Adaptive Bandwidth Balancing Mechanisms for DQDB Networks

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Abstract

To improve fairness in DQDB Metropolitan Area Networks a mechanism known as bandwidth balancing (BWB) has been introduced in the final version of the IEEE 802.6 standard document. Since then several changes to the basic mechanism, attempting to adhere to different interpretations of the fairness concept and to match the needs of different categories of users, have been proposed. In this paper attention is focused on the adaptive class of fairness control mechanisms and two solutions are analyzed and compared.

In order to do this, analytical models suited to study DQDB networks under overload conditions are introduced. The models are also amenable to the evaluation of the transient behaviour of DQDB networks, thus enabling a thorough investigation of the performance that can be obtained by adopting different fairness control mechanisms. The analytical models have been validated through the use of a software simulator. Numerical indices measuring the performance of the balancing mechanisms mentioned above are also given.

keywords: MAN, DQDB, Performance Evaluation.

1 Introduction

The Distributed Queue Dual Bus (DQDB) is the access technique which has been adopted by IEEE for the Metropolitan Area Network (MAN) standard (IEEE 802.6) [2]. A DQDB network is structured as a pair of unidirectional fiber optic buses, and the medium access protocol is based on a distributed procedure aimed at implementing a global FIFO distributed queue to which fixed length packets (also called segments) are appended for transmission during fixed length time slots.

Since its introduction DQDB has shown a clearly unfair behaviour [4] [5]. In fact, due to the nature of the basic access method to the communication medium, under normal operating conditions the stations at the end of the transmission bus suffer from higher access delays with respect to the stations placed at the head of the bus. If, instead, the network is overloaded, the last stations are penalized in terms of the system bandwidth which is actually obtained. Moreover, in such a case, it has been shown that the final distribution of the available bandwidth among the different stations depends on the transient occurred to reach the steady state. This causes the network behaviour to be unpredictable, and hence unreliable, for most of the communication needs.

To overcome this problem, a bandwidth balancing (BWB) mechanism has been introduced in the final draft of the DQDB standard [2, 6, 7]. This mechanism, whose behaviour depends on a parameter called the bandwidth balancing modulus (BWBM), requires each station to leave one usable slot empty, and therefore available, to the downstream stations when it has already used a number of slots equal to BWBM. In this way a sort of channel of free slots is created on each of the two buses, which permits an effective distributed control on the sharing of the system bandwidth.

The net effect is that each station is granted at least a minimum amount of bandwidth to be available all the time. This value is called the control rate. When the network is overloaded, the stations offering a load under the control rate (the so-called non-limited stations) manage to transmit all their offered traffic, whereas the bandwidth which is not used by the non-limited stations is divided evenly among the other stations. The cost that must be paid for such an improvement in fairness is a modest loss in the total available bandwidth (however, a modification to the conventional BWB scheme has been presented recently [15] which permits a full utilisation of the bus bandwidth). It should also be noted that the unfairness observed under low traffic conditions in the distribution of access delays is not solved by the BWB mechanism – this inconvenience is not as serious as the unpredictability of the bandwidth sharing.

Since fairness is a quite generic concept, researchers have investigated several variations of the basic BWB mechanism, each one aimed at enforcing a given type of fair behaviour. Some authors [8, 9] have pointed out that, in some circumstances, it may be desirable to assign bandwidth to overloaded nodes in a non-uniform way. For example, if the nodes do not serve the same numbers of users, and an even distribution of bandwidth among the users is aimed for, the bandwidth must be assigned to the nodes in proportion to the number of users they serve. It has also been shown [8] that this kind of non-uniform distribution of the bandwidth can be achieved by setting a distinct BWBM value for each network node. This means that the control rate, which is the minimum portion of bandwidth granted to each node, is not the same for all the stations, but is proportional to the BWBM value which has been selected.

Furthermore, the subdivision of the available bandwidth among the heavily loaded nodes is not necessarily fixed, but it may change as time elapses especially when particular kinds of applications are run over the network [10, 11]. For example, in [10] video services which require time-varying bandwidth assignments are considered and it is proposed that such situations are dealt with by a periodical re-assignment of the BWBM parameters in a DQDB network. In [1], a really adaptive mechanism is proposed in which the BWBM parameters are proportional to the load offered at each station: when the load changes, the BWBM parameter, and hence the relevant bandwidth, is adjusted dynamically. In this way, the fraction of traffic lost when the network is overloaded is equalized among the stations.

More recently, another scheme has been proposed, i.e. the guaranteed bandwidth (GBW) protocol [3], which is suited to support the connection-oriented variable bit rate (CO VBR) traffic [13] required by applications such as for example compressed video.

This mechanism is based on the use of priority levels provided by the original DQDB protocol and ensures a deterministic upper bound on the transmission times for delay sensitive traffic (whose peak rate is known in advance, when the connection is established). GBW, however, does not address the problem of a fair distribution of the bandwidth left unused by CO VBR traffic among the stations transmitting low priority connectionless (CL) traffic. Such an issue is best dealt with adopting the usual bandwidth balancing mechanism (or its modifications) for segments sent at priority 0, as mentionned in [14].

In this paper attention is focused on the adaptive fairness control mechanisms based on dynamic variation of the BWBM parameters, and in particular two mechanisms are considered: the first is the one described in [1], whilst the second is a new one, which has been conceived to equalize both the assigned bandwidth and the transmission delays in overload conditions [12].

Up to now DQDB networks in general and fairness control mechanisms in particular have been studied mainly when operating in steady-state conditions. In this paper, this assumption is relaxed, and overloaded networks working in non-stationary conditions are also considered. In particular, the approximated analytical model developed here enables us to study the transient condition following a peak of generated traffic, and to evaluate how parameters such as the length of the local queues or the throughput can vary over time. This kind of analysis is particularly important when adaptive fairness control mechanisms are evaluated.

The results obtained by means of the approximated model are then checked through the use of simulations. It is shown that the simulated results closely match very well those obtained analytically, thus validating the assumptions made in developing the model.

The paper is structured as follows: in section 2 the two adaptive fairness control mechanisms considered are briefly described. In section 3, the analytical model which is also valid for non-stationary conditions is introduced. In section 4 the model is used to study the transient period following an abrupt change in the load offered, whilst section 5 presents the results of the simulations that have been carried out to validate the model.

2 The adaptive fairness control mechanisms

The two fairness control mechanisms that are studied in this paper both rely for their operation on the standard BWB mechanism, however they both require a periodic recomputation of the BWBM parameter value. They can be classified as "adaptive" mechanisms, in that their main objective is to have the ability to change bandwidth allocation dynamically, according to some network parameters. Thus, unlike many other proposals aimed at improving fairness in a DQDB network, these mechanisms are highly compatible with the DQDB networks already operating according to the standard specifications, and therefore it is simple and feasible to upgrade them with an adaptive control scheme.

The first mechanism was originally proposed in [1]. The BWBM parameter in this case is taken to be proportional to the traffic offered at each station. The offered traffic can be evaluated by each station by counting the number of segments submitted for transmission inside successive temporal windows of fixed length. As already observed [1], this mechanism enforces an equalization of the percentage lost traffic.

A second mechanism, which is not found in the literature but is first presented in this paper, assumes the BWBM for each station to be proportional to the length of the local queue, i.e. the queue where the segments submitted for transmission are temporarily stored waiting to be sent in an empty bus slot. In this way a station with many segments stored in its local buffer waiting to be delivered is automatically given a greater slice of bandwidth, thus contrasting the filling up of its local queue. It can be shown [12] that the policy enforced by such a mechanism is to equalize the access delays of the different stations, irrespective of the station's offered traffic. Moreover, this mechanism is the most effective in avoiding some queues filling up, thus it may help to prevent the loss of submitted segments during temporary overload conditions. Congestion control has been recognised as a major problem when routers or gateways are connected to the network backbone, due to the limitation of available buffer space. In [16] another mechanism is proposed which can share all the buffers in the networks, however it needs substantial modifications to be made to the basic DQDB protocol.

In the following, the standard BWB mechanism is indicated with the term FIX_BWB, whereas the terms AT_BWB and AQ_BWB represent the two mechanisms mentioned above, that enforce a control on the offered traffics and on the length of the local queues respectively.

3 The analytical model

Since the behaviour of a DQDB network is symmetrical with respect to the two buses, in the following we consider only one bus, to which all the quantities introduced are referred. In a stationary situation where ρ_i is the (mean) offered load at node i, and β_i is the BWBM value of node i, the BWB control rate mechanism is such that the throughput which can be obtained by node i is upper bounded by the so-called control rate R_i, which is given by

$$R_i = \frac{\beta_i}{1+\beta_i}\left(1 - \sum_{j \neq i} \gamma_j\right) \quad (1)$$

or, equivalently

$$R_i = \frac{\beta_i}{1+\sum_{j \in N_L} \beta_j}\left(1 - \sum_{j \in N_{NL}} \gamma_j\right) \quad (2)$$

where γ_i is the throughput actually obtained by node i, N_L is the set of stations limited by the control rate mechanism (i.e. the stations whose offered load exceeds the control rate), while N_{NL} is the set of stations not limited by the BWB mechanism. In practice, we have

$$\gamma_i = R_i, \forall n_i \in N_L \quad (3)$$

and

$$\gamma_i = \rho_i, \forall n_i \in N_{NL} \quad (4)$$

Since the aim is to study the behavior of various control rate mechanisms under non-stationary conditions, the following instantaneous quantities are defined:

- $q_i(t)$ is the size of the local queue of node i, at time t
- $\beta_i(t)$ is the BWBM value of node i, at time t

- $\rho_i(t)$ is the instantaneous generation rate at node i, at time t. If $N_i(t)$ is the cumulative number of segments generated up to time t at node i, we have that $\rho_i(t) = \frac{dN_i(t)}{dt}$.

- $\gamma_i(t)$ is the instantaneous throughput at node i, at time t. If $D_i(t)$ is the cumulative number of segments transmitted up to time t at node i, we have that $\gamma_i(t) = \frac{dD_i(t)}{dt}$.

If it is assumed that the statistical characteristics of $\rho_i(t)$ and $\gamma_i(t)$ can vary slowly with respect to the network settling time, the results of the steady-state analysis can be used as a basis on which to derive an approximated model which is valid for the non-stationary analysis. As mentionned in [1] the settling time of a DQDB network (i.e., how long it takes for the network to reach a steady-state throughput distribution) depends on several factors, among which the inter-station spacing and the BWB modula choosen for the different stations. This implies that our model is more accurate when the inter-station spacing and the BWBM values are small. If traffic fluctuates faster than the network settling time the model can be still applied, however it does not provide a very good approximation of the actual network behaviour. This is not a serious limitation, since we have used the model mostly to study the network when a temporary overload takes place whose duration is not negligible (i.e. which can last enough to allow the local queues of some stations to fill up) in order to establish some trends.

The concept of a station limited by the control rate mechanism must be redefined as a time-dependent attribute of a station. It must be noted that the BWB mechanism is such that a certain period of time elapses before a variation of the BWBM parameters affects the network behaviour. However, for our purposes, it is convenient to assume that the effect of such variations on the distribution of throughput be immediate. As a consequence of this assumption at a specific time a node can be either limited or not-limited by the BWB mechanism. In practice, the time taken by a node to change its state is neglected.

It seems reasonable to assume that the limitation state of a node depends on the length of the local queue. In fact, if a restricted time interval is considered, the offered load and the rate with which segments are submitted to the distributed queue are not necessarily the same, in that they tend to be decoupled by the local queue. This implies that the throughput obtained in a restricted time interval does not depend only on the submission rate: stations with several segments waiting in their local queue continuously submit segments to the distributed queue, and the throughput they obtain is bounded by the control rate mechanism. Thus, when the local queue contains several segments we can consider the station to be limited. Instead, when the local queue is empty the submission rate can be identified with the offered load.

Let us now define a bound for the queue length to be used in determining the limitation state of a station. Let $q_i^{(NL)}$ represent the average length of the local queue of the non-limited station i: we must remember that when a station is not limited by the BWB mechanism its queue length is usually small but, from a statistical viewpoint, its mean value is not null, due to the fluctuations in the submission process (as it happens in all the queueing systems). Such a mean length seems to be the most suitable value to be used for the bound, however it is a generally unknown value in that it depends on the offered load distribution. Since the model being considered is to be used mainly to study a network in overload conditions, in the following we assume $q_i^{(NL)} = 0$; the obtained results confirmed that such a choice provides a good degree of approximation.

In the following, since we are interested in statistical average behaviour, we shall consider the stations with $E[q_i(t)] > q_i^{(NL)}(t)$ as the limited stations ($E[]$ is the statistical average operator). Let us define $N_L(t)$ as the set of stations whose throughput is being limited by the control rate mechanism at time t, and $N_{NL}(t)$ as the set of stations which are not being limited. Moreover, let us define the average control rate at time t as

$$R_i(t) = \frac{E[\beta_i(t)]}{1 + \sum_{j \in N_L(t)} E[\beta_j(t)]} \left(1 - \sum_{j \in N_{NL}(t)} E[\gamma_j(t)] \right) \tag{5}$$

We assume that, at time t, $E[\gamma_i(t)]$ can be approximately evaluated as

$$E[\gamma_i(t)] = R_i(t), \forall n_i \in N_L(t) \tag{6}$$

for the limited stations and as

$$E[\gamma_i(t)] = E[\rho_i(t)], \forall n_i \in N_{NL}(t) \tag{7}$$

for the non-limited stations.

In the following, such assumptions will be used to derive approximate analytical results for the behavior of the different control rate mechanisms under non-stationary conditions.

3.1 Throughput and queue length

If the local queue of station i is unbounded, the following equation holds:

$$q_i(t) = \int_{t_0}^{t} (\rho_i(t) - \gamma_i(t))\, dt + q_i(t_0) \tag{8}$$

Taking the statistical averages, because of the linearity of the above system, we have:

$$E[q_i(t)] = \int_{t_0}^{t} (E[\rho_i(t)] - E[\gamma_i(t)])\, dt + E[q_i(t_0)] \tag{9}$$

Hereafter, the statistical average time-dependent quantities $E[q_i(t)]$, $E[\beta_i(t)]$, $E[\rho_i(t)]$ and $E[\gamma_i(t)]$ will be referred to as $\overline{q}_i(t)$,$\overline{\beta}_i(t)$, $\overline{\rho}_i(t)$ and $\overline{\gamma}_i(t)$ respectively.

These concepts can now be applied to the two adaptive BWB mechanisms we have considered. Unlike the standard mechanism, that specifies a single constant value for the BWBM, for every node in the network, the adaptive mechanisms let β_i to depend on some measurable parameter on each node. The outcome is that these parameters vary in time, thus from now on the bandwidth balancing modulus of station i at time t will be referred to as $\beta_i(t)$.

AQ_BWB

In AQ_BWB, the BWBM for each node is proportional to the local queue length, that is

$$\beta_i(t) = \eta_q q_i(t) \tag{10}$$

The average control rate $R_i(t)$ can be expressed as

$$R_i(t) = \frac{\eta_q \overline{q}_i(t)}{1 + \eta_q \sum_{j \in N_L} \overline{q}_j(t)} \left(1 - \sum_{j \in N_{NL}} \overline{\gamma}_j(t)\right) \tag{11}$$

From equation (11) it can be observed that, when this mechanism is applied, it makes little sense to discriminate between limited and non-limited stations. In fact, for a station that is being limited by the BWB mechanism, the obtained throughput (equal to the control rate) is proportional to the length of the local queue. Vice versa, at a non-limited station the local queue will shrink until the BWBM becomes so low that the station gets limited. Thus the size of the queue at each station is such that it satisfies equation (11) with $R_i(t) = \overline{\rho}_i(t)$, at least as long as it is not full.

From these considerations it follows that it is possible to study the system assuming that all the nodes be limited by the BWB mechanism, and equation (11) becomes

$$\overline{\gamma}_i(t) = \frac{\eta_q \overline{q}_i(t)}{1 + \eta_q \sum_{j \in N} \overline{q}_j(t)} \tag{12}$$

which is valid for all the stations irrespective of their limitation state. Note that in this case a limited station can still obtain all the bandwidth it needs to deliver its generated traffic.

The behaviour of the network is thus described by the following set of differential equations

$$\frac{d\overline{q}_i}{dt} = \overline{\rho}_i(t) - \frac{\overline{q}_i(t)}{\frac{1}{\eta_q} + \sum_{j \in N} \overline{q}_j(t)} \tag{13}$$

for which a closed-form solution is not known. Let $Q(t) = \sum_j \overline{q}_j(t)$ and $T(t) = \sum_j \overline{\rho}_j(t)$. With the assumption $\sum_{j \in N} \overline{q}_j(t) \gg \frac{1}{\eta_q}$, which is true if it is assumed that at least some nodes have several segments queued, it is possible to neglect the term $\frac{1}{\eta_q}$ and the equation (13) becomes

$$\frac{d\overline{q}_i}{dt} = \overline{\rho}_i(t) - \frac{\overline{q}_i(t)}{Q(t)} \tag{14}$$

By adding the terms related to the various stations on the left and right sides of equations (13) respectively we get

$$\frac{dQ}{dt} = T(t) - 1 \tag{15}$$

Let us assume that the traffic $\overline{\rho}_i(t)$ is piece-wise linear, that is it takes values (indicated as $\overline{\rho}_i$) which are constant within some defined time intervals. Moreover let T be the mean total offered traffic $T(t)$ within one of such intervals and let Q_0 be the sum of the lengths $\overline{q}_i^{(0)}$ of the local queues for $t = 0$:

$$Q_0 = \sum_{i \in N} \overline{q}_i^{(0)} \tag{16}$$

Equation (15) admits a simple solution in the form

$$Q(t) = Q_0 + (T-1)t \tag{17}$$

that is valid for $Q(t) \geq 0$.

Substituting (17) in (14) we obtain

$$\frac{d\overline{q}_i}{dt} = \overline{\rho}_i - \frac{\overline{q}_i(t)}{Q_0 + (T-1)t} \tag{18}$$

that, when solved for $T \neq 1$ gives

$$\overline{q}_i(t) = \frac{\overline{\rho}_i}{T}\left[Q_0 + (T-1)t\right] + \xi_i\left[Q_0 + (T-1)t\right]^{-\frac{1}{T-1}} \tag{19}$$

which is valid for $Q(t) \geq 0$, that is for

$$\begin{cases} t \geq -\frac{Q_0}{T-1} & \text{, when } T > 1 \\ t \leq -\frac{Q_0}{T-1} & \text{, when } T < 1 \end{cases} \tag{20}$$

When $T = 1$ the solution is instead

$$\overline{q}_i(t) = \overline{\rho}_i Q_0 + \xi_i e^{-\frac{1}{Q_0}t} \tag{21}$$

In both cases, the coefficients ξ_i satisfy the following condition

$$\sum_i \xi_i = 0 \tag{22}$$

Equations (19) and (21) are valid within each time interval in which the offered traffic is constant. From these equations it is possible to see that if $T \geq 1$ the plots of $\overline{q}_i(t)$ for increasing values of the elapsed time asymptotically tend to straight lines, whose expressions are given by

$$\overline{q}_i(t) = \overline{\rho}_i\left(1 - \frac{1}{T}\right)t + \overline{\rho}_i\frac{Q_0}{T} \tag{23}$$

The approximate expression for the throughput $\overline{\gamma}_i(t)$ can be obtained by substituting the above expressions for $\overline{q}_i(t)$ and $Q(t)$ in equation (12):

$$\overline{\gamma}_i(t) = \frac{\overline{q}_i(t)}{Q(t) + \frac{1}{\eta_q}} \tag{24}$$

AT_BWB

In AT_BWB, the BWBM for each node is proportional to the offered load, that is

$$\beta_i(t) = \eta_t \rho_i(t) \tag{25}$$

The control rate $R_i(t)$ for a generic node is

$$R_i(t) = \frac{\eta_t \overline{\rho}_i(t)}{1 + \eta_t \sum_{j \in N_L} \overline{\rho}_j(t)} \left(1 - \sum_{j \in N_{NL}} \overline{\gamma}_j(t) \right) \tag{26}$$

Let T(t) be the total traffic offered to the network

$$T(t) = \sum_{j \in N} \overline{\rho}_j(t) = \sum_{j \in N_{NL}} \overline{\rho}_j(t) + \sum_{j \in N_L} \overline{\rho}_j(t) = T_{NL}(t) + T_L(t) \tag{27}$$

where $T_L(t)$ and $T_{NL}(t)$ represent the traffic offered by the limited and by the non-limited nodes respectively. Remembering that for the non-limited nodes $\overline{\gamma}_j(t) = \overline{\rho}_j(t)$, equation (26) can be rewritten as

$$R_i(t) = \overline{\rho}_i(t) \frac{1 - T_{NL}(t)}{T_L(t) + \frac{1}{\eta_t}} \tag{28}$$

and from this we get

$$T(t) > \left(1 - \frac{1}{\eta_t} \right) \Leftrightarrow R_i(t) < \overline{\rho}_i(t), \forall i \tag{29}$$

If the condition $T(t) > \left(1 - \frac{1}{\eta_t}\right)$, depending only on the total offered traffic $T(t)$, is satisfied then $R_i(t) < \overline{\rho}_i(t)$ and so each node is limited independently of the traffic $\overline{\rho}_i(t)$ which it offers. This means that when such a condition is met the limitation state applies to the overall network, and the throughput $\overline{\gamma}_i(t)$ obtained by a generic node is equal to the control rate $R_i(t)$

$$\overline{\gamma}_i(t) = \overline{\rho}_i(t) \frac{1}{T(t) + \frac{1}{\eta_t}} \tag{30}$$

It must be noted that the converse is non true, that is the condition $T(t) < \left(1 - \frac{1}{\eta_t}\right)$ does not imply that all the nodes are non-limited at that specific time. In this case all that can be said is that, since for each node $\overline{\rho}_i(t) < R_i(t)$, the queues of the limited nodes will shrink so as to return to the non-limited state. The time taken to pass from the limited to the non-limited state is usually different from node to node.

Substituting equation (28) in (9) it is possible to write, for a node which is being limited by the BWB mechanism,

$$\frac{d\overline{q}_i}{dt} = \overline{\rho}_i(t)\left(1 - \frac{1 - T_{NL}(t)}{T_L(t) + \frac{1}{\eta_t}}\right) \tag{31}$$

whose solution can be obtained by integration. Assuming the functions $\overline{\rho}_i(t)$ to be piece-wise linear, and the network to be globally overloaded, then the solution of equation (31) is

$$\overline{q}_i(t) = \overline{\rho}_i\left(1 - \frac{1}{T + \frac{1}{\eta_t}}\right)t + \overline{q}_i^{(0)} \tag{32}$$

which is the equation of a straight line. The slope of this line, which represents the rate at which the local queue fills up, is proportional to the offered load $\overline{\rho}_i(t)$ of the node.

3.1.1 Steady-state throughput

For the sake of completeness let us derive the expressions describing the throughput in a DQDB network under steady-state conditions. In fact, while the results related to AT_BWB have been already derived in other papers, those related to the AQ_BWB can not be found elsewhere in the literature.

AQ_BWB

As for the case of the transient analysis, it is possible to assume that in steady-state conditions each node is limited by this BWB control mechanism. In this case the control rate and hence the obtained throughput depend on the length q_i of the local queue

$$\gamma_i = \frac{q_i}{\frac{1}{\eta_q} + Q} \tag{33}$$

Being this mechanism an adaptive one, the local queue of each node will tend to assume a length such as to allow all its generated traffic to be sent on the network. If a station is not overloaded the condition $\gamma_i = \rho_i$ holds and the length of the local queue can be expressed by

$$q_i = \rho_i\left(Q + \frac{1}{\eta_q}\right) \tag{34}$$

Since the length q_i of the queue can not exceed the its maximum size $q_i^{(Max)}$, the following expression must hold for every node

$$q_i \leq q_i^{(Max)} \tag{35}$$

thus the maximum allowable throughput $\gamma_i^{(Max)}$ can be found to be equal to

$$\gamma_i^{(Max)} = \frac{q_i^{(Max)}}{\frac{1}{\eta_q} + Q} \tag{36}$$

Only the nodes for which $\rho_i \leq \gamma_i^{(Max)}$ will succeed in delivering all the generated load, while those exceeding such a threshold will saturate their local queue and hence they will lose a fraction of their own local offered traffic. In the following we will refer to the nodes that can not deliver all the submitted segments due to the saturation of their local queue as blocked stations.

The steady state behaviour of the AQ_BWB is very similar to that of the usual FIX_BWB mechanism described in the standard. In fact, being Q the total number of segment queued in the network

$$Q = \sum_{i \in N_B} q_i + \sum_{i \in N_{NB}} q_i \tag{37}$$

where N_B e N_{NB} respectively are the set of the blocked nodes and the set of the non-blocked nodes, and remembering that for a blocked node $q_i = q_i^{(Max)}$, from equations (37) and (34) we get

$$Q = \sum_{i \in N_B} q_i^{(Max)} + \sum_{i \in N_{NB}} \rho_i \left(Q + \frac{1}{\eta_q} \right) = \sum_{i \in N_B} q_i^{(Max)} + \left(Q + \frac{1}{\eta_q} \right) \sum_{i \in N_{NB}} \rho_i \tag{38}$$

and, from this

$$Q = \frac{\sum_{i \in N_B} q_i^{(Max)} + \frac{1}{\eta_q} \sum_{i \in N_{NB}} \rho_i}{1 - \sum_{i \in N_{NB}} \rho_i} \tag{39}$$

Substituting such an expression in the equation (36) and since for the non-blocked nodes $\rho_i = \gamma_i$, we obtain

$$\gamma_i^{(Max)} = \frac{\eta_q q_i^{(Max)}}{1 + \sum_{i \in N_B} \eta_q q_i^{(Max)}} \left(1 - \sum_{i \in N_{NB}} \gamma_i \right) \tag{40}$$

The above equation specifies the maximum amount $\gamma_i^{(Max)}$ of bandwidth available to the blocked nodes. It must be noted that it is very similar to the equation (2) for the control rate R_i of the standard mechanism, with the substitution $\beta_i = \eta_q q_i^{(Max)}$ and replacing the concept of limitation with the concept of blocking.

Hence, for what concerns the steady-state distribution of the obtained throughput we can study the AQ_BWB as the standard FIX_BWB mechanism, assuming the parameter BWBM to be equal to

$$\beta_i = \eta_q q_i^{(Max)} \tag{41}$$

This statement is valid irrespective of the blocking state of the different nodes in the network. Note that the behaviour of AQ_BWB differs from that of FIX_BWB when considering the delay time experienced.

AT_BWB

When a steady-state condition is considered, from the equation 29 we get

$$T > 1 - \frac{1}{\eta_t} \Leftrightarrow n_i \in N_L, \forall i \tag{42}$$

In fact, if $T > 1 - \frac{1}{\eta_t}$ as already said $\rho_i > R_i$ and then each node is limited.

Vice-versa, if $T < 1 - \frac{1}{\eta_t}$, then $\rho_i < R_i$ and every node succeeds in transmitting all the generated segments. This descends from the fact that if a node is limited then $\gamma_i = R_i$, but from the above assumption $\gamma_i > \rho_i$ and thus, from equation (8), the length of the queue would be a strictly decreasing function of the time (that is $\frac{dq_i}{dt} < 0$). Since this does not match with the assumption made of steady-state conditions it stem that consequently no node is limited.

The above sentences state that in steady-state conditions the nodes constituting the network may only be either all limited or none of them is limited. If the whole network is overloaded from the equation 30 it can be found that the obtained throughput is equal to

$$\gamma_i = \rho_i \frac{1}{\frac{1}{\eta_t} + T} \tag{43}$$

and each node loses a fraction p_i of its generated traffic equal to

$$p_i = \frac{\rho_i - \gamma_i}{\rho_i} = \left(1 - \frac{1}{\frac{1}{\eta t} + T}\right) \tag{44}$$

From this equation it can be noted that when this mechanism is adopted the fraction of traffic lost is the same for each node, and depends only on the total offered traffic.

3.2 Delay time

Let us define the transmission delay δ_i as the time elapsing from time t_1, when a segment enters the local queue of node i, to time t_2, when it is effectively transmitted on the network, that is

$$\delta_i = t_2 - t_1 \tag{45}$$

If the length of the local queues is not negligible, this delay can be reliably approximated with the time spent in the local queue. A segment entering the queue of node i at time t_1 will see $q_i(t_1)$ segments already queued, which, because of the FIFO policy, must be transmitted first.

Since $\gamma_i(t)$ can be considered as the rate at which the local queue at station i empties, the following expression must hold

$$q_i(t_1) = \int_{t_1}^{t_2} \gamma_i(t)dt \tag{46}$$

If the delay δ_i is to be expressed as a function $\delta_i(t)$ of the arrival time of the segment in the local queue, then it is necessary to put $t_1 = t$ and $t_2 = t + \delta_i$ in equation (46). If the temporal behaviour of $q_i(t)$ and $\gamma_i(t)$ is known, equation (46) implicitly gives the solution. Let $G_i(t)$ be given by

$$G_i(t) = \int \gamma_i(t)dt \tag{47}$$

Since $\gamma_i(t)$ is always greater or equal to zero, $G_i(t)$ is a monotonic non-decreasing function. From equations (46) and (47) we get

$$q_i(t) = G_i(t + \delta_i(t)) - G_i(t) \tag{48}$$

Assuming that $\rho_i(t)$ is not identically equal to zero, the same applies to $\gamma_i(t)$ as well, and $G_i(t)$ is a monotonic increasing function. Now let $G_i^{(-1)}(\cdot)$ be the inverse function of $G_i(\cdot)$

$$G_i^{(-1)}(G_i(t)) = t, \forall t \tag{49}$$

the existence of which derives from the assumptions.

The mean delay now can be approximated by

$$\overline{\delta}_i(t) = \overline{G}_i^{(-1)}\left(\overline{q}_i(t) + \overline{G}_i(t)\right) - t \tag{50}$$

and can be expressed in closed form if both $\overline{G}_i(\cdot)$ and $\overline{G}_i^{(-1)}(\cdot)$ can be expressed in a closed form. If we want to evaluate $\overline{\delta}_i(t)$ numerically we can transform both the sides of equation (48) to get

$$\frac{d\overline{q}_i}{dt} = \overline{\gamma}_i\left(t + \overline{\delta}_i(t)\right)\left(1 + \frac{d\overline{\delta}_i}{dt}\right) - \overline{\gamma}_i(t) \tag{51}$$

and from this

$$\frac{d\overline{\delta}_i}{dt} = \frac{\frac{d\overline{q}_i}{dt}(t) + \overline{\gamma}_i(t)}{\overline{\gamma}_i\left(t + \overline{\delta}_i(t)\right)} - 1 \tag{52}$$

which can be solved by numerical integration, if $\overline{\gamma}_i(t)$ is known.

3.2.1 Steady-state delay time

When a steady-state condition is considered, the delay δ experienced by a segment from the time of arrival in the local queue and the effective transmission on the network is obviously a time-independent quantity. From equation (46) we get

$$q_i = \int_{t_1}^{t_2} \gamma_i dt = \gamma_i (t_2 - t_1) = \gamma_i \delta_i \tag{53}$$

irrespective of the values of t_1 and t_2, then

$$\delta_i = \frac{q_i}{\gamma_i} \tag{54}$$

In the case of AQ_BWB the steady-state throughput γ_i is given by the equation (24). The important result obtained is that the delay is the same for all the nodes

$$\delta_i = Q + \frac{1}{\eta_q} \tag{55}$$

and does not depend on whether the node is blocked or not.

In the case of AT_BWB instead the delay time depends on the traffic. If the whole network is overloaded, that is $T > 1 - \frac{1}{\eta_t}$, the throughput is given by the equation (30) and for each node $q_i = q_i^{(Max)}$. From the equation (54) we obtain

$$\delta_i = \frac{q_i^{(Max)}}{\rho_i}\left(T + \frac{1}{\eta_t}\right) \tag{56}$$

from which it is possible to see that the delay is inversely proportional to the offered traffic ρ_i. If the network is underloaded this model is not adequate.

4 Using the model to analyze transient overloads

Let us now apply the results derived in the previous sections to analyze the behaviour of the BWB mechanisms during the transient following a temporary overload condition.

Usually, since it is not possible to transmit all the generated segments at once, they are stored by each node in the local queue waiting for transmission. When the network is globally overloaded, the queue length of some nodes tends to grow up. If this situation holds for a sufficiently long time, the local queue fills up and a fraction of the generated segments is lost. When this condition occurs the node is said to be blocked, according to the definition given in section 3.1.1.

With the standard BWB mechanism, the control rate is the same for all the stations, and only the stations whose offered traffic exceeds this value are limited thus causing their queues to grow. A feature which is common to both the adaptive variations of the basic BWB mechanism is that the growth of the queue length affects all the nodes in the network. Since the ultimate upper bound on the obtainable throughput is fixed, in that it depends on the capacity of the transmission medium, when an adaptive BWB mechanism is brought into effect, the queues at the nodes which are offering more traffic tend to get filled more slowly than in the case when the control rate is fixed. In other words, a network controlled by an adaptive mechanism can tolerate an overload condition for a longer period without losing segments, given a certain maximum size of the local queues.

Let us consider an underloaded network whose nodes initially have empty queues, that is $\overline{q}_i^{(0)} = 0$ and let us assume that beginning with time $t = 0$ the offered traffic grows so as to bring the network into an overload condition. Moreover, let us assume for simplicity that the traffic $\overline{\rho}_i(t)$ offered at each node for $t \geq 0$ is constant, $\overline{\rho}_i$ being the offered traffic at node i.

The temporal behaviour of the length $\overline{q}_i(t)$ of the local queues is given by equation (23) for AQ_BWB and by equation (32) for AT_BWB. Assuming that the term $\frac{1}{\eta t}$ in equation (32) is negligible with respect to T, and remembering that in equation (23) the initial total number of queued segments Q_0 is zero, then both the adaptive BWB mechanisms considered exhibit the same behaviour, and the length of the queue $\overline{q}_i(t)$ is given approximately by

$$\overline{q}_i(t) = \overline{\rho}_i \left(1 - \frac{1}{T}\right) t \qquad (57)$$

From this equation it can be shown that when the network is overloaded the length of the local queues grows linearly and that the filling rate is proportional to the offered traffic.

By contrast, if the standard BWB is adopted, the nodes whose traffic does not exceed the control rate have their local queue emptied or, better, $\overline{q}_i(t) = \overline{q}_i^{(NL)}(t)$, while at the other nodes the length of the queue is given by the expression

$$\overline{q}_i(t) = (\overline{\rho}_i - R_i)t \qquad (58)$$

until it fills up and gets saturated.

5 Model validation and numerical results

The analytical model used in this paper has been validated through the use of simulation. For this purpose an ad-hoc software simulator has been developed, which takes into account all the features of a DQDB network. The only assumption which has been made in developing the program is that the distance between any two stations is an integral number of slots.

In the following, the simulation experiments are described and the simulated numerical results are compared with those obtained analytically. These results are also used to characterize the different BWB mechanisms.

5.1 The simulation experiments

In the simulation experiments suitable values of the parameters were selected to define the network configuration and the way the fairness control mechanisms were to be implemented. In particular, the parameters of the various mechanisms were tuned so as to maximize the performances of each of them.

When FIX_BWB was considered a fixed value of 16 was chosen for the BWBM. In the AT_BWB case the value of a station's BWBM is given by the value of its offered load multiplied by a coefficient equal to 1024. As suggested in [1], each node evaluates its offered load by counting the segments submitted for transmission locally during a timing window of 1024 slots and dividing this value by the window duration. The value of the BWBM parameter is then updated at the end of the window. In contrast with [1], in order to avoid null values for BWBM, a slight modification has been adopted for the AT_BWB: the actual value of the BWBM is obtained by incrementing the computed value by one.

When the AQ_BWB strategy is considered, the value of the BWBM parameter is computed every slot time to be equal to the product of the length of the local queue multiplied by a scaling factor which is assumed to be $\eta_q = 2^{-4}$, and then it is incremented by one as in the AT_BWB. Parameter η_q has been chosen as a power of two in order to speed up the operations needed to compute BWBM. The selected value yields suitable values for the BWBM of the various nodes.

In the simulations, it is assumed that the DQDB network is composed of 20 stations, in addition to the two heads of bus (HOBs) that do not take part in the exchange of data. For the sake of simplicity, all the stations are assumed to be equally spaced on the shared buses, and the distance between any two stations is equal to three slots; this arrangement corresponds to a physical distance of 1638 meters between the stations for a signal rate of 155.52 Mbps. Furthermore, only one priority level for message transmissions was considered.

The traffic generation process at each node has an exponential distribution of the interarrival times between subsequent segments. This kind of generation is fully described by the mean value of the interarrival time τ or equally by its reciprocal $\overline{\rho} = \frac{1}{\tau}$, which represents the average value for the generated load. A symmetrical subdivision of the generated traffic was assumed for the two buses. In other words the probability of a segment generated in a station being transmitted on a given bus is proportional to the number of downstream stations that are found on that bus. Furthermore it is assumed that each station makes the same contribution to the global generated traffic. In this way it is possible to describe the traffic generation process in the network in terms of a set of values, one for each station, which represents the average global traffic generated by the station, no matter what the destination of the segment is.

The behaviour of the balancing mechanisms considered here was studied both in the case when a specific temporary overload condition occurs, due to a temporary increase in the generated traffic at a station, and when the network is under steady-state conditions.

The first kind of study makes it possible to explain some of the benefits which are obtained when the adaptive BWB mechanisms are used instead of the standard one. In fact, such mechanisms tend to follow the changes in the traffic profile of the network.

The length of the local queues and delay time were observed for each node under time-varying traffic conditions, and in the simulations which were considered a maximum queue size of 10,000 segments was assumed so as to minimize the interference with the traffic loss phenomenon.

Initially a symmetrical offered load distribution equal to 90% of the system's bandwidth was applied for a time period of 100,000 slots. Since the network was underloaded, a steady state condition was reached in which each station could send all the traffic generated.

Then, a temporary global overload condition occurred: the station adjacent to the HOB on one of the two buses (i.e. the first station on bus A or station 1) increased the load it generated of a quantity equal to 10% of the overall bandwidth in such a way that the global network load increased to 100%. Due to the symmetrical kind of traffic distribution chosen, however, only bus A was affected by this change, and its load reached 110% (in fact, station 1 sends all of its packets on bus A).

The duration of the overload condition was 300,000 slot times. Afterwards, the load offered at station 1 fell to the initial value, so that the load on bus A went back to a value

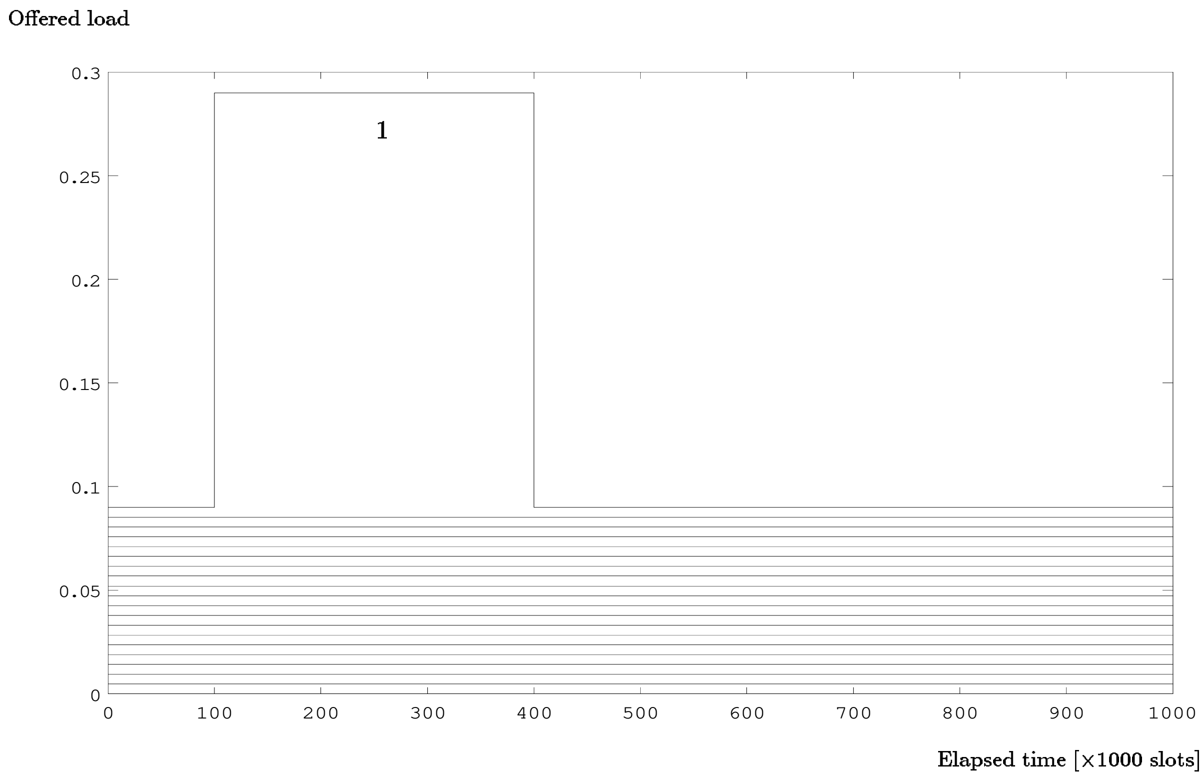

Figure 1: Sample offered load for transient analysis.

of 90%. The sample offered load on bus A versus the elapsed time (expressed in units of 1000 slot times) for all the stations in the network is depicted in Fig. 1. Statistics were collected by observing the system's behaviour for 1,000,000 time slots since this period of time is sufficient for the network to return to the steady-state condition. The parameters observed have been averaged over 1000 slot times wide windows. These windows are wide enough to ensure that reliable average values are obtained, but they are also narrow enough in relation to the changes in the network's parameters.

For what concerns the second kind of study (steady-state case), it has been assumed that the offered load is equal to 120% of the system bandwidth, distributed in a symmetrical way among the two buses. Fig. 2 show the distribution of the traffic generated on bus A and B for all the nodes in the network. Statistics on the network have been collected after a set-up time equal to one million slot times has elapsed. In this way it can be reasonably assumed that the initial transient condition due to network startup has ended.

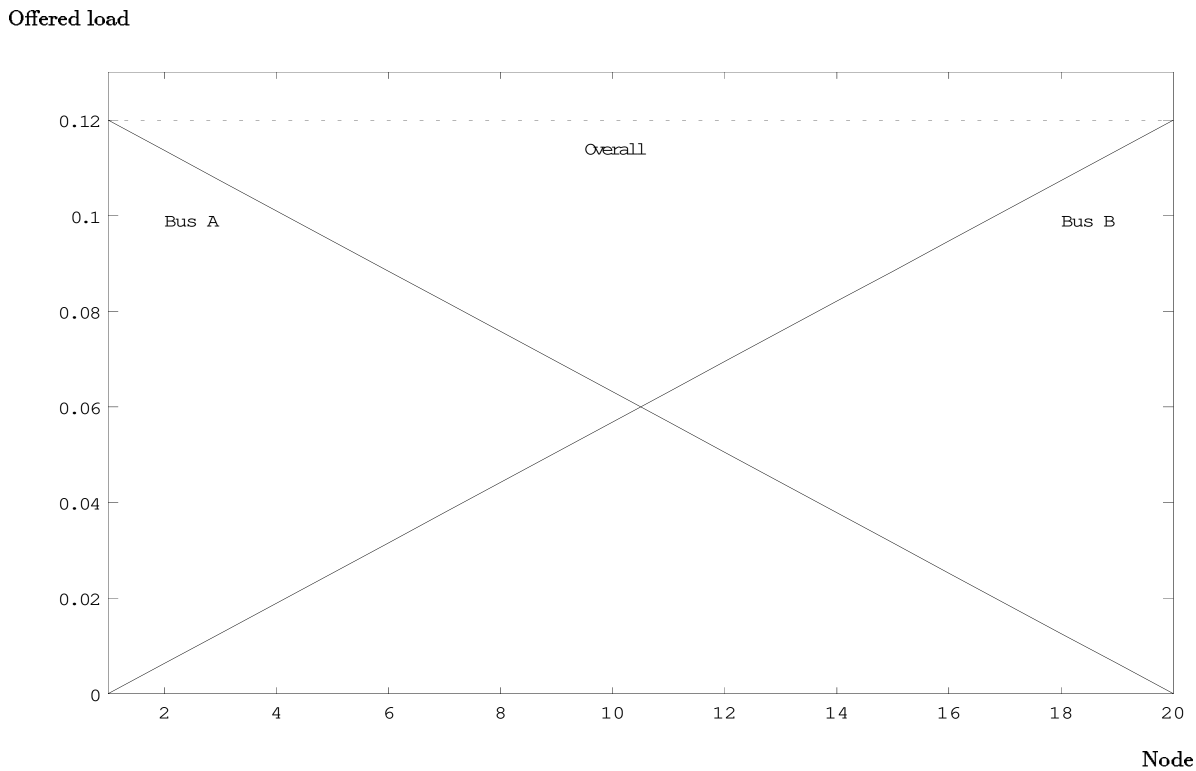

Figure 2: Symmetrical distribution of the traffic among the buses A and B in the steady-state analysis.

To collect meaningful steady-state figures, a total simulation time of ten million slot times has been assumed. The final results are obtained as the average values computed on this interval of the relevant simulated quantities.

5.2 Numerical Results

In this section are presented the results obtained by simulation and those obtained by using the analytical model previously described. A brief comparison is made of the adaptive mechanisms considered here, and the results are also used to validate both the simulations made and the model introduced.

Transient analysis When a fixed bandwidth balancing mechanism is adopted (the one described in the DQDB Standard), only the station which causes the overload is limited. So, while all the other stations receive a throughput at a level which is sufficient to send all the generated load, the limited station is assigned only that portion of bandwidth which is

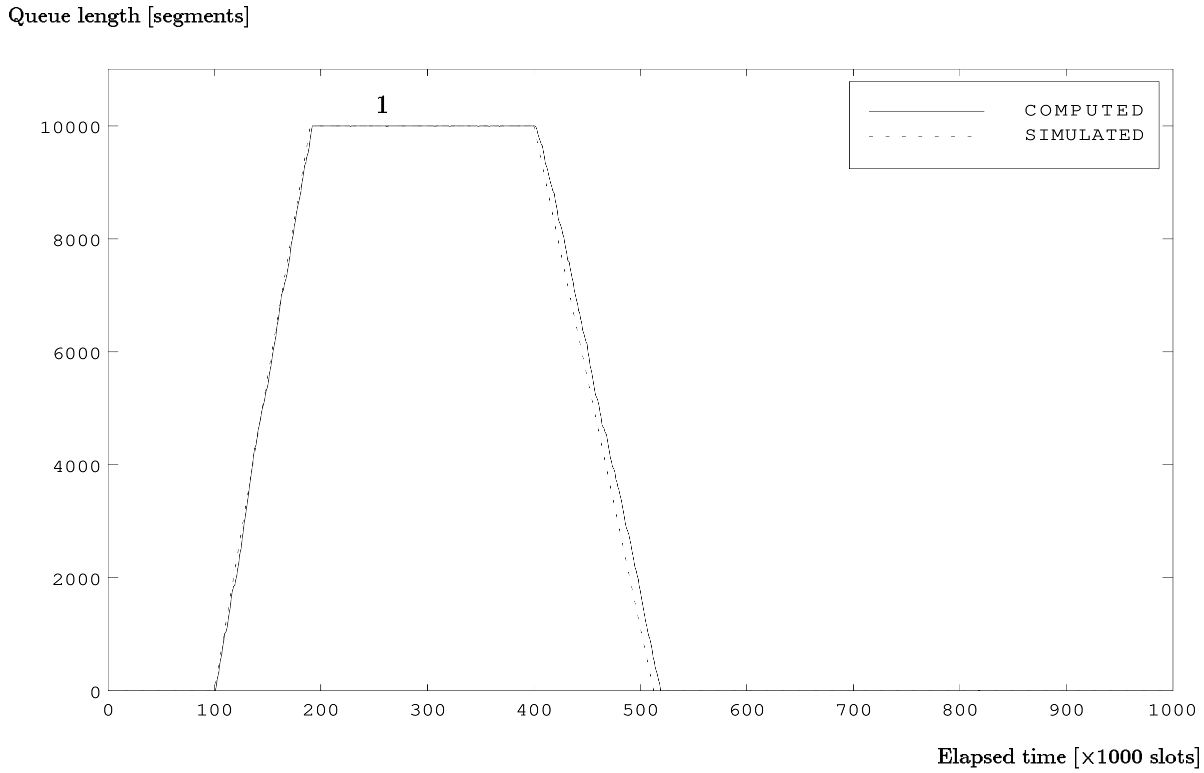

Figure 3: Queue length for FIX_BWB.

not being used by the other stations. Since the throughput obtained by the limited station is lower than the generated traffic, its queue length grows linearly until the maximum limit is reached. When the queue becomes full, the generated load which exceeds the permitted throughput is discarded. It should be noted that there is a significant increase in the delay time only at the station causing the overload.

Figs. 3 and 4 show respectively the queue length and the delay time versus the elapsed time (times are expressed in units of 1000 slot times) experienced by the various stations when FIX_BWB is being used. As already said all the stations except the one exceeding its own control rate show queue lengths and delay times which are absolutely negligible.

If AT_BWB is used, all the stations are limited in the same way when an overload condition arises, no matter which station caused the overload situation. This has two main consequences: first the lengths of all the queues in the stations grow, so transmission times increase. Second, with the same conditions of generated load, no segment is lost because of the saturation of the local queues. In fact all the queues grow at the same time

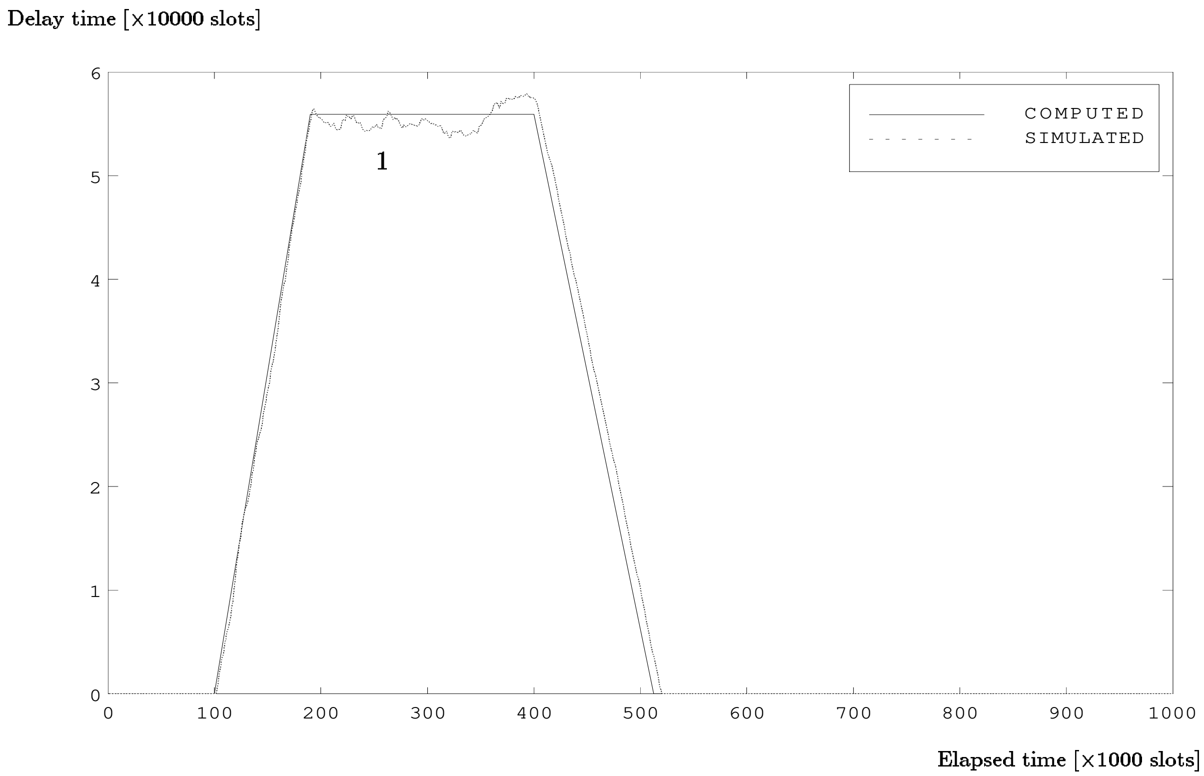

Figure 4: Delay time for FIX_BWB.

and this means that the tolerance of (temporary) overload conditions is improved. One drawback of this mechanism is the increase in the delay time experienced by a station when its offered load is drastically reduced. In fact, when the queue at such a station has almost reached its maximum length, a fall in the generated load causes a decrease in the actual throughput, and this makes it difficult to empty the queue.

Fig. 5 shows the behaviour of the queue length for the station 1 (the one which causes the overload) and for the stations 2 and 10 which are downstream on the bus, while fig. 6 shows the delay times experienced by the same stations. Note that delay times for all the stations but the first are theoretically equal.

In the AQ_BWB case the behaviour is similar to that experienced with AT_BWB, that is to say the overload is distributed among the stations. From this point of view this new balancing method performs better than the others, since its operations are dynamically controlled by the lengths of the queues. In particular it does not suffer from the drawback of the marked growth of the delay times occurring when a station no longer overloads the

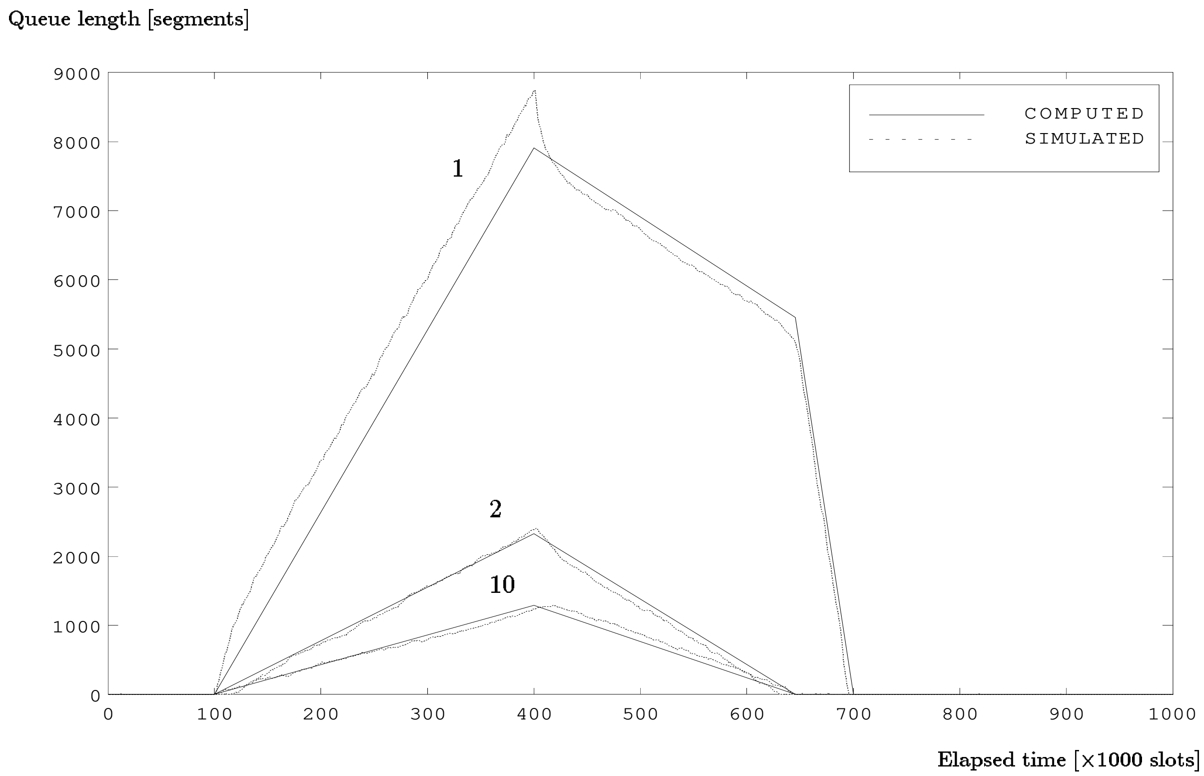

Figure 5: Queue length of stations 1,2 and 10 for AT_BWB

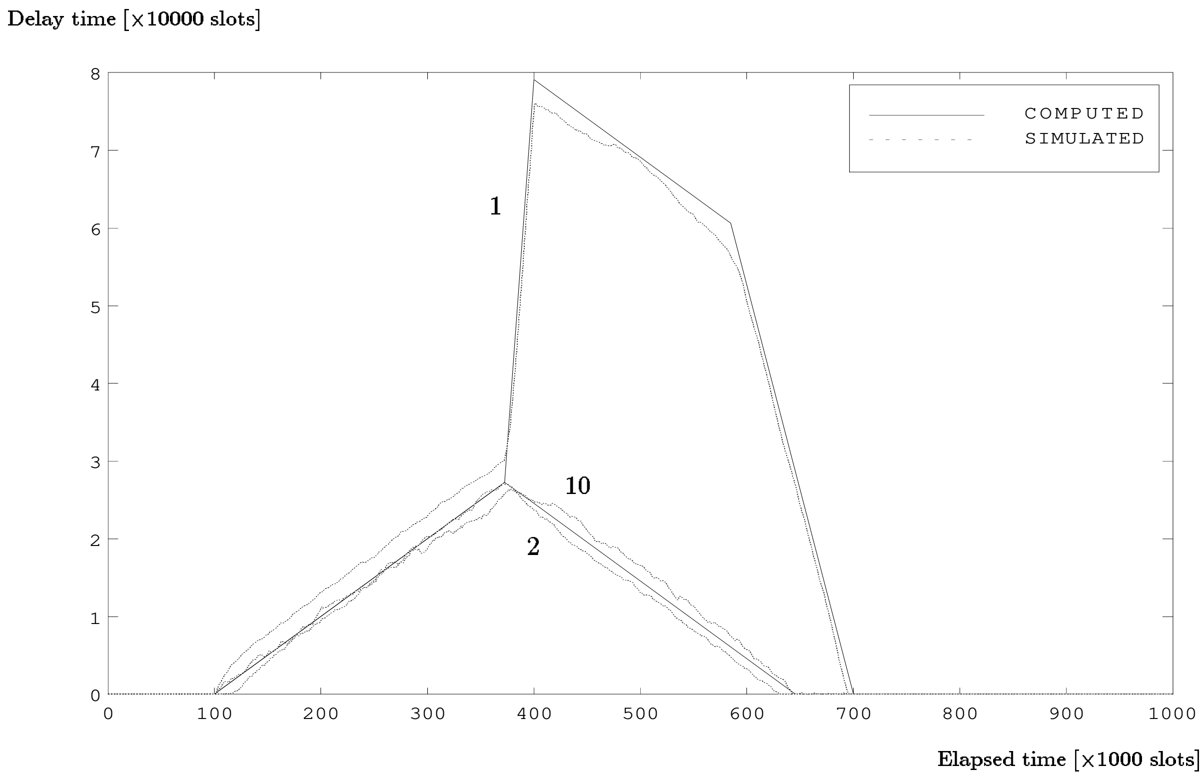

Figure 6: Delay time of stations 1,2 and 10 for AT_BWB

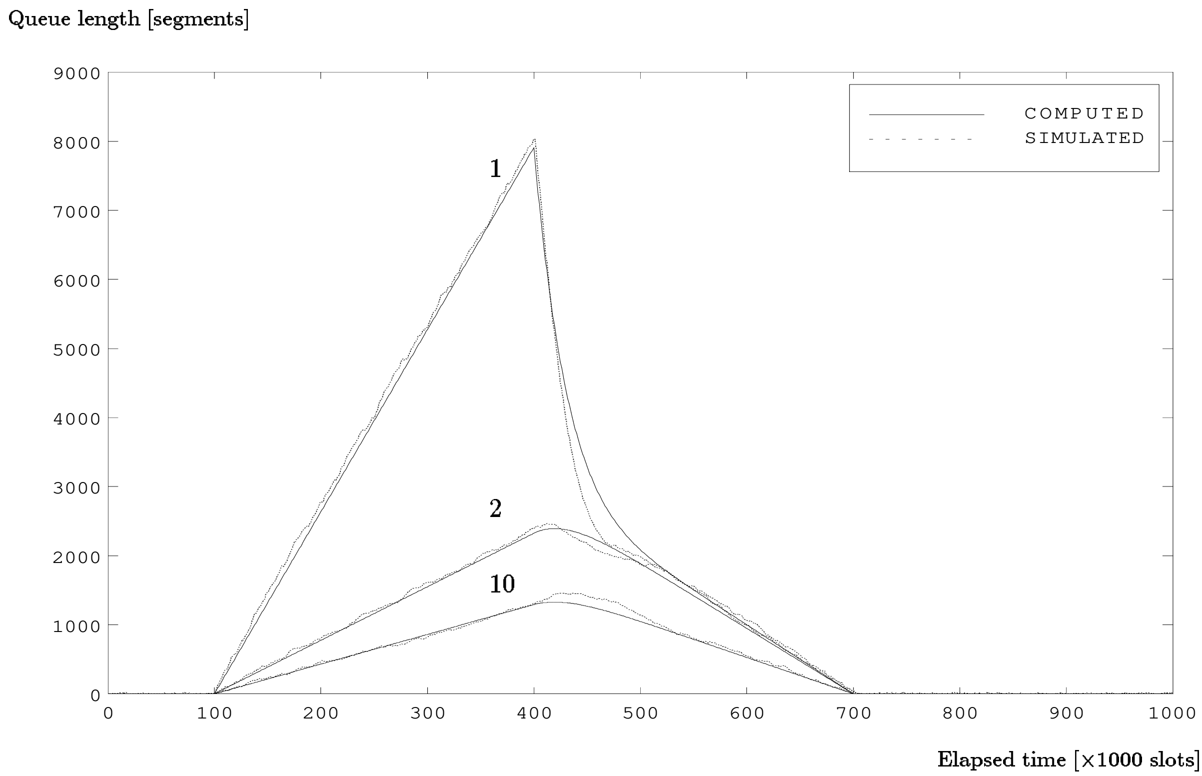

Figure 7: Queue length of stations 1,2 and 10 for AQ_BWB

network.

Fig. 7 and 8 show respectively the queue length and the delay time for the stations 1,2 and 10. Again in this case the analytical model shows that delay times for the non-overloading stations are equal. From the plots shown it can be observed that the analytical model which has been introduced has given results that closely resemble those obtained through simulation. The slight differences between the simulated and the analytically evaluated values are due to the assumption to neglect the delay in the intervention of the BWB mechanism. Such little differences anyway can easily be reduced if a lower value for the η parameters is used. In fact this reduces the BWBM parameter at each station, which in turn lowers the intervention time of the balancing mechanism. Thus it can be assumed that these experiments, very generic in nature, validate our model under non-stationary conditions.

Steady-state analysis When a permanent overload condition occurs some stations are forced to discard a fraction of the generated segments. The lengths of the local queues at

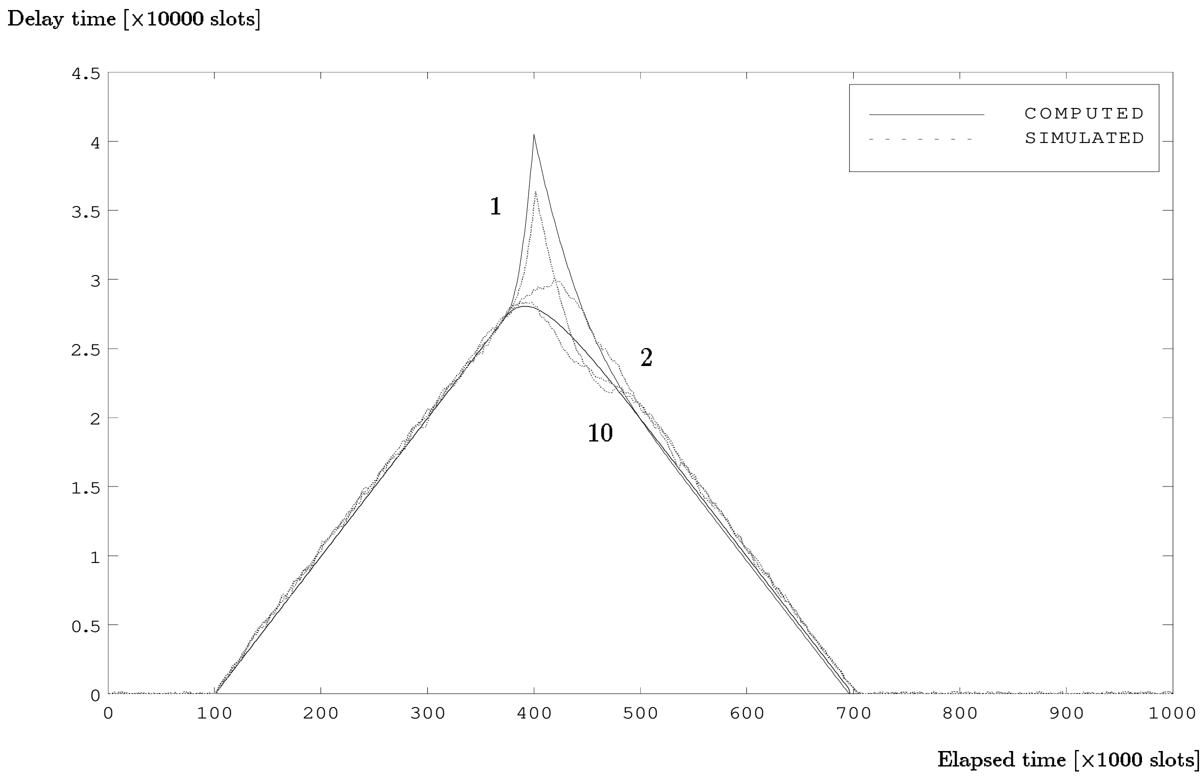

Figure 8: Delay time of stations 1,2 and 10 for AQ_BWB

those stations increase up to the maximum length that, in this experiment, was fixed at one thousand of segments.

Fig. 9 shows the total steady-state throughput on both buses registered at the different stations when the three different balancing mechanisms are used. In the case of FIX_BWB, the same upper bound is put on the obtainable throughput for every station. Specifically this means that stations trying to exceed this bound will be limited, while the others will obtain all the bandwidth they ask for. Due to the assumption that distribution of traffic is symmetrical, limitation occurs for the same number of stations on each bus, resulting in the distribution of the available bandwidth shown in the diagram.

A similar result is obtained for the AQ_BWB mechanism. This is due to the assumption that all the stations have the same size of the queue and the same proportionality coefficient η_q. Stations whose queues become full have the same value for the BWBM, so they behave in the same way as in the case of the FIX_BWB mechanism. The AT_BWB mechanism tries to give all nodes an amount of bandwidth proportional to the gener-

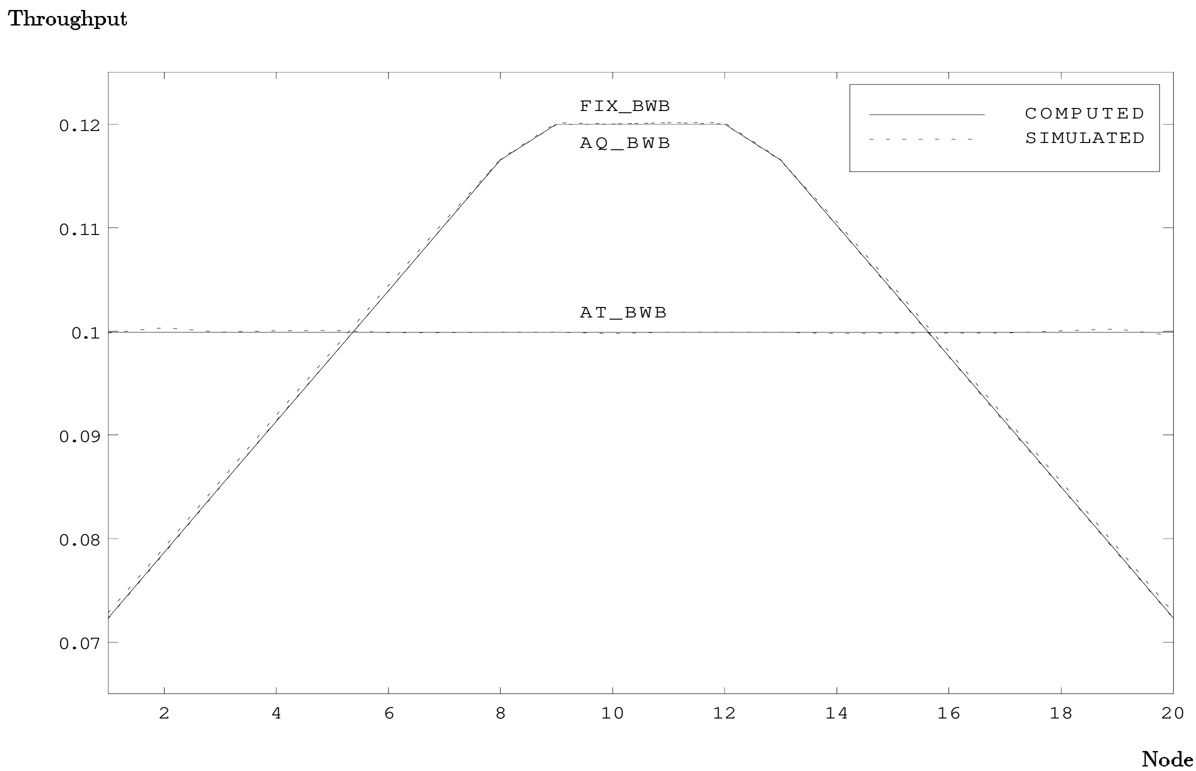

Figure 9: Throughput obtained in steady-state overload condition.

ated traffic. Since it is assumed that the load generated at each node is the same, the throughput for each station is the same.

Similar considerations also apply to the overall lost traffic percentage p. With the FIX_BWB and the AQ_BWB, the diagrams in Fig. 10 show that the nearer a station is to the middle of the bus, the smaller is the fraction of lost traffic. The AT_BWB approach is able to balance the percentage of lost traffic among all the stations, independently of the offered load.

Fig. 11 depicts the delay experienced on one of the two busses (the behaviour of the two buses is symmetrical), expressed in units of 1000 slot times. When FIX_BWB is considered the nodes which are not limited by the BWB mechanism (in our case stations 9 to 20 on bus A) still have very small delays, that are similar to those experienced in underload conditions, whilst the others experience much larger delays (which can be computed using the results from section 3.2.1). In the case of AT_BWB, all the local queues are filled up but, since the actual throughput varies from station to station, the

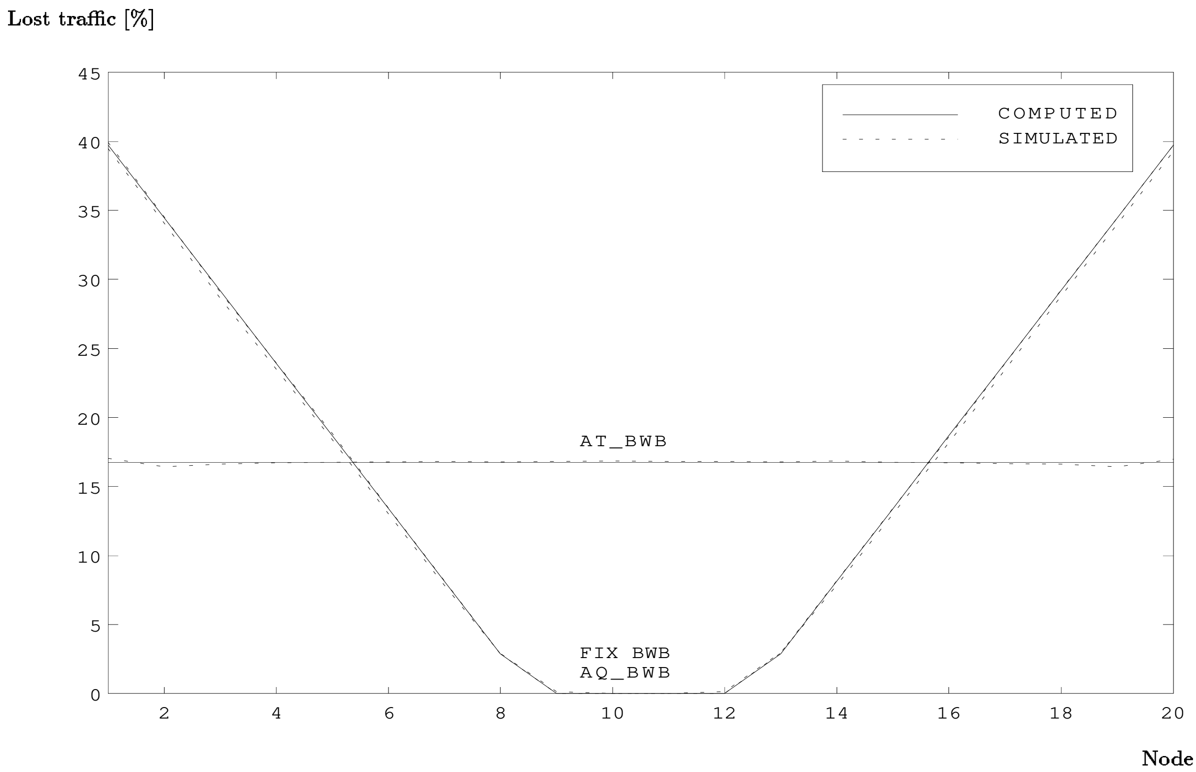

Figure 10: Percentage of lost traffic in steady-state overload condition.

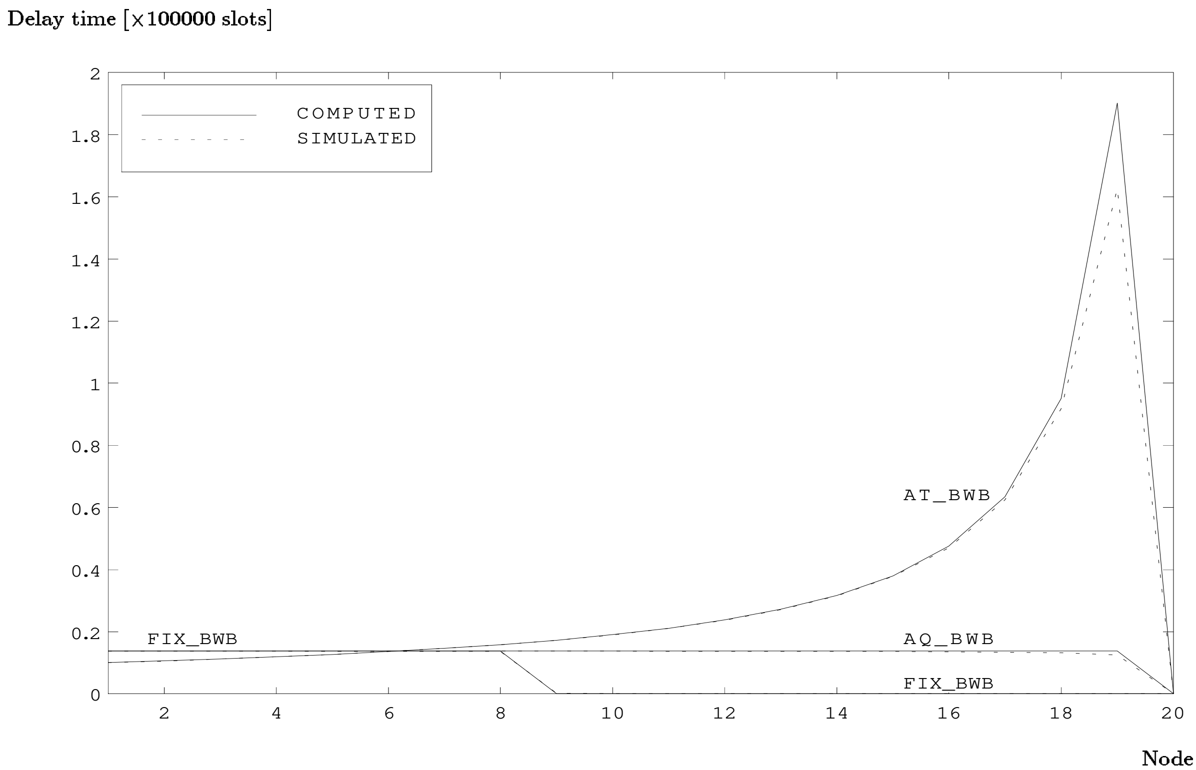

Figure 11: Delay time on bus A in steady-state overload condition.

nodes generating lower traffics experience larger delays. AQ_BWB enforces a uniform distribution of the delays among the nodes, thus allowing a fair behaviour from this point of view. This is because in steady-state conditions the obtained throughput is proportional to the queue length. Note that the delays obtained with FIX_BWB for the stations which are limited by the BWB mechanism (stations 1 to 8) are very similar to those obtained with AQ_BWB, thus confirming the analysis made in section 3.1.1. From the above plots it is possible to see that also in the steady-state case for every considered parameter and for every BWB mechanism adopted the analytical results very closely resemble those obtained from simulation.

6 Conclusions

DQDB networks are intrinsically unfair, thus their basic medium access mechanism has to be modified to include bandwidth balancing. Even if the GBW modification is adopted to support properly high priority CO VBR traffic, BWB mechanisms are necessary to provide a fair share out of the remaining bandwidth among the applications generating CL traffic.

The 802.6 standard includes a basic BWB mechanism, but variations of the standard mechanism have been proposed in the literature, allowing different fairness policies. In this paper the standard BWB mechanism and two other adaptive mechanisms have been compared. The two adaptive mechanisms considered here are the one described in [1] that enforces a control on the offered traffic, and a new one that enforces a control on the length of the local queues. The latter simple variant of the standard BWB fairness control mechanism has the effect of balancing the quality of service received by the various stations in a DQDB network, not only in terms of throughput, but also in terms of access delay. What is more, it is able to prevent in an effective way the local queues of the different stations from filling up (a not unusual event, if we consider low priority CL traffic, whose peak value can not be controlled nor evaluated).

An analytical model has been introduced which is useful for studying an overloaded network both in steady-state conditions and – what is new – in non-stationary conditions.

This model permits us to make a quick and accurate evaluation of network parameters such as the length reached by the local queue or the time submitted segments are delayed when peaks of the offered load temporarily force the network into an overloaded state – the normal cause of actual network overloads. Thus the model can be used profitably both in analyzing and comparing networks. It can also be used to tune some parameters on each node (e.g. buffer size) so as to maximize performance or minimize the probability of the station being blocked without having to run long simulation experiments.

The proposed model can be extended as well to balancing mechanisms other than those described here. In fact all the adaptive mechanisms that rely for their operations on the basic mechanism by reassigning of the BWBM parameters can be modelled and studied.

Simulations have been used to validate our model. In particular experiments have been made with the network under both steady-state and non-stationary conditions, and the results obtained analytically and by the simulator have been compared. This comparison shows that the model is quite enough accurate in all the conditions investigated.

Finally the results obtained are also used to compare the various fairness policies described. Simulation experiments and analytical evaluation have shown that in overload conditions the new AQ_BWB fairness control mechanism helps to prevent queues by filling up. Moreover, in contrast with all the other BWB mechanisms considered, it equalizes the access delay among the stations.

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