Approximate Performance Analysis of the DQDB Access Protocol

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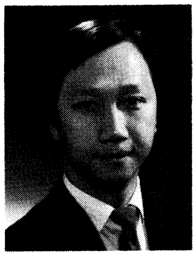
Abstract. We present an approximate performance study of the DQDB medium access protocol. The aim of the queuing analysis described in this paper is to provide close-form solutions, which should be easy to evaluate but deliver sufficiently accurate performance measures describing major behaviors of the protocol. The analysis is based on a decomposition of the medium access delay, using the technique of embedded models. The non-isochronous station-to-station traffic matrix, which consists of traffic streams assumed as Poisson, can be chosen arbitrarily. A percentage of preassigned isochronous traffic in the system is taken into account. It is shown by comparison with simulation results that the approximation technique developed in this paper is appropriate for a wide range of protocol parameters. The efficient analysis method also shows various protocol properties, which have been partly discovered in the literature by means of simulations.

Keywords. Performance analysis, embedded modelling, metropolitan area networks, DQDB, closed form solutions, traffic mixture, fairness.



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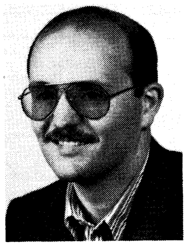
1. Introduction

The Distributed Queue Dual Bus (DQDB) access protocol is a promising candidate for upcoming high-speed local area and metropolitan area network standards, e.g. as being defined in IEEE 802.6. Attentions are devoted to this medium access scheme in some recent studies, both from technological and protocol performance viewpoints.

There is a number of simulation studies [2,5,13] and approximate analysis [14,15,16] dealing with performance aspect of various successive releases of the standardization process [1,6,8–10]. In [13] attentions are devoted to the protocol behavior under saturated traffic conditions. The study gives analytical insight into the station-based traffic discrepancy and the relationship between the overload performance and the initial system state prior to the overload period. A simulation of similar situations is given by Doshi and Fredericks [3], who also suggest some measures to decide whether a particular access method is *fair* or not. A comparative study is given in [5] dealing with the delay performance of FDDI and QPSX/DQDB in high-speed networks. Zukerman [14–16] studied various aspects of DQDB performance using approximate queuing analyses. Filipiak [4] considered some possible changes to the protocol to overcome the unfairness aspects mentioned above.

Since the DQDB medium access protocol is dedicated for use in high-speed metropolitan area networks and large local area networks, the num-



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ber of stations to be considered in performance investigations should be chosen large enough to reflect the real system environments. This choice and the according number of events needed in simulation studies may lead to excessive simulation time. To investigate sufficiently large configurations with varying parameter ranges, analytical investigation methods are required.

The aim of the analysis method developed in this paper is to give close-form solutions, which should be simple to evaluate and have a sufficient approximation accuracy over a realistic range of parameters. The analysis is composed by standard basic models of type M/G/1, whereby the service time of the next model level is composed by the waiting time of the previous modeling level and station-dependent random processes. We refer to this as the concept of embedded models. In Section 2 the main properties of the DQDB medium access mechanism are summarized. Section 3 gives an outline of modelling steps, arising parameters and details of the analysis. Some numerical results for system configurations with symmetrical and nonsymmetrical traffic will be presented in Section 4.

2. The DQDB Access Mechanism

The basic logical structure of a DQDB access system is depicted in Fig. 1. As the details of the protocol can be found in [6], we will summarize below only those characteristics of the DQDB operation, which are relevant in the system modeling context.

The transmission part consists of a pair of slotted unidirectional buses flowing into opposite directions. This dual pair of busses—bus A for downstream and bus B for upstream payload traffic—operates synchronously at MAC layer. A station attached to the dual bus system observes data passing on the two busses and participates in a distributed queuing scheme applied to the global system. The aim of this scheme is to provide each station with information about the overall queuing state of the system. This may help to achieve a system behavior that approaches a global FIFO queue.

Each station is connected to both busses and is able first to read the information on the above read tap and then to write to the appropriate bus on the beneath write tap. Since the access mechamism is identical for the two busses, the description below will focus on one direction. For this, we take the downward data transfer on bus A and the corresponding request transfer on bus B. Furthermore, in the DQDB standard proposal, a station is allowed to send data according to four priority levels. Although this feature can be considered in full detail in the analysis, the case of one priority level will be taken below, in order to simplify the description.

A slot contains an access control field (ACF), a segment header and a segment payload area for isochronous and non-isochronous (asynchronous) traffic. For these different types of traffic two access control modes are provided. The pre-arbitrated access mode is reserved for isochronous services like voice and video. This mode is controlled by the slot generators, which mark the preallocated slots using the BUSY bit in the ACF. Accesses of non-isochronous services are controlled by the station itself according to the queued-arbitrated [6] access mode. A station accessing bus A that works according to this access mode has to follow three main principles

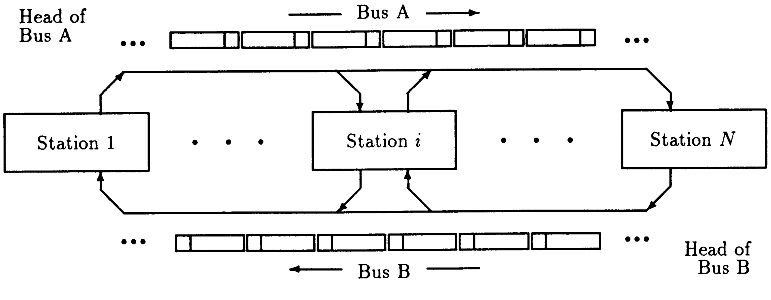

Fig. 1. DQDB system structure.

- broadcast access request to upstream stations,
- keep track of access requests generated by downstream stations,
- access bus A when all requests prior to its own are satisfied.

Now we will discuss this access mode in more detail.

If a station wants to transfer a non-isochronous segment downstream using bus A, it notifies this wish to all stations upstream by sending a request on bus B. This is done by using the request bit on the given priority level. In parallel the station continuously makes note about all requests flowing by on bus B. While the station has several separate queues for segments waiting to be transferred on both busses and different priority levels, the station schedules only one segment per bus. In other words, each station has one schedule position facing to each bus for each priority level, but only one of them can be active. The scheduled segment waiting to be transmitted in the station may not be sent before all preceding requests which were observed on bus B are served. To do this, the station has to wait until the corresponding observed number of free segments has passed on bus A.

Considering only data transfer on bus A and one priority, a station can be in the following two states: IDLE and COUNTDOWN (see Fig. 2). We consider in the following the station i. For each bus and priority level the station has to maintain different counters, in particular the request counter (REQ_CNT) and the countdown counter(CD_CNT).

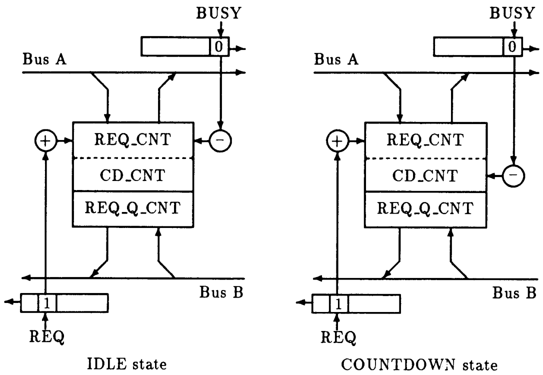

Fig. 2. Logical states of a DQDB station.

(1) *IDLE-state*: the station has nothing to send or was on immediate transition from state COUNTDOWN. The request counter maintains the number of requested transmissions sent by stations $i+1, \ldots, N$. This counter is decremented upon observing a free slot flowing by on bus A and is incremented upon seeing a request passing by on bus B.

(2) *COUNTDOWN-state*: the station has data segments to transmit. A segment has been scheduled at time t_0 for transmission. The request counter indicates the number of request arrivals after t_0. The countdown counter maintains the number of requests which arrived prior to t_0 and have to be served before the scheduled segment. In this state, the countdown counter is decremented by observing a free slot flowing by on bus A while the request counter is incremented upon arrival of a new request on bus B.

(3) *State transitions*: A state transition from IDLE to COUNTDOWN is processed as follows. The station enqueues a request to the local request queue, sets the countdown counter to the actual value of the request counter and then resets the request counter. The station always takes over from COUNTDOWN to IDLE after sending a segment. This is followed immediately by a backward state transition from IDLE to COUNTDOWN if there are still segments waiting in the station.

Each time when a transition form IDLE to COUNTDOWN is executed, a request is generated and placed in the local request queue. This is done by incrementing REQ_Q_CNT by one; it is decremented when a request has been put on bus B. It is important to note that this request queue operates totaly asynchronous to the above data segment queuing system. This is a main difference to one of the predecessors of the analyzed protocol version, where these two systems were synchronized.

3. Modeling and Analysis

3.1. System Model and Assumptions

We consider a network with N attached stations operating with the DQDB access protocol. The distance between station i and j is denoted by r_{ij}. The network carries both isochronous and non-isochronous traffic. The isochronous traffic (e.g., voice, video, etc.) is preallocated slot-wise by the slot generator. As mentioned, in order to simplify the description of the analysis, we consider in the following the simpler case of one priority level. Further, since we have a dual symmetrical bus system with decomposable traffic flows, it is sufficient to investigate only one data flow direction. The analysis of the other direction is analogous.

Hence, we pay now attention on the downstream data traffic on bus A and the corresponding upstream request traffic on bus B. Incoming asynchronous traffic streams are assumed to be Poisson. The traffic intensity of asynchronous traffic from station i to station j is denoted by λ_{ij} ($\lambda_{ii} = 0$). Thus, the total traffic Λ_i generated at station i to be transferred on bus A and the total asynchronous traffic Λ on bus A can be written as

$$\Lambda_i = \sum_{j=i+1}^{N} \lambda_{ij} \quad \text{and} \quad \Lambda = \sum_{i=1}^{N-1} \Lambda_i. \tag{1}$$

We denote p_{I} and $(1 - p_{\mathrm{I}})$ the percentages of the isochronous traffic and the remaining bandwidth available to asynchronous traffic. With τ be the slot duration, the asynchronous bus utilization ρ_i of station i and the total asynchronous traffic ρ on bus A are

$$\rho_i = \Lambda_i \cdot \tau \quad \text{and} \quad \rho = \sum_{i=1}^{N} \rho_i. \tag{2}$$

We observe in the following a segment, which is generated in the station i and passed across the medium access control. It is then to be transmitted to the station j ($j > i$). The segment itself will be transferred on bus A and its request on bus B. As depicted in Fig. 3, we take into account the following time instants, which are significant for the calculation of the segment transfer time according to the DQDB access mechanism:

(1) arrival epoch of the segment,

(2) time instant, at which the observed segment is scheduled for transmission on bus A; at this time a request is created and is to be sent on bus B. The segment is ready to be transmitted, but still has to wait according to the FIFO discipline in the globally distributed queue,

(3) the segment is at the head of the global queue and is enabled to be sent, but still has to wait for a free slot flowing by on bus A,

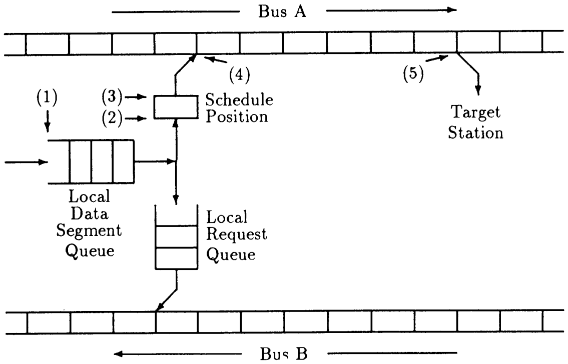

Fig. 3. Sending part and modeling concept.

(4) end of the transmission on the bus,

(5) the segment has arrived at the receiving station j.

This observation leads to a decomposition of the segment transfer time, where the following random variables (r.v.) are defined:

T_{12} = r.v. for the waiting time in the local queue in station i; each priority level has a separate local queue,

T_{23} = r.v. for the waiting time in the schedule position in station i; this waiting time is dependent on the state of the global queue, in conjunction with the distributed queueing scheme,

T_{34} = r.v. for the virtual transmission time,

T_{45} = propagation delay from station i to station j.

According to this observation, the medium access delay is T_{14} and the segment transfer time is T_{15}.

3.2. Embedded Modeling and Medium Access Delay

We will consecutively determine the distribution functions of T_{34}, T_{23} and T_{12}, which finally deliver the distribution of the medium access delay T_{14}.

The r.v. T_{34} can be interpreted as the interval between free slots seen from the station i. Station i sees a slot stream on bus A, where two types of busy slots can be observed:

(i) isochronous slot patterns which are periodically allocated and

(ii) slots already occupied by non-isochronous traffic from stations $1, \ldots, i-1$.

The distribution of isochronous patterns on the

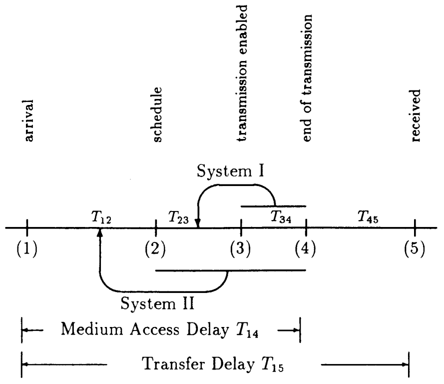

Fig. 4. Segment lifetime and analysis concept.

slot stream is assumed to be uniform. Considering in this paper the two special cases $p_I = 0$ and $p_I = 50\%$, we describe approximately the interval between free slots seen from station i with the following geometric distribution:

$$\Pr\left\{T_{34} = k\frac{1}{p_I}\text{slots}\right\} = q_i^{k-1}(1-q_i), \quad k = 1, 2, \ldots \tag{3}$$

with $q_i = \Sigma_{j=1}^{i-1}\rho_i/(1-p_I)$. The according Laplace–Stieltjes transform (LST) is

$$\Phi_{34}(s) = \frac{(1-q_i)z}{1-q_i z} \quad \text{where } z = e^{-s\tau/p_I}. \tag{4}$$

From modeling point of view, T_{34} is the service time seen from all segments waiting for transmission, which have been noticed from station i. Thus we model the waiting behavior T_{23} of segments in the schedule position (cf. Fig. 3) with a standard M/G/1 system (system I of Fig. 4). The service time of this system is T_{34}. To obtain the traffic intensity of system I we take into account all segments arrival processes of the stations i, $i+1, \ldots, N$. The LST of the distribution function is (see [7])

$$\Phi_{23}(s) = \frac{s(1-\Gamma_i ET_{34})}{s-\Gamma_i(1-\Phi_{34}(s))} \quad \text{where } \Gamma_i = \sum_{j=i}^{N}\Lambda_j. \tag{5}$$

One important property of system I is that the mean service time increases while the arrival rate decreases with higher number i of the observed station. It should be noted here that for analyses with multi-classes of priorities, system I should be modified to a non-preemptive priority M/G/1 system with $K = 4$ priority classes. From eqs. (4) and (5), we arrive at the LST for the interval T_{24} between scheduling instant of the segment and the end of the segment transmission.

$$\Phi_{24}(s) = \Phi_{23}(s)\Phi_{34}(s). \tag{6}$$

As mentioned, the interval T_{24} can be seen as the virtual transmission time seen from those segments, which arrived at station i to be transferred on bus A. We describe again the waiting process in the local queue (see Fig. 3) by means of a M/G/1 system (system II in Fig. 4). The service process is modelled using the embedded modeling concept, i.e. the service time of system II consists of waiting time components, which had been calculated in system I. The decomposition of the medium access delay as shown in Fig. 4 is not only a time decomposition, but contains nested intervals computed by different submodels. The LST of the distribution function of the waiting time T_{12} in system II can be given accordingly:

$$\Phi_{12}(s) = \frac{s(1-\Lambda_i ET_{24})}{s-\Lambda_i(1-\Phi_{24}(s))}. \tag{7}$$

Finally, we arrive at the medium access delay

$$\Phi_{14}(s) = \Phi_{12}(s)\Phi_{23}(s)\Phi_{34}(s). \tag{8}$$

To obtain the total transfer delay, the propagation delay T_{45}, which can be easily estimated from the station-to-station distance r_{ij}, has to be added. Out of eqs. (3)–(8) values of interest like means and coefficients of variation of the medium access delay and the total transfer time can be derived. An explicit calculation of these two values is given in the Appendix.

3.3. Extensions of the Analysis Concept

The analysis concept described above can be used also in the general case of multiple priority classes. The system I should be remodelled as a non-preemptive priority system. The system II consists of a number of M/G/1 queues, which operate in parallel according to the existing priority classes.

To model more realistic traffic processes, the Poisson input streams should be replaced by general renewal processes. The systems I and II are then G/G/1 systems, which can be analyzed numerically using discrete-time analysis techniques (cf. [12]). On the one hand, we have in this case no longer a close-form solution. On the other hand, the numerical computation of the whole distribution becomes tractable using discrete-time transform methods. This is done in a research report [11], which is currently under preparation.

4. Numerical Results

To validate the approximate analysis, we consider a metropolitan area network with $N = 49$ stations, which are equidistantly located on a dual bus system of length 100 kilometers and transmission capacity 136 Mbps each. The slot length is chosen at 69 bytes (64 bytes segment payload, 4 bytes header, 1 byte ACF). The percentage of isochronous traffic is taken at $p_I = 50\%$. In the diagrams shown, we normalized the asynchronous traffic to the available bandwidth for non-isochronous traffic streams as $\rho^* = \rho/(1 - p_I)$. Delays are given in μs.

We consider two traffic configurations:

(i) configuration 1 with symmetrical traffic and

(ii) configuration 2 with nonsymmetrical traffic: an overloaded station 25 having 15% of the total offered traffic and all other stations symmetrically loaded.

The delay is measured for one transmission direction (bus A) only.

The comparison with simulation results shows that the analysis is sufficiently accurate for dimensioning purposes.

Figures 5 and 6 show the mean access delay for the two configurations 1 and 2 respectively. As expected, according to the often observed unfairness behavior of the DQDB protocol (cf. [5]), the mean access delay is station-dependent. For both configurations, the first station has the smallest access delay. For configuration 1, the station 35 has the largest access delay, and behind this station the mean access delay starts to decrease again. Note that the capacity limit of the entire system is defined by the station with the largest access delay. It is clearly shown that for a given total traffic, the capacity limit of the system is strongly dependent on the distribution of the traffic according to the traffic matrix. For configurations 1 and 2 it is about 0.9 and 0.8, respectively; this indicates that a non-symmetrical traffic distribution leads to a worse system performance.

Figure 7 describes the dependency of the station position to its corresponding medium access delay for configuration 1. The maximum for $\rho^* = 0.8$ can be found at about station 40, where the ratio of arriving requests and passing free data slots leads to the worst results. Adding up both directions of data transfer shows that the middle station 25 has to deal with the highest medium access delay. It should be mentioned that the

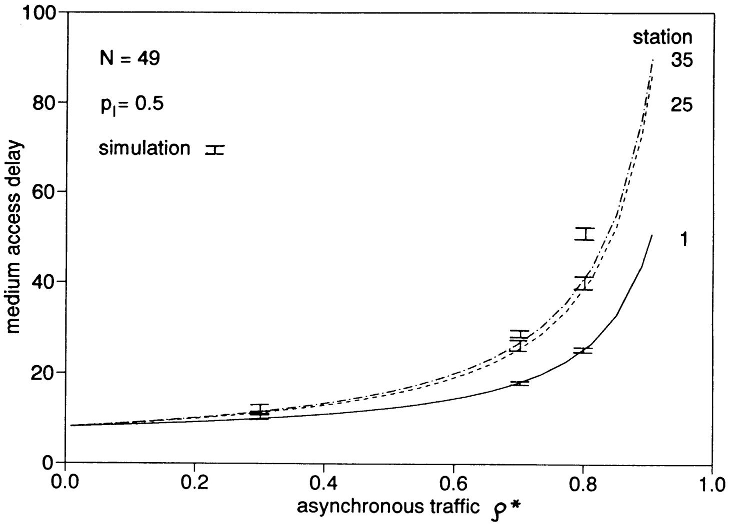

Fig. 5. Medium access delay vs. asynchronous traffic.

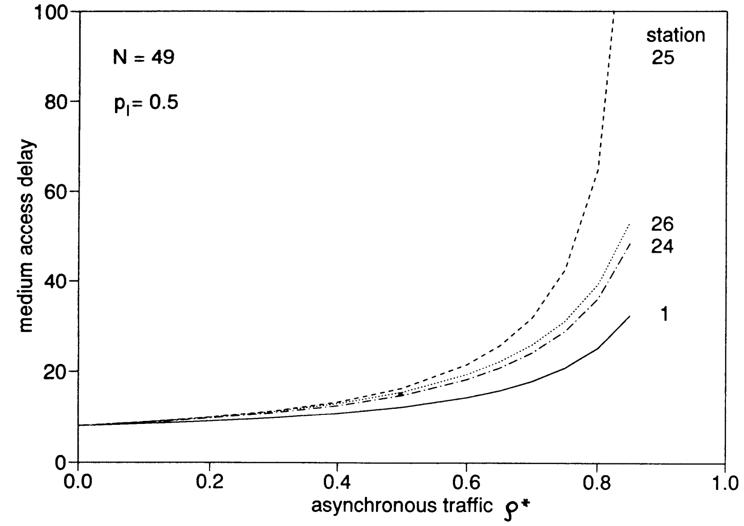

Fig. 6. Influence of nonsymmetrical traffic.

corresponding transmission delays are much lower than those of the head end stations, which is important when round trip delays between communicating processes are concerned.

We observe more closely the influence of the overload in station 25 of configuration 2 on the following stations in Fig. 8. The station-dependent mean access delays for the total asynchronous traffic $\rho^* = 0.3$, $\rho^* = 0.5$ and $\rho^* = 0.7$ are depicted. The phenomenon of acquired overload can be seen here, showing that a station located behind the overloaded station suffers larger delay than a station positioned in front of it. It has to be noted that the peak at the central station in Fig. 8

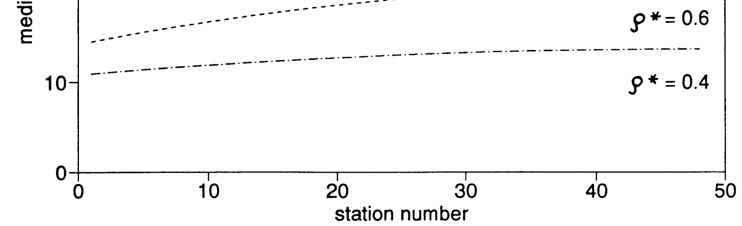

Fig. 7. Location dependency of medium access delay.

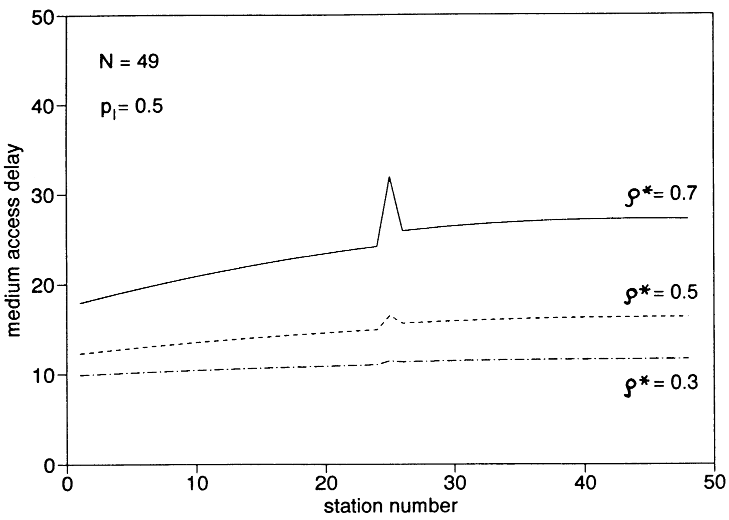

Fig. 8. Nonsymmetrical traffic and acquired overload.

cannot be seen in the simulation results while the larger delays of stations behind station 25 can still be observed.

5. Conclusion and Outlook

An approximate performance study of the DQDB medium access protocol has been presented. The main results obtained are approximate expressions for various delays in the system like the medium access delay given in the form of Laplace–Stieltjes transform. From these basic relationships, further measures of interest like the mean and the coefficient of variation of the mean access delay can be derived. The analysis is based on a decomposition approach of the medium access delay, using embedded modeling technique. Non-isochronous station-to-station traffic matrices can be chosen arbitrarily. As shown in comparisons with simulations, the accuracy of the approximation is sufficient for a wide range of protocol parameters.

Some major properties of DQDB had been carried out with the analysis showing by means of numerical results:

(i) the station-location dependency of the medium access time which can be interpreted as a unfairness property of the DQDB protocol and

(ii) the sensitivity of the overall system performance (capacity limit) concerning the station-to-station traffic matrix.

The modeling and analysis approach as presented in this paper is being extended to cope with more general input processes to describe more realistic traffic streams in data networks. The extension is done in the context of discrete-time queuing systems. The submodels used in these analyses are of type G/G/1, for which methods operating in both time and transform domain can be employed.

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Appendix. Formulae for Mean and Coefficient of Variation of the Medium Access Delay

Starting with the observation of T_{34} seen by station i (cf. eq. (3)) we can calculate its ordinary moments

$$E[T_{34}] = \frac{T_{\text{slot}}}{1 - q_i}, \tag{9}$$

$$E\left[T_{34}^2\right] = \left(\frac{T_{\text{slot}}}{1 - q_i}\right)^2 (1 + q_i), \tag{10}$$

$$E\left[T_{34}^3\right] = \left(\frac{T_{\text{slot}}}{1-q_i}\right)^3 \left(1 + 4q_i + q_i^2\right), \tag{11}$$

$$E\left[T_{34}^4\right] = \left(\frac{T_{\text{slot}}}{1-q_i}\right)^4 \left(1 + 11q_i + 11q_i^2 + q_i^3\right) \tag{12}$$

with

$$q_i = T_{\text{slot}} \sum_{j=1}^{i-1} \sum_{k=j+1}^{N} \lambda_{jk}. \tag{13}$$

Using these moments and the recursion formula (cf. [7])

$$\overline{\omega^k} = \frac{\lambda}{1-\rho} \sum_{i=1}^{k} \binom{k}{i} \frac{b_{i+1}}{i+1} \overline{w^{k-i}} \tag{14}$$

for the jth moments $\overline{b^j}$ and $\overline{w^j}$ of the service and waiting time in a M/G/1 system, the first three moments of T_{23} can be obtained for station i

$$E\left[T_{23}\right] = \frac{\sum_{j=i}^{N} \sum_{k=j+1}^{N} \lambda_{jk}}{1-\overline{\rho}_i} \tfrac{1}{2} E\left[T_{34}^2\right], \tag{15}$$

$$E\left[T_{23}^2\right] = \frac{\sum_{j=i}^{N} \sum_{k=j+1}^{N} \lambda_{ji}}{1-\overline{\rho}_i} \times \left(E\left[T_{34}^2\right] E\left[T_{23}\right] + \tfrac{1}{3} E\left[T_{34}^3\right]\right), \tag{16}$$

$$E\left[T_{23}^3\right] = \frac{\sum_{j=i}^{N} \sum_{k=j+1}^{N} \lambda_{jk}}{1-\overline{\rho}_i} \times \left(\tfrac{3}{2} E\left[T_{34}^2\right] E\left[T_{23}^2\right] + E\left[T_{34}^3\right] E\left[T_{23}\right] + \tfrac{1}{2} E\left[T_{34}^4\right]\right) \tag{17}$$

with

$$\overline{\rho}_i = \sum_{j=i}^{N} \sum_{k=j+1}^{N} \lambda_{jk} E\left[T_{34}\right]. \tag{18}$$

The moments of the sum of these random variables are simply for T_{24},

$$E\left[T_{24}\right] = E\left[T_{23}\right] + E\left[T_{34}\right], \tag{19}$$

$$E\left[T_{24}^2\right] = E\left[T_{23}^2\right] + E\left[T_{34}^2\right] + 2E\left[T_{23}\right] E\left[T_{34}\right], \tag{20}$$

$$E\left[T_{24}^3\right] = E\left[T_{23}^3\right] + E\left[T_{34}^3\right] + 3E\left[T_{23}^2\right] E\left[T_{34}\right] + 3E\left[T_{23}\right] E\left[T_{34}^2\right]. \tag{21}$$

Again applying eq. (14) we obtain for T_{12},

$$E\left[T_{12}\right] = \frac{\sum_{k=i+1}^{N} \lambda_{ik}}{1-\rho_i} \tfrac{1}{2} E\left[T_{24}^2\right], \tag{22}$$

$$E\left[T_{12}^2\right] = \frac{\sum_{k=i+1}^{N} \lambda_{ik}}{1-\rho_i} \left(E\left[T_{24}^2\right] E\left[T_{12}\right] + \tfrac{1}{3} E\left[T_{24}^3\right]\right) \tag{23}$$

with

$$\rho_i = \sum_{k=i+1}^{N} \lambda_{ik} E\left[T_{24}\right]. \tag{24}$$

These results can be used to yield the mean and the second moment of the medium access delay T_{14}, like T_{24} above

$$E\left[T_{14}\right] = E\left[T_{12}\right] + E\left[T_{24}\right], \tag{25}$$

$$E\left[T_{14}^2\right] = E\left[T_{12}^2\right] + E\left[T_{24}^2\right] + 2E\left[T_{12}\right] E\left[T_{24}\right] \tag{26}$$

and the coefficient of variation

$$c_{14} = \frac{\sqrt{E\left[T_{14}^2\right] - E\left[T_{14}\right]^2}}{E\left[T_{14}\right]}. \tag{27}$$

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