

Dual Bus MAN's with Multiple-Priority Traffic

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Abstract—The IEEE 802.6 standard for metropolitan area networks does not provide multiple priority traffic for connectionless data services. A priority mechanism that was considered in earlier versions of the standard showed to be not effective. As of now, there exists no protocol for multiple access dual bus networks that is able to implement preemptive priorities and, at the same time, can satisfy minimal fairness requirements for transmissions at the highest priority level. In this study, a protocol with strictly preemptive priorities, i.e., a protocol that does not admit low-priority traffic if the load from high-priority traffic exceeds the capacity of the transmission channel, is presented. In addition, the protocol guarantees fairness for transmissions at the highest priority level. By introducing a general characterization of bandwidth allocation schemes for dual bus networks, existing priority mechanisms can be categorized according to the provided quality of service. The unique existence of a bandwidth allocation scheme for multiple priority traffic is shown with a full utilization of the channel capacity, with a fair distribution of bandwidth respective to traffic from a particular priority level and with preemptive priorities. The performance of the presented protocol is compared to existing proposals for multiple priority mechanisms. It is shown that adopting the new protocol results in shorter access delays for high-priority transmissions. The protocol allows the stations of the network to react quickly to load changes. It is shown that the effectiveness of the priority scheme, compared to priority schemes using the bandwidth-balancing mechanism, is less dependent on increasing the transmission speed of the network.

I. INTRODUCTION

IN July 1991, the Distributed Queue Dual Bus (DQDB) protocol was released as the IEEE 802.6 standard for metropolitan area networks [11]. The standard left the protocol without an effective mechanism to support multiple priority traffic. Even though IEEE 802.6 supports the assignment of priorities, all connectionless data traffic must be sent at the lowest priority level [11, p. 46]. However, it is widely acknowledged that the support of multiple priority levels is needed to provide a variable quality of service to the stations of the network. Support of high-priority traffic is especially needed for network control and management.

It is agreed upon that a satisfactory media access scheme for dual bus networks with multiple priority traffic should satisfy the following requirements [8]:

1. The bandwidth allocated to high-priority traffic is independent from low-priority traffic.
2. Within any priority level, the maximum bandwidth that can be allocated is equal for all stations.
3. Bandwidth is never wasted.

As of now, a priority mechanism is missing that satisfies all three requirements.

In this study, we present a protocol for dual bus networks with multiple levels of priorities that satisfies all of these requirements. We present a formal characterization for multiple priority access schemes in dual bus networks. This allows us to present a unified view on bandwidth allocation schemes for dual bus networks. We are able to show the deficiencies of existing priority mechanisms. We show the unique solution to a bandwidth allocation scheme with a preemptive priority mechanism that does not waste bandwidth and satisfies fairness conditions for transmissions within each priority level. We develop a new protocol that is based on this unique solution. The new protocol uses results from [1] where we presented a unipriority access protocol for dual bus networks that does not waste bandwidth and guarantees a fair distribution of bandwidth to the stations.

The paper is organized as follows. In Section II, we review the priority mechanism of the DQDB protocol. We discuss recent proposals that attempt to improve the priority mechanism of the DQDB protocol. In Section III, we categorize bandwidth allocation schemes for dual bus networks with multiple priorities, and derive a bandwidth allocation scheme that agrees with the above-mentioned requirements 1–3. In Section IV, we present a new protocol that implements the concept of a so-called *strongly fair* and *waste-free* bandwidth allocation with preemptive priorities. We compare the performance of our protocol with an implementation of a priority mechanism that satisfies requirements 2 and 3. We conclude our results in Section V.

II. MEDIA ACCESS PROTOCOLS FOR DQDB NETWORKS WITH MULTIPLE PRIORITIES

A *DQDB* network consists of two unidirectional buses with data flow in opposite directions. One bus is denoted by bus A and the other by bus B as shown in Fig. 1. A slot generator at the head of each bus emits empty fixed sized slots at a constant rate. Each station is connected to both buses. A station transmits data by filling in an empty slot on a particular bus. Note that, due to the topology of the dual bus, each station has to make a routing decision whether to use bus A or bus B for transmission dependent on the physical location of the destination station. Since the architecture of a dual bus network is symmetric, we will focus on data transfer on bus A.

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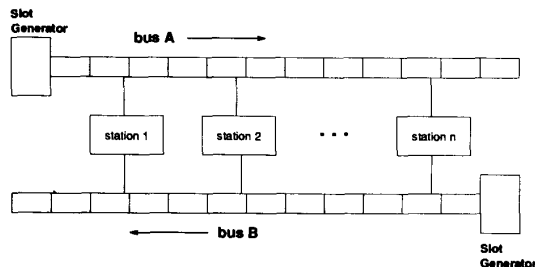


Fig. 1. DQDB network.

In Section II-A, we describe the media access protocol of the DQDB network with multiple priority levels that was used in early draft versions of the IEEE 802.6 standard [10]. In Section II-B, we discuss proposals from the literature that attempt to enhance the priority mechanism in DQDB networks.

A. Media Access in a DQDB Network with Multiple Levels of Priorities

The DQDB protocol prevents the stations close to the head of a bus from acquiring all empty slots by implementing a reservation scheme. A station having a segment ready for transmission on bus A notifies the stations closer to the head of bus A by sending a reservation request on bus B.

In a DQDB network with P priority levels, each slot contains $(P + 1)$ access fields: a busy bit and P request bits, one request bit for each priority level. A slot with the busy bit set indicates that the slot contains data. The request bit of priority p set indicates a reservation request at priority level p ($1 \leq p \leq P$). If a station writes data into an empty slot, it sets the busy bit. A reservation request of priority p is submitted by setting the priority- p request bit.

For each priority level, a station keeps a queue of untransmitted segments. Only the segment at the head of a queue is allowed to submit a reservation request at the particular priority level. Note that setting the request bit may be delayed since a station has to wait for a slot which has the request bit not set. At each priority level, a station determines its turn to transmit a segment of priority p with two counters: the request counter (RQ_p) and the countdown counter (CD_p) ($1 \leq p \leq P$).

If a station does not have segments of priority level p queued for transmission, it increments its RQ_p counter for each passing slot on bus B having the request bit set at equal or higher-priority levels ($q \geq p$). It decrements RQ_p for each empty slot the station detects on bus A. Upon arrival of a segment with priority p to the station, RQ_p is copied to CD_p and then set to zero. Then, RQ_p is incremented for slots on bus B having the priority- p request bit set. CD_p is decremented for each empty slot passing by the station on bus A and incremented by one for each slot on bus B having the request bit set at higher priority levels ($q > p$). When CD_p reaches zero, the segment of priority level p is allowed to take the next empty slot for transmission.

The so-called *bandwidth balancing mechanism* [7] was included into the standard to achieve a fair distribution of

bandwidth within a single priority class if the network is heavily loaded. The bandwidth balancing mechanism enforces at each priority level that a station uses only a fraction of the available bandwidth for transmissions. This is achieved by incrementing RQ_p each time after a fixed number of β^1 transmissions of priority- p segments.

B. Enhancements to the Priority Mechanism

The priority mechanism as described in the previous subsection (including bandwidth balancing) is not effective. It was shown that it merely guarantees that stations with high-priority traffic do not obtain more bandwidth than stations with low-priority traffic [5], [15], [16]. Without the bandwidth balancing mechanism, it is possible that stations with low-priority traffic obtain more bandwidth than stations with high-priority traffic [18].

Nonunity ratio bandwidth balancing [17] enforces that high-priority traffic is assigned more bandwidth than low-priority traffic by using different values of β for traffic from different priority levels. Higher values for β are used for high-priority traffic. Note that high-priority traffic is not independent from low-priority traffic, i.e., increasing the amount of low-priority traffic results in decreased traffic at higher priorities.

In *symmetric bandwidth balancing* [4], stations with low-priority traffic leave an additional empty slot that is otherwise used for transmission each time after receiving a fixed number of high-priority requests.

In [3], a priority mechanism with preemptive priorities is presented. Using additional bits in the slot header, stations notify each other about the highest priority level currently active on the network. A station refrains from transmitting if the highest active priority level is higher than the priority level of segments stored at the station. A fair distribution of bandwidth to stations transmitting at the highest priority level is not guaranteed.

In *bandwidth balancing with global priority information* [8], the slot header carries information on the priority level of transmitted data. The bandwidth balancing modulus (β) is set equal for all priority levels. Under heavy load, this priority mechanism distributes the bandwidth equally among transmissions at the same priority level. In addition, high-priority traffic is independent from traffic at lower priorities. However, the scheme never utilizes the entire bandwidth of the bus. Variations of this scheme can be found in [9], [12], [13]. We refer to [14] for a detailed discussion of the literature on DQDB.

As mentioned before, none of these schemes achieve at the same time the independence of high-priority traffic from low-priority traffic, and equal maximum bandwidth allocation for stations transmitting at a particular priority level and a full utilization of the bandwidth of the dual bus.

III. PROPERTIES OF BANDWIDTH ALLOCATIONS WITH MULTIPLE LEVELS OF PRIORITIES

In this section, we formally define properties of bandwidth allocation schemes for dual bus networks with multiple prior-

¹The default value is $\beta = 8$.

ities. Because of the symmetry of the dual bus topology, we only consider transmissions on one bus. Formally, a bandwidth allocation maps the traffic load from all stations into individual portions of the bandwidth that can be used for transmission.

Let $\mathcal{N} = \{1, 2, \dots, N\}$ be a set of stations and let $\mathcal{P} = \{1, 2, \dots, P\}$ be a set of priority levels. A high-priority index denotes a high-priority level. Let $\lambda_{ip} (\lambda_{ip} \geq 0)$ denote the load and $\gamma_{ip} (0 \leq \gamma_i \leq 1)$ denote the allocated bandwidth for station i ($1 \leq i \leq n$) at priority level p ($1 \leq p \leq P$). Let the $(N \times P)$ matrices Λ and Γ be given by:

$$\Lambda = \begin{pmatrix} \lambda_{11} & \lambda_{12} & \cdots & \lambda_{1P} \\ \lambda_{21} & \lambda_{22} & \cdots & \lambda_{2P} \\ \vdots & \vdots & \ddots & \vdots \\ \lambda_{N1} & \lambda_{N2} & \cdots & \lambda_{NP} \end{pmatrix}$$

$$\Gamma = \begin{pmatrix} \gamma_{11} & \gamma_{12} & \cdots & \gamma_{1P} \\ \gamma_{21} & \gamma_{22} & \cdots & \gamma_{2P} \\ \vdots & \vdots & \ddots & \vdots \\ \gamma_{N1} & \gamma_{N2} & \cdots & \gamma_{NP} \end{pmatrix}.$$

We define $\|\Gamma\|$ and $\|\Lambda\|$ as:

$$\|\Lambda\| = \sum_{i=1}^N \sum_{p=1}^P \lambda_{ip} \quad \text{and} \quad \|\Gamma\| = \sum_{i=1}^N \sum_{p=1}^P \gamma_{ip}.$$

Further, we define $\Lambda_p, \|\Lambda_p\|, \Gamma_p$ and $\|\Gamma_p\| (1 \leq p \leq P)$ as:

$$\Lambda_p = \begin{pmatrix} \lambda_{1p} \\ \lambda_{2p} \\ \vdots \\ \lambda_{Np} \end{pmatrix} \quad \text{and} \quad \|\Lambda_p\| = \sum_{i=1}^N \lambda_{ip}$$

$$\Gamma_p = \begin{pmatrix} \gamma_{1p} \\ \gamma_{2p} \\ \vdots \\ \gamma_{Np} \end{pmatrix} \quad \text{and} \quad \|\Gamma_p\| = \sum_{i=1}^N \gamma_{ip}.$$

Definition 1: A bandwidth allocation for multiple priority levels is defined as a relation $\Omega \subseteq (\Lambda \times \Gamma)$ such that for all i and p ($1 \leq i \leq N, 1 \leq p \leq P$) $\gamma_{ip} \leq \lambda_{ip}$ and $0 \leq \|\Gamma\| \leq 1$.

Although relation Ω does not necessarily determine Γ uniquely for given Λ , we will use the notation $\Gamma = \Omega(\Lambda)$. We denote the element in row i and column p of $\Omega(\Lambda)$ by $\Omega_{ip}(\Lambda)$. We denote the p th column of $\Omega(\Lambda)$ by $\Omega_p(\Lambda)$. We use $\|\Omega(\Lambda)\|$ and $\|\Omega_p(\Lambda)\|$ to denote the sum of all elements in matrix $\Omega(\Lambda)$ and vector $\Omega_p(\Lambda)$, respectively.

We define the following fairness criteria for traffic of a particular priority level.

Definition 2: Ω is fair if, for all Λ ,

$$1) \quad (\forall p)(1 \leq p \leq P)(\forall i, j)(1 \leq i, j \leq N) : \\ (\lambda_{ip} < \lambda_{jp} \rightarrow \Omega_{ip}(\Lambda) \leq \Omega_{jp}(\Lambda)), \text{ and}$$

$$2) \quad (\forall i, j)(1 \leq i, j \leq N) : (\lambda_{ip} = \lambda_{jp} \rightarrow \Omega_{ip}(\Lambda) = \Omega_{jp}(\Lambda)).$$

The fairness conditions guarantee that, within each priority level, a station does not obtain more bandwidth than a station with a higher arrival rate, and stations with the same arrival rate obtain the same bandwidth.

Definition 3: Ω is strongly fair if, for all Λ ,

$$(\forall p)(1 \leq p \leq P)(\exists \alpha_p^* > 0)(\forall i)(1 \leq i \leq N) : ((\lambda_{ip} \leq \alpha_p^* \\ \rightarrow \Omega_{ip}(\Lambda) = \lambda_{ip}) \wedge (\lambda_{ip} > \alpha_p^* \rightarrow \Omega_{ip}(\Lambda) = \alpha_p^*)).$$

Strong fairness guarantees for priority level p that stations with a load less than a threshold value α_p^* obtain all the bandwidth they need. All stations with a load exceeding the threshold value obtain the same bandwidth. Note that the condition for strong fairness implies fairness.

Next, we formally describe bandwidth allocations that are able to utilize the entire bandwidth of the communication channel.

Definition 4: Ω is waste free if, for all Λ ,

i) If

$$\|\Lambda\| < 1, \text{ then } \|\Omega(\Lambda)\| = \|\Lambda\|, \text{ and}$$

ii) If

$$\|\Lambda\| \geq 1, \text{ then } \|\Omega(\Lambda)\| = 1.$$

If the traffic load from all stations is less than the capacity of the bus, a waste-free bandwidth allocation guarantees that all stations can transmit their load. If the traffic load exceeds the capacity, the entire bandwidth can be used for transmission, i.e., no bandwidth is wasted.

The quality of service of the priority mechanism of a bandwidth allocation is categorized as follows.

Definition 5: Ω implement pseudopriorities if, for all Λ ,

$$(\forall p, q)(1 \leq p < q \leq P) : (\|\Lambda_q\| > \|\Lambda_p\| \rightarrow \|\Omega_q(\Lambda)\| \\ \geq \|\Omega_p(\Lambda)\|).$$

Pseudopriorities just guarantee that a station with high priority does not obtain less bandwidth than a station with low-priority traffic.

Definition 6: Ω implements weak priorities if, for all Λ ,

$$(\forall p, q)(1 \leq p < q \leq P) : \\ (\|\Lambda_q\| > \|\Lambda_p\| \rightarrow \|\Omega_q(\Lambda)\| > \|\Omega_p(\Lambda)\|)$$

and

$$(\forall p)(1 < p \leq P)(\exists \epsilon)(\epsilon > 0) :$$

$$(\|\Omega_p(\Lambda)\| < \\ \left\| \Omega_p \begin{pmatrix} \lambda_{11} + \epsilon & \cdots & \lambda_{1p-1} + \epsilon & \lambda_{1p} & \cdots & \lambda_{1P} \\ \lambda_{21} + \epsilon & \cdots & \lambda_{2p-1} + \epsilon & \lambda_{2p} & \cdots & \lambda_{2P} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \lambda_{N1} + \epsilon & \cdots & \lambda_{Np-1} + \epsilon & \lambda_{Np} & \cdots & \lambda_{NP} \end{pmatrix} \right\|).$$

Weak priorities guarantee that high-priority traffic is allocated more bandwidth than low-priority traffic. However, if the traffic load from low-priority levels is increased by a constant ϵ the allocated bandwidth to the high-priority stations is decreased. Therefore, weak priorities allow that stations with low-priority traffic obtain a portion of the bandwidth even though the arrival rate of high-priority traffic exceeds the total capacity of the bus.

Definition 7: Ω implements *strong priorities* if, for all Λ ,

$$(\forall p, q)(1 \leq p < q \leq P) : \\ (||\Lambda_q|| > ||\Lambda_p|| \rightarrow ||\Omega_q(\Lambda)|| > ||\Omega_p(\Lambda)||)$$

and

$$(\forall p)(1 < p \leq P)(\forall \epsilon)(\epsilon > 0) : \\ (\Omega_p(\Lambda) = \\ \Omega_p \left(\begin{array}{cccccc} \lambda_{11} + \epsilon & \cdots & \lambda_{1p-1} + \epsilon & \lambda_{1p} & \cdots & \lambda_{1P} \\ \lambda_{21} + \epsilon & \cdots & \lambda_{2p-1} + \epsilon & \lambda_{2p} & \cdots & \lambda_{2P} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \lambda_{N1} + \epsilon & \cdots & \lambda_{Np-1} + \epsilon & \lambda_{Np} & \cdots & \lambda_{NP} \end{array} \right)).$$

Strong priorities assign more bandwidth to high-priority traffic than to low-priority traffic. In addition, the bandwidth allocated to high-priority traffic is independent from the load of low-priority traffic.

Definition 8: Ω implements *preemptive priorities* if, for all Λ ,

$$(\forall p)(1 \leq p \leq P) : \left(\sum_{q>p} ||\Lambda_q|| > 1 \rightarrow ||\Omega_p(\Lambda)|| = 0 \right).$$

An allocation with preemptive priorities does not admit low-priority traffic if the traffic demand from higher priorities exceeds the total bandwidth. Note that strong priorities imply weak priorities, and weak priorities imply pseudopriorities. In addition, we can follow from Definitions 4 and 7 that a waste-free bandwidth allocation Ω with strong priorities implements preemptive priorities, and preemptive priorities require a waste-free allocation with strong priorities. In [1], we showed the following properties for dual bus networks with a single level of priorities:

Lemma 1: Unipriority DQDB without bandwidth balancing [10] is waste free, but not fair.

Lemma 2: Unipriority DQDB with bandwidth balancing [11] is strongly fair, but not waste free.

With Definitions 5–8, we can show the following properties of priority mechanisms for dual bus networks:

Lemma 3:

1. The priority mechanism of IEEE 802.6/D12 [10] implements pseudopriorities.
2. The priority mechanism of nonunity ratio bandwidth balancing [17] allows to implement weak but not strong priorities.
3. The priority mechanism of DQDB with bandwidth balancing and global priority information [8] has strong priorities, but not preemptive since the bandwidth allocation is not waste free.

Proof:

1. Since the bandwidth balancing mechanism ensures strong fairness [1], it clearly guarantees pseudopriorities. To show that the conditions for weak priorities are not satisfied, assume a network where each station transmits at one priority level and each station is heavily loaded. Then, the allocated bandwidth to a station i transmitting

with priority p is given by [8]:

$$\Omega_{ip}(\Lambda) = \frac{\beta}{1 + \sum_{r=1}^P \beta \cdot K_r} \quad (1)$$

where K_r denotes the number of stations transmitting at priority level r . Since $\Omega_{ip}(\Lambda) = \Omega_{jq}(\Lambda)$ (for $1 \leq i, j \leq N, 1 \leq p, q \leq P$) regardless of the load at different priority levels, the condition for weak priorities is clearly violated.

2. We consider the heavy load scenario as given above. In nonunity ratio bandwidth balancing, we have different values for the modulus at each priority level, with $\beta_q > \beta_p$ if $q > p$. The bandwidth allocated to a station is calculated by [17]:

$$\Omega_{ip}(\Lambda) = \frac{\beta_p}{1 + \sum_{r=1}^P \beta_r \cdot K_r} \quad (2)$$

Then, $\Omega_{iq}(\Lambda) > \Omega_{jp}(\Lambda)$ if $q > p$. However, strong priorities are not satisfied since the bandwidth allocation to stations with high priorities is dependent on low-priority traffic.

3. Again, we consider the heavy load scenario. The allocated bandwidth to station i with priority- p traffic is given by [8]:

$$\Omega_{ip}(\Lambda) = \frac{\beta}{\prod_{r=p}^P (1 + \beta \cdot K_r)} \quad (3)$$

Weak priorities are satisfied since $\prod_{r=q}^P (1 + \beta \cdot K_r) < \prod_{r=p}^P (1 + \beta \cdot K_r)$ for $q > p$. The conditions for strong priorities are satisfied since the allocated bandwidth Ω_{iq} is independent from priority- p traffic with $p < q$ (3). To show that the allocation is not waste free, we simply verify that:

$$\sum_{p=1}^P \sum_{i=1}^{K_p} \frac{\beta}{\prod_{r=p}^P (1 + \beta \cdot K_r)} < 1. \quad (4)$$

An ideal bandwidth allocation with multiple priority traffic combines strong fairness, waste freedom, and strong priorities. The following theorem states that such an allocation can be found.

Theorem 1: There exists exactly one bandwidth allocation Ω^* that is strongly fair, waste free, and has strong priorities for all Λ . Ω^* is determined by the unique solution to the following system of equations:

$$\Omega_{ip}^*(\Lambda) = \begin{cases} 0 & \text{if } (\exists q)(q > p) : (|\mathbf{O}_q| > 0) \\ \min \left\{ \lambda_{ip}, \frac{q \geq p, j \in \mathbf{U}_q}{|\mathbf{O}_p|} \right\} & \text{otherwise} \end{cases} \quad (5)$$

where

$$U_p = \{j | \lambda_{jp} = \Omega_{ip}^*(\Lambda)\} \quad (6)$$

$$O_p = \{j | \lambda_{jp} > \Omega_{ip}^*(\Lambda)\} \quad (7)$$

$(1 \leq i \leq N, 1 \leq p \leq P).$

U_p denotes the set of *underloaded stations* with priority- p traffic, i.e., stations which can satisfy their bandwidth demand of priority- p traffic. O_p denotes the set of *overloaded stations* with priority- p traffic, i.e., stations with a load at priority level p exceeding the allocated bandwidth. We use $|O_p|$ to denote the cardinality of set O_p . Note that no bandwidth is allocated to a station if the set of overloaded stations at higher priority levels is nonempty.

Proof: The proof is given in Appendix A.

In the remaining part of this section, we show that the strongly fair and waste-free bandwidth allocation with strong priorities can be obtained in a distributed way. Recall that a waste-free bandwidth allocation with strong priorities is preemptive.

Definition 9: For each (i, p) ($1 \leq i \leq N, 1 \leq p \leq P$), define $O_p^{(>i)}$ by

$$O_p^{(>i)} = \{j | j \in O_p \wedge i < j \leq N\}. \quad (8)$$

$O_p^{(>i)}$ denotes the set of stations in the overload set of priority level p with a higher index than i .

Theorem 2: Given a strongly fair and waste-free bandwidth allocation Ω^* with strong priorities. Then, $i \in O_p$ if and only if

$$\lambda_{ip} > \delta_{ip} \quad (9)$$

with

$$\delta_{ip} = \begin{cases} 0 & \text{if } (\exists q)(q > p) : (|O_q^{(>i)}| > 0) \\ 1 - \frac{\sum_{q \geq p, j < i} \Omega_{jq}^*(\Lambda) - \sum_{q > p} \Omega_{iq}^*(\Lambda) - \sum_{q \geq p, j > i, j \in U_q} \lambda_{jq}}{|O_p^{(>i)}| + 1} & \\ \text{otherwise} & \end{cases} \quad (10)$$

Proof: The proof is given in Appendix B.

From the proof of Theorem 2, we additionally obtain:

Corollary 1: Given a strongly fair and waste-free bandwidth allocation with strong priorities. For all $i \in O_p$,

$$\Omega_{ip}^*(\Lambda) = \frac{1 - \sum_{q \geq p, j > i, j \in U_q} \lambda_{jq} - \sum_{q > p} \Omega_{iq}^*(\Lambda) - \sum_{q \geq p, j < i} \Omega_{jq}^*(\Lambda)}{|O_p^{(>i)}| + 1}. \quad (11)$$

Corollary 2: The strongly fair and waste-free bandwidth allocation with strong priorities can be implemented if each station i with $\lambda_{ip} > 0$ knows the following set of parameters:

$$\left(|O_p^{(>i)}|, \sum_{j > i, q \geq p, j \in U_q} \lambda_{jq}, \sum_{q > p} \Omega_{iq}^*(\Lambda), \sum_{j < i, q \geq p} \Omega_{jq}^*(\Lambda) \right).$$

In the following section, we present a media access protocol for dual bus networks with multiple priority levels that uses the results from Theorem 2 and Corollaries 1 and 2.

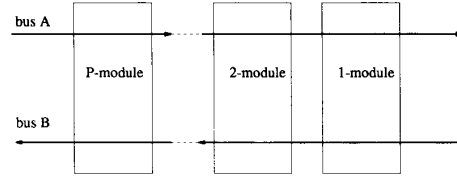


Fig. 2. Priority modules of a station.

IV. A STRONGLY FAIR AND WASTE-FREE MULTIPLE ACCESS PROTOCOL WITH PREEMPTIVE PRIORITIES

We only consider data transmission on bus A. We will use the station index to denote the relative physical distance to the slot generation of bus A. So, station 1 will denote the station closest to the slot generator of bus A, station 2 the second closest station, etc. The stations with a greater index than station i are referred to as the downstream stations of station i , while stations with a smaller index are referred to as the upstream stations.

A. Design Concepts

Transmission of traffic from a station is handled independently for each priority level. Each station consists of so-called *modules* that control the transmission of traffic from a particular priority level. The modules of a station are organized such that modules for high-priority traffic are upstream from the modules for low priorities (Fig. 2). We denote the module that controls traffic of priority level p as the p module. Each module is considered as either *underloaded* or *overloaded*. An underloaded p module can satisfy its bandwidth requirements at priority p , and an overloaded p module is characterized by an offered load that exceeds the allocated bandwidth. Both underloaded and overloaded modules use bus B to send reservation requests to upstream stations. Underloaded p modules send a priority p reservation request for each segment. If an underloaded p module becomes overloaded, it stops sending reservation requests and sends a signal on bus B to notify the upstream stations that it is overloaded. Once the signal is sent, no more reservation requests are submitted. If an overloaded p module becomes underloaded, it sends a signal on bus B to indicate to upstream stations that it became underloaded. Then, the p module resumes sending priority p reservation requests, one for each segment of priority p .

Before a p module is allowed to transmit a segment of priority p , it has to consider all reservations from downstream modules with equal or higher priority. For each reservation request of priority $\geq p$ and for each overloaded module of priority p downstream, the station has to leave an empty slot on bus A. If a station receives an overload signal of priority $> p$, it ceases transmission until the opposite signal is received.

From Theorem 2, we know the necessary and sufficient overload conditions for the p module of station i . Since we use the station index to denote the relative position of a station and since the modules of a station are ordered as given in Fig. 2, the values in (10) can be calculated by (see the top of the next page):

$$\lambda_i: \quad \text{load of priority } p \text{ traffic to } p \text{ module} \\ \text{of station } i,$$

$$\sum_{q \geq p, j < i} \Omega_{jq}^*(\Lambda) + \\ \sum_{q > p} \Omega_{iq}^*(\Lambda): \quad \text{rate of busy slots on bus A from priorities } \geq p \\ \text{seen by } p \text{ module of station } i$$

$$\sum_{q \geq p, j > i, j \in U_q} \lambda_{jq}: \quad \text{rate of reservations requests on bus B of priorities} \\ \geq p, \text{ received by } p \text{ module of station } i$$

$$|O_p^{(>i)}|: \quad \text{number of overloaded } p \text{ modules downstream on bus A.}$$

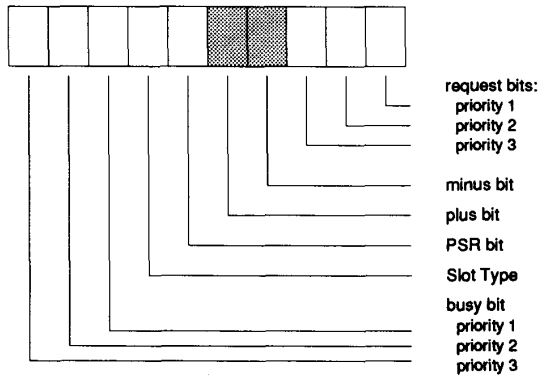


Fig. 3. Access control field.

B. Implementation

Each slot carries the following bits in the slot header: one request bit and one busy bit for each priority level, a *plus bit*, and a *minus bit*. For three priorities ($P = 3$), the access control (ACF) field of the slot header has a structure as shown in Fig. 3². The p th busy bit is set by a module of priority level p when inserting a segment of priority p into a slot.

Each underloaded p module sends one reservation request for the segment on top of the queue of untransmitted priority p segments. This is done by setting the request bit of priority p in a slot on bus B. If an underloaded module becomes overloaded, it sets a plus bit and a priority p request bit in a slot on bus B. After setting the plus bit, no more reservation requests are transmitted. If an overloaded p module becomes underloaded, it sets a minus bit and a request bit of priority p in a slot of bus B, and resumes setting priority p request bits (one for each segment). Note that neither plus nor minus bits can be set in slots that have the request bit set at any priority level. Note, however, that request bits in a slot can be set at all priority levels.

²The slot-type bit and the PSR bit are described in the IEEE 802.6 standard [11]. Note that the ACF control field in [11] needs to be extended to accommodate busy bits for different priority levels.

A p module determines its turn to transmit a (priority p) segment with five counters, the request counter (RQ), the countdown counter (CD), the overload request counter (ORQ), the overload countdown counter (OCD), and the stop-transmission counter ($STOP$). An idle p module, i.e., a p module that does not have a priority p segment queued for transmission, increments RQ for each passing slot on bus B with the request bit set at priority level p or higher. ORQ is incremented when a slot on bus B passes by with both the plus bit and the priority p request bit set. ORQ is decremented by 1 for each slot with both the minus bit and the priority p request bit set. Note that ORQ exactly represents $|O_p^{(>i)}|$ in Theorem 2, i.e., the contents of ORQ contains the number of overloaded p modules downstream on bus A. $STOP$ is incremented by 1 if a slot passes by with both the plus bit set and a request bit at a priority $> p$ set, and $STOP$ is decremented by one for each slot with both the minus bit and the request bit at a priority $> p$ set. Thus, $STOP$ contains the number of overloaded q modules downstream with $q > p$. We enforce Theorem 2 by preventing a p module from transmitting if $STOP > 0$.

At an idle p module, RQ is decremented for each empty slot and for each busy slot with the busy bit set at priority $< p$ that passes by on bus A (RQ is not decremented if $RQ = 0$).

When a priority p segment arrives at an idle module, the contents of RQ and ORQ are copied to CD and OCD , respectively, and RQ is set to zero. The value of ORQ remains unchanged. Now, RQ is incremented for each slot with set request bit at priority p on bus B. CD is incremented for each slot on bus B with the request bit set at priority $> p$. ORQ is incremented for each slot on bus B with the plus bit and the priority p request bit set, and ORQ is decremented for each slot on bus B with both the minus bit set and the priority p request bit set. For each empty slot and for each busy slot of priority $< p$ on bus A, CD is decremented by 1. If CD is zero, the module decrements OCD by 1. If an empty slot arrives at the p module and CD , OCD and $STOP$ are zero, then the empty slot is used for transmission of the segment. If the p module has more segments waiting for transmission, RQ and ORQ are copied to CD and OCD , respectively, and RQ is set to zero.

TABLE I
SIMULATION PARAMETERS

Station	Start of Transmission	Priority Level
Station 1	$t = 1,000$	1
Station 2	$t = 4,000$	2
Station 3	$t = 9,000$	2
Station 4	$t = 17,000$	3

With Theorem 2, each p module can determine by itself whether it is overloaded or underloaded. The rates needed to calculate (9) are obtained from the values of counters. Most of the required information is already stored in counters RQ , CD , ORQ , and $STOP$. Three additional counters are needed. $NoSeg$ contains the total number of segments (of priority p) queued for transmission at the p module, $SlotCtr$ is incremented for each arriving slot on bus B, and Bsy is incremented for each busy slot read on bus A with priority p or higher. A p module determines its state each time $Basis^3$ slots have passed by on bus B ($SlotCtr = Basis$). Then, it calculates:

$$Quota = \begin{cases} 0 & \text{if } STOP > 0 \\ \frac{Basis - Bsy - RQ - CD}{ORQ + 1} & \text{otherwise} \end{cases} \quad (12)$$

and sets counters $SlotCtr$ and Bsy to zero. $Quota$ provides the maximum number of slots a module is allowed to transmit during a period of $Basis$ slots. If $NoSeg > Quota$, the p module is overloaded; otherwise, the p module is underloaded.

C. Evaluation

In order to show that our protocol achieves the objectives of strong fairness, waste freedom, and preemptive priorities, we execute simulation runs of file transfer scenarios⁴. We compare our protocol with the priority scheme presented in [8], which to our knowledge is the only (verified) bandwidth allocation scheme that satisfies the conditions for both strong priorities and strong fairness.

We study a dual bus network with four stations that start file transfers on bus A at different times. Each station transmits at a particular priority level. Starting time and priority level of the file transfers for all stations are shown in Table I⁵. We assume that station 4 transmits a file with a length of 5,000 segments; the files transmitted by other stations are assumed to be significantly larger. We set the distance between adjacent stations to $\Delta = 25$ slots⁶. The total round-trip delay of the bus is, therefore, given by 150 slots. Once every round-trip delay, we measure the number of segments that each station was able to transmit. The total observation period is set to 35,000 slots.

Fig. 4 shows the results of the simulation for the new protocol with $Basis = 150$. Each point in Fig. 4 gives the percentage of the bandwidth on bus A that is used by a

³We set $Basis$ to the round-trip slot delay of the bus, i.e., the sum of the slot lengths of bus A and bus B [1].

⁴The simulations were implemented using the simulator for dual bus network protocols presented in [2].

⁵The time unit is one slot. The simulation starts at $t = 0$.

⁶At a transmission rate of 155 Mb/s, one slot corresponds to a distance of about 500 m and to a transmission delay of about 2.8 μ s.

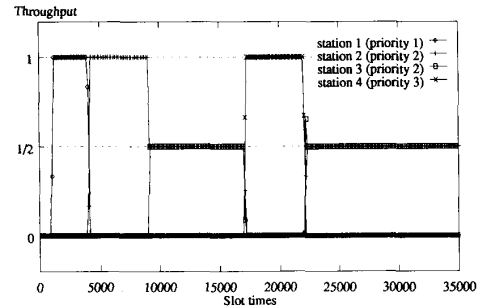


Fig. 4. File transfer with new priority scheme ($Basis=150$).

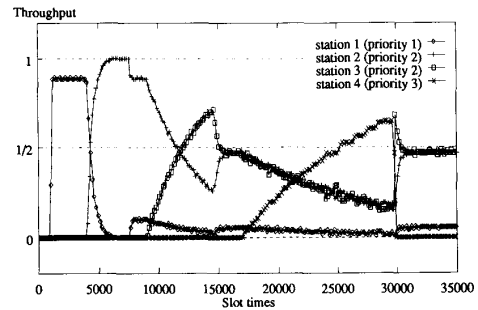
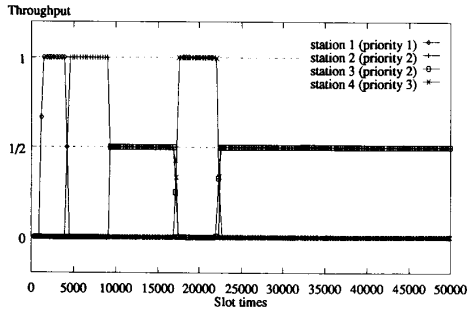
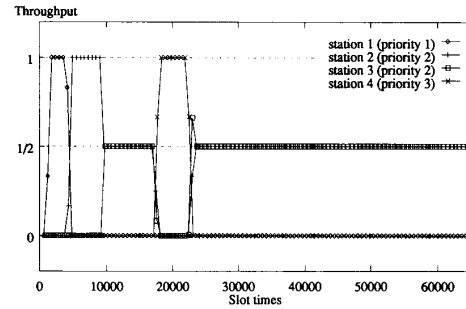
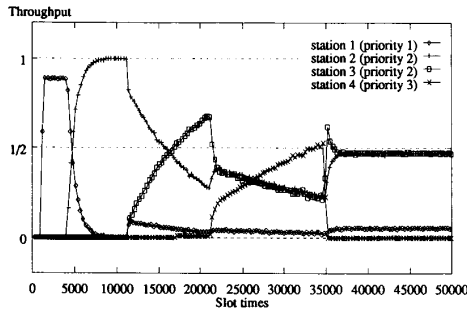
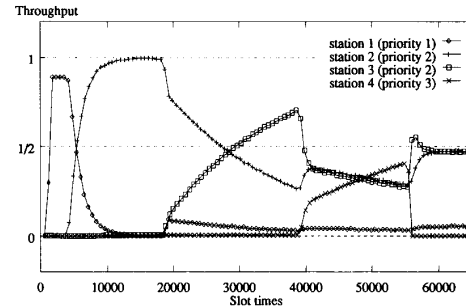


Fig. 5. File transfer with priority scheme in [7] ($\beta=8$) (round-trip delay=150 slots).

station for transmission, i.e., the throughput of the station, in an interval of one round-trip delay. When station 1 starts transmission (at priority level 1), it seizes the entire bandwidth. As soon as station 2 with priority 2 traffic becomes active, it immediately preempts transmissions from station 1. When station 3 begins transmitting with priority 2, it shares the bandwidth with station 2 such that both stations 2 and 3 obtain half of the total bandwidth. At $t = 17,000$, station 4 with traffic at priority level 3 preempts any traffic with a lower priority. When all 5,000 segments of station 4 are transmitted, stations 2 and 3 again share the available bandwidth. Note how quickly the new protocol can adapt to changes in the network load.

For comparison, in Fig. 5 we present a simulation of the same scenario with the priority scheme given in [8]. As mentioned in Section II-B, the scheme given in [8] is based on the bandwidth balancing mechanism. We use the default value for the bandwidth balancing modulus ($\beta = 8$). Fig. 5 shows that each time the load of the network changes, it takes considerable time to adjust to the new network load. Because of the long convergence time, station 4 is not able to preempt the traffic from lower-priority stations. This results in significantly higher transmission times for high-priority traffic compared to the new protocol.

The advantages of the new protocol become even more apparent when the slot distance between stations is increased. Increasing the slot distance corresponds to increasing the physical distance between stations or, equivalently, increasing the transmission speed of the network. We present the same simulation scenario in Table I for a dual bus network with a slot distance of $\Delta = 50$ and $\Delta = 100$ slots between

Fig. 6. File transfer with new priority scheme ($Basis=300$).Fig. 8. File transfer with new priority scheme ($Basis=600$).Fig. 7. File transfer with priority scheme in [7] ($\beta=8$) (round-trip delay=300 slots).Fig. 9. File transfer with priority scheme in [7] ($\beta=8$) (round-trip delay=600).

two adjacent stations. Again, we measure the throughput once every round-trip delay. For $\Delta = 50$ slots, we present simulation results for a total observation period of 50,000 slots. The results are shown in Fig. 6 for the new priority scheme (with $Basis = 300$) and in Fig. 7 for the priority scheme from [8]. The new priority scheme is insensitive to doubling the slot distance between the stations, i.e., doubling the transmission rate of the bus. However, using the priority scheme from [8], the convergence time after load changes increases significantly compared to the previous simulation.

For $\Delta = 100$, we choose an observation period of 65,000 slots. Again, the priority scheme of our protocol shows to be effective as shown in Fig. 8. In Fig. 9, we show that the bandwidth balanced priority scheme [8] is almost ineffective. Although station 4 (with priority 3) becomes active at $t = 17,000$, it achieves a nonzero throughput for the first time at about $t = 40,000$.

In Table II, we present the exact transmission time of the priority 3 file transmitted from station 4 for all simulation runs. The transmission time is the interval slot times (see footnote 5) from the time station 4 becomes active (at $t = 17,000$) until the last of its 5,000 segments is transmitted. The table clearly shows the superiority of our new protocol.

V. CONCLUSIONS

We provided a unified view on priority mechanisms for dual bus networks by formalizing properties of bandwidth allocation schemes. We showed deficiencies of existing protocols that support multiple priority traffic. We presented a new priority mechanism that does not waste bandwidth, provides a

	$\Delta = 25$	$\Delta = 50$	$\Delta = 100$
New Protocol	5,076	5,152	5,302
Protocol in [8] with $\beta = 8$	12,732	17,785	38,440

fair distribution of bandwidth within each priority level, and provides preemptive priorities. We proved the uniqueness of the priority mechanism. We introduced a media access protocol that is able to provide the unique priority mechanism. We showed that the new protocol achieves the implementation of preemptive priorities. The performance of the protocol was compared to an implementation of a priority mechanism that provides strong priorities and strong fairness (according to our terminology used in Section III). Our protocol adapts quicker to changes in the network load. We achieve a significantly lower transmission delay for high-priority traffic compared to other priority schemes.

APPENDIX A PROOF OF THEOREM 1

We first prove the existence and uniqueness of a solution for Ω^* . Then, we show that Ω^* is strongly fair, waste-free, and implements strong priorities.

1) *Existence of Solution for Ω^** : Since Ω^* is determined by a solution to the equation system consisting of equations

(5)–(7), we construct such a solution. Denote \hat{p} by:

$$\hat{p} = \begin{cases} 0 & \text{if } \|\Lambda\| < 1 \\ \max_p \left\{ \sum_{q=p}^P \|\Lambda_q\| > 1 \right\} & \text{otherwise.} \end{cases} \quad (13)$$

Without the loss of generality, we reorder the station indexes within priority level \hat{p} such that $\lambda_{i\hat{p}} \leq \lambda_{j\hat{p}}$ if $i < j$. Note that, in this case, $i \in \mathcal{U}_{\hat{p}}$ implies $j \in \mathcal{U}_{\hat{p}}$, if $j < i$. A solution to Ω^* is then given by:

a) $p < \hat{p}$:

$$\mathcal{U}_p = \{j | \lambda_{jp} = 0\} \quad (14)$$

$$\mathcal{O}_p = \{j | \lambda_{jp} > 0\}. \quad (15)$$

Note that this implies that $\Omega_{ip}^*(\Lambda) = 0$ for all $p < \hat{p}$ and all i ($1 \leq i \leq N$).

b) $p = \hat{p}$:

$$\mathcal{U}_p = \left\{ j | \lambda_{jp} \leq \frac{1 - \sum_{i=1}^j \lambda_{ip} - \sum_{k=1}^N \sum_{q=p+1}^P \lambda_{kq}}{N - j} \right\} \quad (16)$$

$$\mathcal{O}_p = \mathcal{N} \setminus \mathcal{U}_p \quad (17)$$

c) $p > \hat{p}$:

$$\mathcal{U}_p = \mathcal{N} \quad (18)$$

$$\mathcal{O}_p = \emptyset. \quad (19)$$

2) *Uniqueness of Solution for Ω^** : We assume the existence of a solution to (5)–(7) that is different from the solution given by (13)–(19). Assume that the solution satisfies:

$$(\exists p')(p' < \hat{p})(\exists i)(1 \leq i \leq N)(\lambda_{ip'} > 0 \Omega_{ip'}^*(\Lambda) > 0). \quad (20)$$

Since $\sum_{q=\hat{p}}^P \|\Lambda_q\| > 1$ [(13) and (19)], there exists a pair (j, q) ($1 \leq j \leq N, \hat{p} < q \leq P$) such that $\lambda_{jq} > \Omega_{jq}(\Lambda)$. Because of (7), we obtain $|\mathcal{O}_q| > 0$, and from (5) $\Omega_{ip'}(\Lambda) = 0$. But this contradicts the assumption.

Assume that there exists a solution to (5)–(7) which satisfies:

$$(\exists p)(p > \hat{p})(|\mathcal{O}_p| > 0). \quad (21)$$

Let p be the highest priority level p with $p > \hat{p}$. For each $j \in \mathcal{O}_{p''}$, we have (5):

$$\lambda_{jp''} > \frac{1 - \sum_{q \geq p'', j \in \mathcal{U}_q} \lambda_{jq}}{|\mathcal{O}_{p''}|}. \quad (22)$$

Summing over all $j \in \mathcal{O}_{p''}$, we obtain:

$$\sum_{j \in \mathcal{O}_{p''}} \lambda_{jp''} > 1 - \sum_{q \geq p'', j \in \mathcal{U}_q} \lambda_{jq} \quad (23)$$

$$= 1 - \sum_{j \in \mathcal{U}_{p''}} \lambda_{jp''} - \sum_{j=1}^N \sum_{q=p''+1}^P \lambda_{jq} \quad (24)$$

This is equivalent to:

$$\sum_{p \geq p''} \|\Lambda_p\| > 1. \quad (25)$$

But this contradicts (13).

Therefore, any solution to the equation system of (5)–(7) must have \mathcal{U}_p and \mathcal{O}_p as given in (14) and (15) if $p < \hat{p}$, and as given in (18) and (19) if $p > \hat{p}$, respectively. Now, we investigate the case $p = \hat{p}$. We show that any $\mathcal{U}_{\hat{p}}$ and $\mathcal{O}_{\hat{p}}$ that are part of a solution to (5)–(7) are equivalent to $\mathcal{U}_{\hat{p}}$ and $\mathcal{O}_{\hat{p}}$ as given in (16) and (17).

Let \bar{k} be the highest index in $\mathcal{U}_{\hat{p}}$ of (16). Assume a solution to (5)–(7). Denote the underload and overload sets for priority p of these solutions by $\bar{\mathcal{U}}_p$ and $\bar{\mathcal{O}}_p$, respectively. Let k be the highest index in $\bar{\mathcal{U}}_{\hat{p}}$. Per definition of $\mathcal{U}_{\hat{p}}$ (16), it holds that $k \leq \bar{k}$. On the other hand, since $(k+1) \in \bar{\mathcal{O}}_{\hat{p}}$:

$$\lambda_{k+1, \hat{p}} > \Omega_{k+1, \hat{p}}^*(\Lambda) \quad (26)$$

$$1 - \sum_{q \geq \hat{p}, j \in \mathcal{U}_q} \lambda_{jq} = \frac{1 - \sum_{q \geq \hat{p}, j \in \mathcal{U}_q} \lambda_{jq}}{|\bar{\mathcal{O}}_{\hat{p}}|} \quad (27)$$

$$= \frac{1 - \sum_{j=1}^k \lambda_{j\hat{p}} - \sum_{q > \hat{p}, j \in \mathcal{U}_q} \lambda_{jq}}{N - k} \quad (28)$$

$$= \frac{1 - \sum_{j=1}^k \lambda_{j\hat{p}} - \sum_{q > \hat{p}, j \in \mathcal{U}_q} \lambda_{jq}}{N - k} \quad (29)$$

This is equivalent to:

$$\lambda_{k+1, \hat{p}} > \frac{1 - \sum_{j=1}^{k+1} \lambda_{j\hat{p}} - \sum_{q > \hat{p}, j \in \mathcal{U}_q} \lambda_{jq}}{N - k - 1}. \quad (30)$$

From (16), we obtain $k+1 > \bar{k}$ and, as a consequence, $k = \bar{k}$. Therefore, any solution to (5)–(7) is given by (13)–(19).

3) *Ω^* is strongly fair*: If $|\mathcal{O}_p| > 0$ for some p , then the condition for strong fairness is satisfied with $\alpha_q^* = 0$ for all $q < p$. On the other hand, if $|\mathcal{O}_p| = 0$ for all $p > q$, α_q^* is given by:

$$\alpha_q^* = \frac{1 - \sum_{q \geq p, j \in \mathcal{U}_q} \lambda_{jq}}{|\mathcal{O}_q|} \quad (31)$$

4) *Ω^* is waste free*: If $\|\Lambda\| < 1$, then \mathcal{U}_p and \mathcal{O}_p (for all $1 \leq p \leq P$) are given by:

$$\mathcal{U}_p = \mathcal{N} \quad (32)$$

$$\mathcal{O}_p = \emptyset. \quad (33)$$

Then, $\Omega_{ip}^*(\Lambda) = \min\{\lambda_{ip}, \infty\} = \lambda_{ip}$, and $\|\Gamma\| = \|\Omega^*(\Lambda)\| = \|\Lambda\|$. For $\|\Lambda\| > 1$, let \tilde{p} be defined by:

$$\tilde{p} = \max_p \{p | |\mathcal{O}_p| > 0\}. \quad (34)$$

Since $\Omega_{ip}^*(\Lambda) = 0$ for all $p < \tilde{p}$, we obtain:

$$\sum_{i=1}^N \sum_{p=1}^P \Omega_{ip}^*(\Lambda) = \sum_{i=1}^N \sum_{p=\tilde{p}}^P \min \left\{ \lambda_{ip}, \frac{1 - \sum_{q \geq p, j \in U_q} \lambda_{jq}}{|\mathcal{O}_p|} \right\} \quad (35)$$

$$= \sum_{i=1}^N \sum_{p=\tilde{p}+1}^P \lambda_{ip} + \sum_{i=1}^N \min \left\{ \lambda_{i\tilde{p}}, \frac{1 - \sum_{j=1, q=\tilde{p}+1}^N \sum_{j \in U_{\tilde{p}}} \lambda_{jq} - \sum_{j \in U_{\tilde{p}}} \lambda_{j\tilde{p}}}{|\mathcal{O}_{\tilde{p}}|} \right\} \quad (36)$$

$$= \sum_{i=1}^N \sum_{p=\tilde{p}+1}^P \lambda_{ip} + \sum_{i \in U_{\tilde{p}}} \lambda_{i\tilde{p}} + \frac{1 - \sum_{j=1, q=\tilde{p}}^N \sum_{j \in U_{\tilde{p}}} \lambda_{jq} - \sum_{j \in U_{\tilde{p}}} \lambda_{j\tilde{p}}}{|\mathcal{O}_{\tilde{p}}|} \quad (37)$$

$$= 1 \quad (38)$$

5) Ω^* implements strong priorities: The condition for strong priorities holds since the calculation of Ω_{ip}^* in (5)–(7) is independent from arrival rates from lower priority levels $q < p$. \square

APPENDIX B PROOF OF THEOREM 2

For any pair (i, p) ($1 \leq i \leq N, 1 \leq p \leq P$), we distinguish two cases:

1) $(\exists q > p)(|\mathcal{O}_q| > 0)$: Since Ω^* has a unique solution, we know from the construction of the solution in (13)–(19) that $|\mathcal{O}_q| > 0$ implies for all $p < q$:

$$i \in U_p \leftrightarrow \lambda_{ip} = 0 \quad (40)$$

$$i \in \mathcal{O}_p \leftrightarrow \lambda_{ip} > 0. \quad (41)$$

Therefore, we just need to show that $\delta_{ip} = 0$. If $|\mathcal{O}_q^{(>i)}| > 0$, $\delta_{ip} = 0$ is given by (19). For $|\mathcal{O}_q^{(>i)}| = 0$ (but $|\mathcal{O}_q| > 0$), we define \tilde{j} and \tilde{q} by:

$$\tilde{q} = \max_q \{q > p \wedge |\mathcal{O}_q| > 0 \wedge |\mathcal{O}_q^{(>i)}| = 0\} \quad (42)$$

$$\tilde{j} = \max_j \{j < i \wedge j \in \mathcal{O}_q \wedge j \notin \mathcal{O}_q^{(>i)}\}. \quad (43)$$

Then, we obtain in (5) for all $j \in \mathcal{O}_{\tilde{q}}$:

$$\Omega_{j\tilde{q}}^*(\Lambda) = \frac{1 - \sum_{j \in U_{\tilde{q}}} \lambda_{j\tilde{q}}}{|\mathcal{O}_{\tilde{q}}|}. \quad (44)$$

The sum of all $j \in \mathcal{O}_{\tilde{q}}$ yields:

$$\sum_{j \in \mathcal{O}_{\tilde{q}}} \Omega_{j\tilde{q}}^*(\Lambda) = |\mathcal{O}_{\tilde{q}}| \cdot \frac{1 - \sum_{j \in U_{\tilde{q}}} \lambda_{j\tilde{q}}}{|\mathcal{O}_{\tilde{q}}|}. \quad (45)$$

Since $|\mathcal{O}_{\tilde{q}}^{(>i)}| = 0, j \leq i$ holds for all elements $j \in \mathcal{O}_{\tilde{q}}$. Therefore, (45) gives:

$$\sum_{j \leq i, j \in \mathcal{O}_{\tilde{q}}} \Omega_{j\tilde{q}}^*(\Lambda) + \sum_{j \in U_{\tilde{q}}} \lambda_{j\tilde{q}} = 1. \quad (46)$$

This is equivalent to:

$$\sum_{j \leq i} \Omega_{j\tilde{q}}^*(\Lambda) + \sum_{j > i, j \in U_{\tilde{q}}} \lambda_{j\tilde{q}} = 1. \quad (47)$$

Since Ω^* is strongly fair, waste-free, and has strong priorities, $\Omega_{jq}^*(\Lambda) = 0$ for all $q < \tilde{q}$ and we obtain for δ_{ip} :

$$\delta_{ip} = \frac{1 - \sum_{j \leq i} \Omega_{j\tilde{q}}^*(\Lambda) - \sum_{j > i, j \in U_{\tilde{q}}} \lambda_{j\tilde{q}}}{|\mathcal{O}_p^{(>i)}| + 1}. \quad (48)$$

Inserting (47) into (48) gives:

$$\delta_{ip} = 0. \quad (49)$$

2) $(\forall q > p)(|\mathcal{O}_q| = 0)$: We consider $i \in \mathcal{O}_p$ and $i \in U_p$ separately:

a) $i \in \mathcal{O}_p$: Using (8), we can rewrite (5) as:

$$\begin{aligned} & \Omega_{ip}^*(\Lambda) \cdot (|\mathcal{O}_p^{(>i)}| + 1) + \Omega_{ip}^*(\Lambda) \\ & \cdot (|\mathcal{O}_p| - |\mathcal{O}_p^{(>i)}| - 1) \\ & = 1 - \sum_{q \geq p, j \in U_q} \lambda_{jq}. \end{aligned} \quad (50)$$

Because of (5) and (7), $\Omega_{jp}^*(\Lambda) = \Omega_{ip}^*(\Lambda)$ for all $j \in \mathcal{O}_p$, and we obtain:

$$\begin{aligned} & \Omega_{ip}^*(\Lambda) \cdot (|\mathcal{O}_p^{(>i)}| + 1) \\ & = 1 - \sum_{q \geq p, j \in U_q} \lambda_{jq} - \sum_{j \in \mathcal{O}_p, j < i} \Omega_{jp}^*(\Lambda). \end{aligned} \quad (51)$$

Recall that $\mathcal{O}_q = \emptyset$ for $q > p$. Since load and allocated bandwidth are equal for underloaded stations, i.e., $\Omega_{jr}^*(\Lambda) = \lambda_{jr}$ with $j \in U_r$ and $1 \leq r \leq P$ (6), we have:

$$\begin{aligned} & \Omega_{ip}^*(\Lambda) \cdot (|\mathcal{O}_p^{(>i)}| + 1) \\ & = 1 - \sum_{j > i, q \geq p, j \in U_q} \lambda_{jq} - \sum_{q > p} \Omega_{iq}^*(\Lambda) \\ & \quad - \sum_{j < i, q \geq p} \Omega_{jq}^*(\Lambda) \end{aligned} \quad (52)$$

and for all $i \in \mathcal{O}_p$:

$$\delta_{ip} = \Omega_{ip}^*(\Lambda). \quad (53)$$

Using (7) finally yields (9).

$b) i \in U_p$: If $|O_p^{(>i)}| = 0$, then $j \in U_p$ for $j > i$. On the other hand, we know that $j \in U_q$ for $q > p$. We obtain:

$$\sum_{q \geq p, j > i, j \in U_q} \lambda_{jq} = \sum_{q \geq p, j > i, j \in U_q} \Omega_{jq}^*(\Lambda). \quad (54)$$

Let us assume that $\lambda_{ip} > \delta_{ip}$. Then, (9) reads:

$$\begin{aligned} \lambda_{ip} &> 1 - \sum_{q \geq p, j < i} \Omega_{jq}^*(\Lambda) \\ &\quad - \sum_{q > p} \Omega_{iq}^*(\Lambda) \\ &\quad - \sum_{q \geq p, j > i, j \in U_q} \Omega_{jp}^*(\Lambda). \end{aligned} \quad (55)$$

Since $\lambda_{ip} = \Omega_{ip}^*(\Lambda)$ because $i \in U_p$ (6), (55) contradicts

Definition 1:

$$\sum_{i=1}^N \sum_{p=1}^P \Omega_{ip}^*(\Lambda) = \|\Gamma\| < 1. \quad (56)$$

If $|O_p^{(>i)}| > 0$, we select k such that:

$$k = \min_j \{j \in O_p^{(>i)}\}. \quad (57)$$

From $k \in O_p$, we obtain with (50):

$$\Omega_{kp}^*(\Lambda) = \frac{1 - \sum_{q \geq p, j > k, j \in U_q} \lambda_{jq} - \sum_{q > p} \Omega_{kq}^*(\Lambda) - \sum_{q \geq p, j < k} \Omega_{jq}^*(\Lambda)}{|O_p^{(>k)}| + 1}. \quad (58)$$

Since $j \in U_p$ for $i < j < k$, the following equations hold true:

$$|O_p^{(>i)}| = |O_p^{(>k)}| + 1 \quad (59)$$

$$\sum_{q \geq p, j > i, j \in U_q} \lambda_{jq} = \sum_{q \geq p, j > k, j \in U_q} \lambda_{jq} + \sum_{q \geq p, i < j \leq k} \lambda_{jq} \quad (60)$$

$$\begin{aligned} &= \sum_{q \geq p, j > k, j \in U_q} \lambda_{jq} + \sum_{q \geq p, i < j < k} \lambda_{jq} \\ &\quad + \sum_{q > p} \lambda_{kq} \end{aligned} \quad (61)$$

$$\begin{aligned} &= \sum_{q \geq p, j > k, j \in U_q} \lambda_{jq} + \sum_{q \geq p, i < j < k} \Omega_{jq}^*(\Lambda) \\ &\quad + \sum_{q > p} \Omega_{kq}^*(\Lambda) \end{aligned} \quad (62)$$

$$\sum_{q \geq p, j < i} \Omega_{jq}^*(\Lambda) = \sum_{q \geq p, j < k} \Omega_{jq}^*(\Lambda) - \sum_{q \geq p, i \leq j < k} \Omega_{jq}^*(\Lambda). \quad (63)$$

Therefore, (58) yields:

$$\Omega_{kp}^*(\Lambda) = \frac{1 - \sum_{q \geq p, j < k} \Omega_{jq}^*(\Lambda) - \sum_{q \geq p, j > i} \lambda_{jq} - \sum_{q \geq p} \Omega_{iq}^*(\Lambda)}{|O_p^{(>i)}|}. \quad (64)$$

This can be rewritten as:

$$\begin{aligned} &\Omega_{kp}^*(\Lambda) \cdot |O_p^{(>i)}| + \Omega_{ip}^*(\Lambda) \\ &= 1 - \sum_{q \geq p, j < k} \Omega_{jq}^*(\Lambda) - \sum_{q \geq p, j > i} \lambda_{jq} - \sum_{q > p} \Omega_{iq}^*(\Lambda). \end{aligned} \quad (65)$$

Now, since $i \in U_p$, we have $\lambda_{ip} = \Omega_{ip}^*(\Lambda)$. And since $i \in U_p$ and $k \in O_p$, we obtain $\Omega_{ip}^*(\Lambda) < \Omega_{kp}^*(\Lambda)$. Then, (65) yields:

$$\lambda_{ip} < \frac{\sum_{q \geq p, j < k} \Omega_{jq}^*(\Lambda) - \sum_{q \geq p, j > 1} \lambda_{jq} - \sum_{q > p} \Omega_{iq}^*(\Lambda)}{|O_p^{(>i)}|}. \quad (66)$$

□

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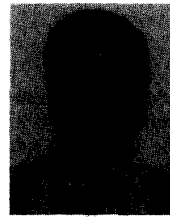
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