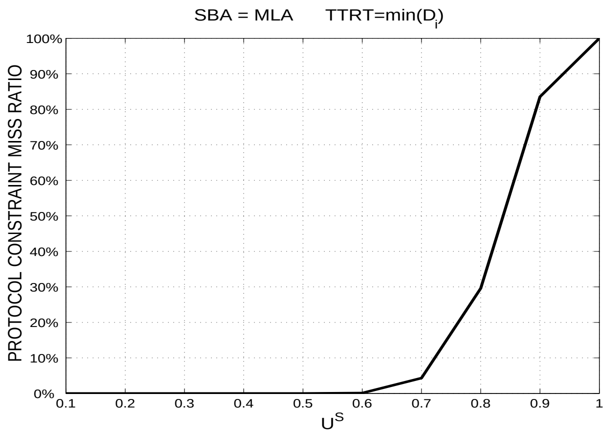

Figure 5. Protocol Constraint Miss Ratio for the MLA scheme.

Figure 4 shows the results obtained with the LA scheme, while Figure 5 shows the results obtained with the MLA scheme.

As predicted by the theory, under LA all the stream set having $U^S \leq 0.33$ meet the Protocol Constraint, hence also the Deadline Constraint is met (see Section 4.2.1). Notice that, PCMR is equal to 0.037% for $U^S = 0.4$, therefore it may not be detected in the figure.

Under MLA, as long as $U^S \leq 0.5$, all stream sets meet the Protocol Constraint, hence the Deadline Constraint is met for FDDI-M and BuST, while it is not met for FDDI as stated in Section 4.2.2. Notice that, for $U^S = 0.6$ the PCMR is equal to 0.093%, hence it is not visible in the figure.

It is worth observing that the PCMR for MLA outperforms that one provided by LA. This confirms that, under MLA, both BuST and FDDI-M can guarantee a larger number of stream set with respect to FDDI under the LA scheme.

6 Conclusions and Future work

This paper analyzed the performance of the BuST protocol in comparison with FDDI and FDDI-M, when the EPA, LA and MLA budget allocation schemes are used. The analysis has been performed both theoretically and by simulation. The analysis showed that, for real-time traffic, the performance of BuST is equal, or at least comparable to that of FDDI-M, while BuST performs better than FDDI in all cases.

It has been shown that FDDI-M can not serve non real-time traffic under the EPA scheme. Conversely, it has been shown that BuST overcomes this drawback guaranteeing a minimum bandwidth also for non real-time messages. Moreover, for each considered SBA scheme, several properties have been provided for the considered protocols. Such properties can be exploited as schedulability tests, or to select a value of $TTRT$ suitable to achieve the feasibility of a stream set.

Future work comprises the analysis of other SBA schemes proposed in the literature, to extend the comparison between BuST and timed token protocols.

Appendix

Lemma 4 *For all $y \in \mathbb{R}$, $y \geq 1$, given $U \in \mathbb{R}^+$, if $U \leq \frac{1}{2}$, then $\lceil Uy \rceil \leq y$. If $U > \frac{1}{2}$, then there exist an $y \geq 1$ such that $\lceil Uy \rceil > y$*

Proof. Let consider three cases:

1. $U = \frac{1}{2}$, if $1 \leq y < 2$, then $\lceil \frac{1}{2}y \rceil = 1 \leq y$.
   $\lceil \frac{1}{2}y \rceil < \frac{1}{2}y + 1 \leq y$, hence, $\frac{1}{2}y + 1 \leq y$ if and only if $y \geq 2$. It follows that, for any $y \geq 1$, $\lceil \frac{1}{2}y \rceil \leq y$.
2. $U = \frac{1}{2} - \varepsilon, 0 < \varepsilon \leq \frac{1}{2}$, we have to verify that $\lceil (\frac{1}{2} - \varepsilon)y \rceil = \lceil \frac{1-2\varepsilon}{2} y \rceil \leq y$.
   For $1 \leq y < 2$, $\lceil \frac{1-2\varepsilon}{2} y \rceil \leq \lceil 1 - 2\varepsilon \rceil \leq 1 \leq y$.
   For $y \geq 2$, $\lceil \frac{1-2\varepsilon}{2} y \rceil < \frac{1-2\varepsilon}{2} y + 1 \leq y$,
   thus $\frac{1-2\varepsilon}{2} y + 1 \leq y$ if and only if $y \geq \frac{2}{1+2\varepsilon}$. Being $\frac{2}{1+2\varepsilon} < 2$, then $\lceil (\frac{1}{2} - \varepsilon)y \rceil \leq y$ for any $y \geq 1$.
3. $U = \frac{1}{2} + \varepsilon, \varepsilon > 0$. We have to verify that, for any $\varepsilon > 0$, there exists at least a y such that $\lceil (\frac{1}{2} + \varepsilon)y \rceil = \lceil \frac{1+2\varepsilon}{2} y \rceil > y$.
   We consider $y \leq 2$, let $y = 2 - \delta$, $\delta > 0$, then $\lceil \frac{1+2\varepsilon}{2}(2 - \delta) \rceil > 2 - \delta$,
   hence $\lceil 1 + (2\varepsilon - \frac{\delta}{2}(1 + 2\varepsilon)) \rceil > 2 - \delta$ if and only if $2\varepsilon - \frac{\delta}{2}(1 + 2\varepsilon) > 0$, then $\delta < \frac{4\varepsilon}{1+2\varepsilon}$. Given $\varepsilon > 0$, it is always possible to choose δ, $0 < \delta < \frac{4\varepsilon}{1+2\varepsilon}$, such that for $y = 2 - \delta$, $\lceil (\frac{1}{2} + \varepsilon)y \rceil > y$.

□

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