On Multicasting ABR Protocols for Wireless ATM Networks

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Abstract

The major challenges of designing multicast rate-control protocols for a combined wired/wireless network are the varying transmission characteristics (bandwidth, error, and propagation delay) of the wireless and wired media, and the different, possibly conflicting flow control requests from multiple receivers. To address these issues, in this paper we study multicasting rate-control ABR algorithms for a combined wired/wireless network with unreliable links and irregular network feedback. We propose a new ABR multicast extension algorithm that can readily extend any unicast ABR rate control scheme for multicast services. By formal analysis, we show that it is max-min fair, and that its maximum cell loss is less than or equal to that of an existing algorithm proposed by Siu and Tseng [15]. We also extend the definition of global feasibility to multicast flows, and propose a delayed-increase policy to ensure global feasibility. Both the waiting time of the delayed-increase policy, and the maximum cell loss in the absence of the policy are formally analyzed. The new algorithm requires a waiting time no longer than, and has a maximum cell loss less than or equal to, that of the existing algorithm. The significance of our approach is illustrated by the formal analysis, which allows us to design a new multicast extension algorithm that is max-min fair, results in a small cell-loss bound, and achieves global feasibility. The analytical method may also assist the design and analysis of other multicasting flow algorithms over ATM and wireless ATM, and other network protocols such as multicast IP and mobile IP.

1 Introduction

The concept of "wireless ATM," first proposed by Raychaudhuri, *et al.* in [11, 12], is under active consideration as a potential framework for the next-generation wireless communication networks able to support integrated multimedia services with guaranteed quality of service (QoS). Since then, and especially in the last two years, to extend the standard ATM protocol over a wireless network interface, wireless ATM has been an active research and development focus in many research laboratories and organizations worldwide [3, 8, 9], including the ATM Forum [2]. The efforts have especially been encouraged when multiple industry consortia recently petitioned the FCC (Federal Communications Commission) and European Regulatory Commission to reallocate a block of unused spectrum at 5.2 Ghz [6], on which small-sized packet like the ATM cell is a particularly well-suited transmission format [7].

Research, architectures, and prototypes in the area of wireless ATM have tended to focus on high speed air interface and media access control, data link and error controls, routing and handoff controls, and connection and location management. Relatively little has been reported on traffic management and control issues when low bandwidth, error-prone wireless networks interface with much higher-speed and reliable wired networks [13].

To address this need, we investigate multicasting ABR algorithms in a combined wired/wireless network with unstable links and conflicting requests. We examine an existing max-min fair multicasting ABR control algorithm proposed by Siu and Tseng [14, 15], and formally analyze its maximum cell loss. A new algorithm is then proposed. Both the maximum cell loss and max-min fairness of new algorithm are analyzed.

Maintaining feasibility is an effective way to minimize the queue length, and thus cell loss, at a switch. It is especially crucial for multicasting services. We extend the definition of global feasibility to the multicasting environment. To ensure global feasibility, we extend the delayed-increase policy proposed by Charny, Ramakrishan, and Lauck [5], to multicasting ABR sources. The delay period required to achieve global

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feasibility and the maximum cell loss in the absence of delayed-increase policy are analyzed, both for switches using Siu and Tseng's algorithm, and for those using our new algorithm.

2 Related Work

For multicasting flow control over ATM networks, Siu and Tseng have established a unified framework to derive a multicast protocol from a given unicast ABR rate-based congestion control protocol [14, 15]. By generalizing a known necessary and sufficient condition on the max-min fairness of unicast rate allocation for multicast service, they showed that their multicast derivation preserves fairness characteristics of the underlying unicast protocol. Another rate-based flow control mechanism for multicast ABR traffic has been proposed by Cavendish, Mascolo, and Gerla [4]. It is a multicast extension of the SP-EPRCA unicast algorithm they previously proposed [10]. None of them include a formally analysis of possible cell loss when a lower-rate request has been delayed and thus ignored in the current iteration (of merging RM cells). This issue is critical in a combined wired/wireless environment network feedback from paths of the same session may likely to be irregular and conflicting.

On the multicast flow control over combined wired/wireless networks, Wang and Schwartz have recently proposed a general framework [16, 17]. It is based on a simple scenario of two mobile receivers located at different distances from the source located within the (error-free) wired network. They have analytically evaluated two algorithms: LSQ and Source Estimation (SE), and compared their performance with an open-loop control mechanism by simulation.

3 Preliminary Studies

Siu and Tseng have proposed an algorithm to extend a unicast ER protocol to a multicast environment. They have proven that if a unicast explicit rate protocol is max-min fair, then the resulting multicast protocol derived using their extension algorithm is max-min fair [15].

Multicast Extension Algorithm - Siu and Tseng [15] *Let $s \in S$ denote a multicast session and P_s denote the paths of s that traverse a switch w. Each source/destination in s behaves as if it is in a unicast environment. Each iteration with respect to the session s and the switch w is defined to be the period such that w receives at least a new BRM cell along each (backward) path in P_s. At the end of each iteration, the switch transmits an RM cell to the source of s with a new RM-ER value equal to the smallest RM-ER value among all RM cells received and the ER values corresponding to the outgoing links of this session in the same iteration.*

In the above algorithm, each iteration is a controlled interval, and is defined to be the period such that at least a new BRM cell is received. This, however, may result in serious cell loss if the BRM cell received indicates a rate increase, while many other paths of the same session actually require a much lower rate. Based on this observation, we define each controlled interval (iteration) as the period when at least one of the following conditions hold:

- *C1:* At least a new BRM cell with a requested rate *less than or equal to* the current rate is received by w.
- *C2:* At least a new BRM cell has been received by w, and a FRM cell arrival triggers the switch to compute an explicit rate that is *less than or equal to* the current rate.
- *C3:* BRM cells have been received by w from *every* backward path in P_s.
- *C4:* At least a new BRM cell has been received by w, and a *controlled timing parameter* Δ time-units have elapsed since the last BRM cell has been sent by w,

In the above, C1 and C2 ensure that a BRM with non-increasing rate will be honored promptly, C3 prevents premature rate-increase, and finally C4 prevents deadlock or infinite wait due to (temporarily or permanently) broken links which might be quite frequent in wireless networks.

Multicast Extension Algorithm - Moh *Let $s \in S$ denote a multicast session and P_s denote the paths of s that traverse a switch w. Each source/destination in s behaves as if it is in a unicast environment. Each iteration with respect to the session s and the switch w is defined to be the period such that at least one condition among C1, C2, C3, and C4 holds. At the end of each iteration, the switch transmits an RM cell to the source of s with a new RM-ER value equal to the smallest RM-ER value among all RM cells received and the ER values corresponding to the outgoing links of this session in the same iteration.*

4 Analysis of Siu and Tseng's Multicasting ABR Algorithm

For a precise analysis, an example protocol proposed by Siu and Tseng is included. It follows the multicast ER algorithm presented in the previous section.

The example protocol assumes that switches can periodically compute the maximum allowed rate of each session, denoted as ER_{sw}. The switch also maintains a register MER and a $READY$ flag, for each multicast virtual connection. One temporary variable MXR is also employed in the computation.

Algorithm 1 (Siu and Tseng) [15]

I. Upon the receipt of RM(ACR, DIR = forward, ER) cell:

1. *Multicast this RM cell to all participating branches.*
2. *If (READY = 1) then*
   (a) *Let MXR =ER;*
   (b) *Let MER = min (MER, ER_{sw});*
   (c) *return RM(ACR, DIR = backward, ER=MER) cell to the source;*
   (d) *let MER = MXR;*
   (e) *let READY = 0.*

II. Upon the receipt of RM(ACR, DIR = backward, ER) cell:

1. *let READY = 1;*
2. *let MER = min (MER,ER);*
3. *discard this BRM cell.*

As discussed above, one disadvantage of Algorithm 1 is in steps II and II.1, where READY is set to 1 as soon as one BRM cell is received, regardless of whether other BRM cells have been received. Thus, during one iteration, the minimum ER value among the computed ER_{sw} and ER values carried by BRM cells received during this iteration will be sent upstream, carried by a BRM cell generated when a new FRM cell is received. It is possible that BRM cells of congested paths carrying smaller ERs are delayed. In particular, the BRM cell with the ER value that is the minimum among all those requested may also be delayed. This ER value will only be considered in some later iteration.

In the following, we derive the maximum loss resulted from Algorithm 1. Consider the situation when one BRM cell with a high ER, say ER_1, has arrived at the source of session i, (or simply source i), causing ACR increase, while the BRM cell with the actual minimum ER value (ER of the bottleneck link/destination), denoted by $\widehat{ER}$, has been delayed. As a result, cell loss occurs due to excess cell transmission between the arrival of these two BRM cells. Note that we consider only the case when ER_1 and $\widehat{ER}$ are ER values of *different paths*. If they are that of the same path, then delay (and thus cell loss) is unavoidable.

The following theorem shows the maximum cell loss that may result in the above worst-case scenario. Its proof, including two additional lemmas, is given in Appendix A.

Theorem 4.1

Consider some arbitrary time t_0. Let $t >= t_0$ be the time that the first BRM cell arrives at source i since time t_0, carrying an ER value denoted by $ER_i(t)$, and that $ER_i(t) > ACR(t)$. Let $\widehat{ER}_i(t)$ be the actual minimum ER value requested among **all** *the paths of session i; $ER_i(t) \geq \widehat{ER}_i(t)$. Let N_{PATH_i} be the total number of paths of session i. The maximum cell loss of session i due to excess transmission at source i between the arrival of the two ER values is given by:*

$$
\begin{aligned}
loss1_i \quad &= \quad D1_{BRM_i} \times (ER_i(t) - \widehat{ER}_i(t)) \times N_{PATH_i} \\
&\leq \{(\frac{N_{SW_i} \times (N_{SW_i}+1)}{2}) \times \Theta \ + N_{SW_i} \times (T_{rm} + T_{sw}) \\
&\quad + 2 \times D_{PROP_i}\} \times (ER_i(t) - \widehat{ER}_i(t)) \times N_{PATH_i} \\
&\leq \{(\frac{N_{SW_i} \times (N_{SW_i}+1)}{2}) \times \Theta + N_{SW_i} \times (T_{rm} + T_{sw}) \\
&\quad + 2 \times D_{PROP_i}\} \times (ER_i(t) - MCR) \times N_{PATH_i}
\end{aligned}
$$

5 New Multicasting ABR Algorithm

In the following, we propose an example protocol similar to Algorithm 1 based on the new multicast extension algorithm presented in Section 3. The new example protocol aims to reduce cell loss due to potentially excess cell transmission in Algorithm 1, based on the four conditions C1 - C4 listed in Section 3.2. To implement these four conditions, we use a flag $READY_p$ for each path p of session i traversing this switch. In addition, a timer, *TIMER*, which expires when the last BRM cell has been sent no less than Δ (representing the time-out period) time-units, is used to avoid deadlock. In summary, we propose the following modifications made to Algorithm 1:

1. If the ER value carried by this BRM cell is no higher than the MER value of the switch, than the $READY$ flag is set to 1 immediately. This is an indication that there is a potential decrease in ER value, thus a BRM cell should be generated as soon as a FRM cell is received. This implements C1.
2. Upon the arrival of a FRM cell, if ER_{sw} is no greater than MER, there is a potential of ER reduction, therefore if at least one BRM cell has

been received, a BRM cell is generated and sent upstream, carrying the appropriate ER value. This implements C2.

3. Upon the arrival of a BRM cell, if the ER value carried by this BRM cell is *higher* than the MER value of the switch, only the $READY_p$ flag is set to 1 (but not the $READY$ flag). The $READY$ flag is set by logically AND the $READY_p$ flags of all the paths of sessions i. This implements C3.

4. Upon the arrival of a FRM cell, if *TIMER* has expired, then if at least one BRM cell has been received, a BRM cell is also generated and sent upstream. This is to avoid infinite delay of BRM cell (or deadlock) when (3) has been true, (1) and (2) are both false, and the switch is still waiting for the BRM cells of one or more paths to set the $READY$ flag. This implements C4.

Algorithm 2 (Moh)

0. Continually decrement TIMER;

I. Upon the receipt of RM(ACR, DIR = forward, ER) cell:

1. *Multicast this RM cell to all participating branches;*
2. *set MXR =ER;*
3. $$\begin{aligned} &if \quad (READY = 1) \\ &or \ \{(\bigvee_{\substack{\text{every } p\in i \\ \text{at the switch}}} READY_p \ ) \\ &and \ ((ER_{sw} \leq MER) \ or \ (TIMER \leq 0) \ )\}) \end{aligned}$$

   then

   (a) *set MER = min (MER, ER_{sw});*
   (b) *return RM(ACR, DIR=backward, ER=MER) cell to the source;*
   (c) *set (READY = 0)*
   (d) *set ($READY_p$ = 0) for each $p \in i$ sharing this switch;*
   (e) *set (TIMER = Δ);*
4. *else*
   set MER = min (MER, ER_{sw});
5. *set MER = MXR;*

II. Upon the receipt of an RM(ACR, DIR = backward, ER) cell from path p:

1. *If ER $\leq$ MER then*
   set READY = 1;
2. *else*
   (a) *set* $READY_p = 1$;
   (b) *set* $READY = \bigwedge_{\substack{\text{every } p\in i \\ \text{at the switch}}} \{READY_p\}$;
3. *set MER = min (MER, ER);*
4. *discard this BRM cell.*

Note that to completely eliminate cell loss considered in Theorem 4.1, we should required, in Step I.3, a BRM cell be generated and sent upstream only when

$$READY = \bigwedge_{\substack{\text{every } p\in i \\ \text{at the switch}}} \{READY_p\} \ = \ 1.$$

This, however, might result in excess delay in returning BRM cells, thus cause serious In the case of a broken link due to unreliable wireless link or mobility, a deadlock might occur when switches are waiting indefinitely for a BRM cell of the broken link.

6 Analysis of the New Multicast ABR Algorithm

6.1 Cell Loss Analysis

Recall that, upon receiving a FRM cell, a switch running Algorithm 1 will always generate and return a BRM cell if at least one BRM cell has been received since the last FRM cell received. If the same switch runs Algorithm 2, however, the switch may generate a BRM cell right away or at some later time, depending on the condition presented in Step I.3 of Algorithm 2. The following theorem compares the maximum cell losses of the two algorithms. The proof, including an additional lemma, is presented in Appendix B.

Theorem 6.1
Maximum cell loss in Algorithm 2 is at most as much as that in Algorithm 1. More formally, let $loss1_i$ denote the maximum cell loss of Algorithm 1 considered in Theorem 4.1, and $loss2_i$ denotes that of Algorithm 2, then

$$loss2_i \ \leq \ loss1_i$$

6.2 Max-Min Fairness Analsis

Max-Min fairness has been adopted by the ATM Forum as a criterion for evaluation ABR protocols [1]. Siu and Tseng have generalized a known necessary and sufficient condition for unicast max-min fairness to multicast services [15], and described three important characteristics, *P1, P2, and P3* [15], in many explicit rate control algorithms for unicast VC (Virtual

Circuits) proposed at the ATM Forum, and used them to prove their proposed multicast extension algorithm (described in Section 3) is max-min fair. In the following, we state the max-min fairness property of our proposed multicast extension algorithm described in Section 3. The detailed proof is omitted due to length limitation.

Theorem 6.2

If a unicast explicit rate protocol is max-min fair; i.e., it satisfies the three properties P1, P2, and P3. Then the resulting multicast protocol derived using multicast extension algorithm by Moh (described in Section 3), with the example protocol Algorithm 2, is max-min fair.

Proof: (Brief)

Intuitively, note that the only differences between the two algorithms that relate to the three properties P1 - P3 are: (1) The time for a switch to generate and send back a BRM cell, and (2) the ER value carried by this BRM cell; both have been carefully analyzed in Lemma B.1.

7 Global Feasibility

Maintaining feasibility is an effective way to minimize the queue length, and thus cell loss due to buffer overflow, at a switch. Extending the definition given by Charny, Ramakrishan, and Lauck [5], the definition of feasibility for multicast flow, can be rewritten as follows, where $SCCR_s$ is the source current cell rate of session s, and $N_{PATH_{sl}}$ is the number of paths of session s traversing link l.

Definition 7.1

Global feasibility of transmission rate is defined as, for all links, at all times, the actual transmission rates $SCCR$ of all sources satisfy

$$\begin{aligned} F_l &= \sum_{\substack{\text{every path } p \\ \text{passing link } l}} r_p \\ &= \sum_{\text{all } s \in S} \Big(\sum_{\substack{\text{every } p \in P_s \\ \text{passing link } l}} N_{PATH_{sl}} \times r_s(t) \Big) \leq C_l \end{aligned}$$

To guarantee global feasibility in a unicast ABR flow control, a increase-rate policy has been proposed [5]; it requires an ABR source to wait for some period W, before increasing ACR [5]. In this section, we extend the policy for multicasting service, and renamed it as *delayed-increase policy*, to multicast ABR control.

In a multicast flow environment, cell loss occurs when a particular multicast source i is allowed to increase its ACR, while at least one source should reduce its ACR but has not been notified to do so. Thus, the delayed-increase policy should delay the rate increase (ACR increase) at a multicast ABR source i, until all other sources sharing one or more links traversed by some path of i receive network feedback and adjust their rates accordingly.

The following theorem states the sufficient condition; i.e., the minimum waiting time of the delayed-increase policy, to ensure global feasibility. The proof makes use of a lemma on estimating the time intervals, $D1_{BRM_j}$ and $D2_{BRM_j}$, source i should wait before increasing its ACR for both Algorithm 1 and Algorithm 2. Both the proof and the lemma are given in Appendix C.

Theorem 7.1

Let $W1_i$ be the minimum waiting time of the delayed-increase policy, i.e., the time for a multicasting ABR source i to wait before increasing its ACR when Algorithm 1 is used as rate-control algorithm, and $W2_i$ be the minimum waiting time when Algorithm 2 is used. Also let Λ_i be the set of sources each of which shares some link traversed by some path of source i. The network is globally feasible if

$$\begin{aligned} W1_i &= MAX_{j \in \Lambda_i}\{D1_{BRM_j}\} \\ W2_i &= MAX_{j \in \Lambda_i}\{D2_{BRM_j}\} \\ W1_i &= W2_i \end{aligned}$$

where $D1_{BRM_j}$ and $D2_{BRM_j}$ are defined and analyzed in Lemma C.1.

In the next theorem, we analyzed the maximum cell loss in the absence of delayed-increase policy based on Theorem 7.1. We show that the maximum cell loss of Algorithm 2, in the absence of delayed-increase policy, is less than or equal to that of Algorithm 1. The proof is given in Appendix D.

Theorem 7.2

In the absence of delayed-increase policy, cells transmitted by source i or any source $j \in \Lambda_i$ may be lost when source i starts increasing its rate. Denote the maximum cell loss by $LOSS1_i$ when Algorithm 1 is used, and by $LOSS2_i$ when Algorithm 2 is used. Consider some arbitrary time t_0. Let $t \geq t_0$ be the time that the first BRM cell arrives at source i since time t_0, carrying an ER value denoted by $ER1_i(t)$ (or $ER2_i(t)$), and indicating a rate increase; i.e., $ER1_i(t) > ACR(t)$, when Algorithm 1 (or 2) is used. Let $t_j \geq t$ be the time that the first BRM cell arrives at source j since time t_0, carries the ER value that is the minimum requested by all the paths, denoted by $E\hat{R}1_j(t)$ (or $E\hat{R}2_j(t)$), when Algorithm 1 (or 2) is used. Then

$$\begin{aligned} LOSS1_i &= loss1_i \\ &+ \sum_{j \in \Lambda_i} (D1_{BRM_j} \times (ACR_j(t_j) - E\hat{R}1_j(t_j)) \times N_{PATH_j}) \end{aligned}$$

$$
\begin{aligned}
LOSS2_i &= loss2_i \\
&+ \sum_{j \in \Lambda_i} (D2_{BRM_j} \times (ACR_j(t_j) - \hat{ER}2_j(t_j)) \times N_{PATH_j}) \\
LOSS2_i &\le LOSS1_i
\end{aligned}
$$

8 Summary and Conclusion

We have proposed a new multicasting ABR extension algorithm that can be readily applied to existing unicast ABR algorithms. We have shown that the new algorithm is max-min fair, and has cell loss less than or equal to that of an existing algorithm proposed by Tseng and Siu. Finally, to ensure global feasibility for multicast ABR control, we have also proposed a delayed-increase source policy, and shown that our proposed multicast extension algorithm requires a waiting time that is the same, and results a maximum cell loss in the absence of the policy no greater than, the existing algorithm. algorithm. The proposed multicast ABR extension algorithm may be readily applied to existing unicast ABR algorithms. On-going work includes formal proof of the correctness (live-lock and dead-lock free) of the multicast extension algorithm, and integration of existing unicast ABR algorithm into the new multicast ABR extension algorithm.

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Appendix A: Proof of Theorem 4.1

We first estimate the maximum time between the arrival of these two BRM cells at the source. Note that it is the maximum time for a BRM cell carrying a minimum ER value to arrive the source from a farthest destination. In the worst case, at each switch a FRM cell has just arrived right before this BRM cell arrives, and thus the BRM is delayed while the switch waits for the next FRM cell.

Lemma A.1

Let N_{SW_i} be the maximum number of switches, and D_{PROP_i} be the end-to-end propagation delay, traversed by some path p of session i. Let T_{sw} be the upper bound on switch computation (allocation) time. In Algorithm 1, the maximum time for a BRM cell carrying the minimum ER value to arrive at source i from a destination is given by:

$$
\begin{aligned}
D1_{BRM_i} &= \sum_{k=1}^{N_{SW_i}} (D1_{FRM_k} + T_{sw}) + D_{PROP_i} \\
&= \sum_{k=1}^{N_{SW_i}} D1_{FRM_k} + N_{SW_i} \times T_{sw} + D_{PROP_i}
\end{aligned}
$$

where $D1_{FRM_k}$ is the maximum time the BRM cell waits at switch k for a FRM cell.

Proof:
Upon arrival at each switch, the BRM cell carrying the minimum ER would have to first wait $D1_{FRM_k}$ time for a FRM cell, and then wait for T_{sw}, the time for the switch to compute the minimum ER value, before it can be sent upstream. The total delay is thus the sum of $D1_{FRM_k} + T_{sw}$ at each switch, plus D_{PROP_i}. □

$D1_{FRM_k}$ is formulated in the next lemma.

Lemma A.2 *Let Θ be the maximum per-switch queueing delay, and T_{rm} be the inter-departure time of FRM cell from the source of session i. In Algorithm 1, $D1_{FRM_k}$, the maximum time an arrived BRM cell at switch k has to wait for the arrival of a FRM cell, is given by:*

$$
D1_{FRM_k} = (k \times \Theta + T_{rm}) + D_{PROP_i(k-1,k)}
$$

where $D_{PROP_i(k-1,k)}$ is the propagation time from switch k-1 to switch k, and

$$
\begin{aligned}
\sum_{k=1}^{N_{SW_i}} D1_{FRM_k} &= \sum_{k=1}^{N_{SW_i}} (k \times \Theta + T_{rm}) + D_{PROP_i} \\
&= \left(\frac{N_{SW_i} \times (N_{SW_i} + 1)}{2}\right) \times \Theta \\
&\quad + N_{SW_i} \times T_{rm} + D_{PROP_i}
\end{aligned}
$$

Proof:
For convenience we number the switches along the longest path of session i as switches $1, 2, ..., N_{SW_i}$. The longest time a BRM cell has to wait for a FRM cell at switch k is the maximum inter-arrival time of FRM cells at switch k, which occurs when the first FRM cell has gone through switches 1 to k without any queueing delay, while the second FRM cell has been delayed Θ time at every one of switches 1 through k. □

Proof of Theorem 4.1
Assuming that there is no increase in ACR between the arrival of BRM cells carrying the two ER values, the maximum cell loss is the product of excess rate $(ER_i(t) - \widehat{ER}_i(t))$, delay $D1_{BRM_i}$, and total number of paths, N_{PATH_i}. The proof is obtained by substituting the result of Lemmas A.2 into that of Lemma A.1; the last equation is true since $\widehat{ER}_i(t) >= MCR$. □

Appendix B: Proof of Theorem 6.1

We first use a lemma to analyze the departure time of, and the ER value carried by, the next BRM cell.

Lemma B.1

Consider an arbitrary multicast session, and an arbitrary switch k traversed by some paths of this session. Upon receiving a FRM cell by switch k, denote the time that the next BRM cell leaves switch k by τ_j, and the ER value carried by this BRM cell by ER_j, when switch k is running Algorithm j, $1 \leq j \leq 2$. Then:

$$(1) \qquad \tau_1 \leq \tau_2$$
$$(2) \qquad ER_1 \geq ER_2$$

Proof: Omitted due to length limitation. □

Proof of Theorem 6.1

The maximum cell loss in Algorithm 2 is at most as much as that in Algorithm 1. More formally, let $loss1_i$ denote the maximum cell loss of Algorithm 1 considered in Theorem 4.1, and $loss2_i$ denote that of Algorithm 2, then

$$loss2_i \leq loss1_i$$

Proof:

Rewrite the definition of $loss$, given in Theorem 4.1, for Algorithms 1 and 2, respectively, as follows:

$$loss1_i = D1_{BRM_i} \times (ER1_i(t) - \widehat{ER}1_i(t)) \times N_{PATH_i}$$

$$loss2_i = D2_{BRM_i} \times (ER2_i(t) - \widehat{ER}2_i(t)) \times N_{PATH_i}$$

We will proceed by proving the following:

$$D1_{BRM_i} = D2_{BRM_i} \qquad (1)$$
$$ER1_i(t) \geq ER2_i(t) \qquad (2)$$
$$\widehat{ER}1_i(t) = \widehat{ER}2_i(t) \qquad (3)$$

1. To prove $D2_{BRM_i} = D1_{BRM_i}$:
   Since $D2_{BRM_i}$ is the maximum time for a BRM cell carrying the *minimum* ER value to arrive at source i from a destination; whenever this BRM cell arriving at a switch, $READY = 1$ by Step II.1, thus this BRM cell would experience the same delay in Algorithm 2 as in Algorithm 1.

2. To prove $ER1_i(t) \geq ER2_i(t)$:
   The detailed proof is omitted; it is based on an induction proof of Lemma B.1.

3. To prove $\widehat{ER}1_i(t) = \widehat{ER}2_i(t)$:
   $\widehat{ER}1_i(t)$ (or $\widehat{ER}2_i(t)$) is the actual minimum ER value requested among **all** the paths of session i in Algorithm 1 (or Algorithm 2), but the minimum ER value requested is independent of whether the switch is running Algorithm 1 or Algorithm 2, thus $\widehat{ER}1_i(t) = \widehat{ER}2_i(t)$.

The theorem is proven by substituting EQs (1), (2), and (3) into the definition of $loss1_i$ and $loss2_i$ given at the beginning of this proof. □

Appendix C: Proof of Theorem 7.1

We first present Lemma C.1 which estimates the time source i should wait before increasing its ACR, for both Algorithm 1 and Algorithm 2. It assumes that at least one source, say source j, should reduce its ACR but has not receive such a BRM cell. In the worst case, we should assume source j to be the farthest source sharing some link with source i. Note that this particular BRM cell that source j waiting for carries an ER (denote by BRM-ER) smaller than ACR_j, the ACR of source j. For ease and clarity of analysis, we assume that BRM-ER is the smallest ER requested by all the paths of j. (The analytical results will still be the same without the assumption.) It follows that, on the way this BRM cell travels from destination to source, it will be delayed at each switch (running Algorithm 2) as if the switch is running Algorithm 1, according to Step II.1 of Algorithm 2 and EQ (1).

Lemma C.1

Let $D2_{BRM_j}$ be the maximum time for a BRM cell carrying a rate-decreasing ER, which is the minimum ER value requested by all the paths of j, to arrive at source j from a destination when Algorithm 2 is used. Also recall that $D1_{BRM_j}$ is the maximum time for a BRM cell carrying the minimum ER value to arrive at source j when Algorithm 1 is used. Then

$$D1_{BRM_j} = \sum_{k=1}^{N_{SW_j}} (D1_{FRM_k} + T_{sw}) + D_{PROP_j}$$

$$= \sum_{k=1}^{N_{SW_j}} (k \times \Theta + T_{rm} + T_{sw}) + 2 \times D_{PROP_j}$$

$$= (\frac{N_{SW_j} \times (N_{SW_j} + 1)}{2}) \times \Theta$$

$$+ N_{SW_j} \times (T_{rm} + T_{sw}) + 2 \times D_{PROP_j}$$

$$D2_{BRM_j} = D1_{BRM_j}$$

where the variables are as given in Sections 4 and 6.

Proof:

The above equation can be directly derived from from Lemma A.1, Lemma A.2, and EQ (1). □

Proof of Theorem 7.1

To achieve global feasibility, upon receiving a rate-increase BRM cell, source i should wait for the time that guarantees all the sources in Λ_i to receive their next BRM cells informing a possible rate-decrease. Similar argument holds for Algorithm 2. Since $D1_{BRM_j} = D2_{BRM_j}$ by Lemma C.1, it follows that $W1_i = W2_i$. □

Appendix D: Proof of Theorem 7.2

The proof is similar to the proof of Theorem 4.1. In the absence of delayed-increase policy, the maximum cell loss of source i will still be at most $loss1_i$, as analyzed in Theorem 4.1. Maximum cell loss of each of the sources $j \in \Lambda_i$ will be the product of $D1_{BRM_j}$, the maximum time taken for the next BRM cell cell to arrive, the excess rate $(ACR_j(t_j) - E\hat{R}1_j(t_j))$, and N_{PATH_j}. Thus the maximum total cell loss is the sum of loss of all the sources $j \in \Lambda_i$. The same argument holds for Algorithm 2. Finally, $D1_{BRM_j} = D2_{BRM_j}$ from Lemma C.1, and $E\hat{R}1_j(t) = E\hat{R}2_j(t)$ by a similar argument that proves EQ (3) in Theorem 6.1, but $loss2_i \leq loss1_i$ from Theorem 6.1, it follows that $LOSS2_i \leq LOSS1_i$. □

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