A Bandwidth Enhancement Mechanism for the FRR-enabled OBS Networks†

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***Abstract*— Bandwidth usage efficiency and transmission latency are two important figures of merits to evaluate a system design for the next generation network. In this paper, we propose a bandwidth enhancement mechanism for a recently introduced Forward Resource Reservation (FRR) transmission scheme, which is designed to reduce the end-to-end data burst delay in an Optical Burst Switching (OBS) network. After presenting the principle of the bandwidth enhancement mechanism, we analyze and evaluate its performance in terms of the bandwidth savings and the associated operation cost. Simulation results also demonstrate the advantages of the bandwidth enhanced FRR scheme as compared to the basic FRR scheme.**

I. INTRODUCTION

The Forward Resource Reservation (FRR) [1] is a transmission scheme proposed to reduce the end-to-end data burst delay at the edge nodes of the WDM burst-switched network [2], [3]. Specifically, the FRR scheme parallels the execution of the data burst assembly and the lightpath setup, both of which are the important delay contributors in an Optical Burst Switching (OBS) network, thus reducing the transmission latency.

The FRR scheme involves a three-step procedure: 1) predict the data burst length before a burst assembly process begins; 2) pre-transmit the Burst Header Packet (BHP) for resource reservation without waiting for the burst assembly to finish; 3) when the burst assembly is completed, check whether the pre-reserved resource is sufficient to support the actual data burst. Depending on whether the pre-reserved resource is larger or smaller than the actual data burst, a BHP pre-transmission may succeed or fail. In case of failure, the BHP is re-transmitted with a new reservation length equal to the actual data burst length, and the pre-reserved resources are simply left unused. Fig. 1 depicts the principle of the FRR scheme which improves the real-time communication services for applications with time constraints.

Two salient features of the FRR scheme that facilitate the latency reduction functionality are the data burst length prediction and the aggressive reservation strategy. The reservation length (L_r) carried in a pre-transmitted BHP is determined based on the predicted data burst length ($\tilde{L}_d$) and a correction value (δ), defined as $L_r = \tilde{L}_d + \delta$. The correction value δ acts as a reservation compensation which increases the BHP pre-transmission success probability, thus improving the latency reduction capability of the FRR scheme [1].

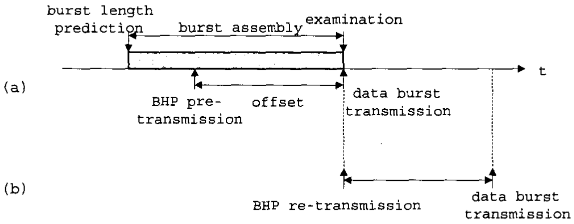

Fig. 1. The FRR scheme principle (a) A BHP pre-transmission succeeds; (b) A BHP pre-transmission fails.

Therefore, the bandwidth usage efficiency of the FRR scheme is affected by two factors: the reservation correction value which is introduced by the aggressive reservation strategy, and the abandoned bandwidth resources due to insufficient forward resource reservations.

Accordingly, there are two disciplines to improve the bandwidth utilization of the FRR-enabled OBS system. The first one is to properly budget the correction value δ in order to balance the performance gains (e.g., the latency reduction capability) and the system costs (e.g., the reservation overhead). A too large δ induces considerable negative impact on the bandwidth utilization with only marginal improvement on the BHP pre-transmission success probability.

The other discipline is to reduce the bandwidth wastage caused by unsuccessful BHP pre-transmissions. In the FRR scheme, nothing is done to the pre-reserved resource which is insufficient to support the transmission of the actual data burst. This results in bandwidth utilization discrepancy, especially when the BHP pre-transmission fails with a high probability. Mechanisms that make intelligent usage of such resources are highly desired.

In this paper, we explore a mechanism to make better usage of the network resources. The aim is to render the bandwidth

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enhancement capability for the FRR scheme, thus improving the bandwidth usage efficiency of the FRR-enabled OBS systems. Hereafter, for simplicity, we will refer to an FRR scheme which adopts the proposed bandwidth enhancement mechanism as the BEFRR (Bandwidth Enhanced FRR) scheme, and that without the bandwidth enhancement mechanism as the basic FRR scheme. Theoretical analysis and simulation results are presented to illustrate the benefits of the BEFRR scheme.

The rest of this paper is organized as follows. Section II describes the system environment based on which our BEFRR scheme is devised. We present the principle of the bandwidth enhancement mechanism and analyze its performance in Section III. In Section IV, the simulation results are shown to demonstrate the advantages of the BEFRR scheme as compared to the basic FRR scheme. We conclude in Section V.

II. SYSTEM MODEL AND DESIGN OBJECTIVE

This section describes the system environment and the design objective of the BEFRR scheme.

A. The System Model and Assumptions

We design the BEFRR scheme based on the same system scenario as that for the basic FRR scheme [1]. Several functionalities of the network that are critical to our current study are further described.

Both the ingress nodes and the intermediate nodes are equipped with timers to make sure an action is carried out within specific time constraints. For example, a Timer A at the intermediate node monitors the channel holding time reserved for a data burst.

The Switching Control Unit (SCU) [2] at the intermediate node is responsible to release–when necessary–the resources which have been reserved for a data burst. The release operation is triggered by either the time-out event from the Timer A, or by a particular message which explicitly requires such an operation.

We assume that the OBS system under consideration adopts a void-filling (VF) strategy for data channel scheduling [4]. The basic idea of the VF-scheduling is that the interval between two previously scheduled periods of resources can be used to transmit the traffic which arrives later, thus filling the void. The void-filling method facilitates flexible utilization of the network resources.

Furthermore, we identify each intermediate node of the core network by an index i, where $i = 1, \dots, n$, and n represents the total number of the intermediate nodes in the core network.

The following notations are defined to simplify our description ($i = 1, \dots, n$):

- T_a: The time when a new burst traffic begins to assemble at the ingress node.
- τ_a: The burst assembly duration at the ingress node.
- $T_h(i)$: The time when a BHP is received at the i-th intermediate node. $T_h(0)$ represents the time when the BHP is transmitted into the the core network at the ingress node.
- $T_c(i)$: The time when the i-th intermediate node receives a signaling message requiring the release of the pre-reserved resources. $T_c(0)$ represents the time when the actually assembled data burst length exceeds the reservation value contained in a pre-transmitted BHP.
- $\vartheta(i)$: The time interval for the SCU of the i-th intermediate node to process a BHP. We assume that $\vartheta(i) = \vartheta$ for all $i \in \{1 \dots n\}$.
- $\theta(i)$: The time interval for the switching matrix configuration at the i-th intermediate node to become stable. We assume that $\theta(i) = \theta$ for all $i \in \{1 \dots n\}$.
- $\tau_o(i)$: The offset between a BHP and its data payload at the output port of the i-th intermediate node. $\tau_o(0)$ represents the initial offset between a BHP and its data payload at the ingress node. $\tau_o(i) = \tau_o(i-1) - \vartheta$.
- $T_s(i)$: The starting time when the resource at the i-th intermediate node is reserved for a data burst ($T_s(i) = T_h(i) + \vartheta(i) + \tau_o(i)$).
- $T_e(i)$: The ending time when the resource at the i-th intermediate node is reserved for a data burst ($T_e(i) = T_s(i) + L_r$).

B. Design Objective

In designing the BEFRR scheme, we are guided by the following considerations:

1) The bandwidth wastage of the basic FRR system, especially that due to the unsuccessful forward resource reservations, is minimized;
2) No extra end-to-end burst delay is introduced;
3) The operation cost of the intermediate node, such as that for the lightpath tear-down and setup, is maintained as low as possible.

The essence of our bandwidth enhancement mechanism is to adopt a crank-back procedure at the intermediate nodes to release the pre-reserved resources which are insufficient to support the corresponding data burst. In order to maintain the BHP pre-transmission success probability, thus satisfying the latency reduction requirement, our BEFRR scheme still employs the aggressive strategy for resource reservation as the basic FRR scheme does. Likewise, the delayed-reservation [5] is utilized to improve the network throughput.

III. THE BANDWIDTH ENHANCED FRR SCHEME

In this section, we describe the bandwidth enhancement mechanism, and assess its performance.

A. The BEFRR Scheme Principle

The proposed bandwidth enhancement mechanism involves both the edge node behavior and the intermediate node behavior. To emphasize the bandwidth enhancement functionality, we present its principle by describing the distinctive characteristics of the BEFRR scheme as compared to the basic FRR scheme:

1) Instead of comparing the data burst length with the reservation length carried in a pre-transmitted BHP until the burst assembly is completed, the Burst Control Unit

(BCU) in the BEFRR scheme begins to monitor the actually assembled burst amount immediately after the BHP is sent out at $T_h(0)$.

If by the time $T_a + \tau_a$ the actual burst length does not exceed the reservation value contained in the pre-transmitted BHP, the forward resource reservation succeeds and the data burst is transmitted without additional action to be taken.

Otherwise, the following steps are executed.

2) As soon as the actual burst length exceeds the pre-reservation length at some time $T_c(0)$, where $T_h(0) < T_c(0) \leq T_a + \tau_a$, the BCU issues a signaling message, namely, a CLEANUP message, to nullify the pre-reservation requirement (i.e., the pre-transmitted BHP). The CLEANUP message carries the identifier of the BHP which it attempts to invalidate.
3) At the i-th intermediate node, upon the reception of the CLEANUP message at $T_c(i)$, the SCU promptly triggers a crank-back procedure. That is, the SCU releases the pre-reserved resources for the corresponding data burst, and makes this period available to other burst transmissions. Simultaneously, the CLEANUP message is forwarded to the next intermediate node until all nodes that have reserved resources for the corresponding data burst are notified.

   If by the time $T_c(i)$ the switching matrix has been configured for the corresponding data burst, i.e., $T_s(i) - \theta \leq T_c(i) \leq T_s(i)$, the switching matrix should be released immediately.

Fig. 2 illustrates the difference between the basic FRR scheme and the BEFRR scheme at the i-th intermediate node. For simplicity, we present only the circumstance when a BHP pre-transmission fails and the crank-back procedure occurs.

Reservation clean-up is an essential feature of the BEFRR scheme to reduce the potential bandwidth wastage due to the insufficient pre-reserved resources. This procedure, in tandem with the VF-scheduling method, enables the intermediate node to make intelligent usage of the available network resources, and improves the system throughput.

Another important feature of the BEFRR scheme is that the delayed-reservation [5] is adopted and the switching matrix is configured in a just-in-time manner, i.e., the lightpath at the intermediate node is not configured for a reservation until $T_s(i) - \theta$. This characteristic enables the CLEANUP message which satisfies $T_h(i) + \vartheta \leq T_c(i) < T_s(i) - \theta$ not only reduces the bandwidth wastage, but also avoids the unnecessary operations for lightpath set-up and tear-down.

The benefits of the BEFRR scheme is facilitated by the message dialog between the ingress nodes and the intermediate nodes. The particular message, i.e., the CLEANUP message, is thus employed to make the intermediate nodes aware of the invalidity of the pre-transmitted reservation requirement.

Comparing with the basic FRR scheme, the system cost of the BEFRR scheme is induced by the extra signaling transmissions, and is equal to $O(m)$, where m is the number of the CLEANUP messages to be transmitted. Taking into account the reduced switching matrix operation and the improved bandwidth usage efficiency, together with the fact that the BHP pre-transmission failure probability is typically small (e.g., less than 5% in a steady system [1]), the benefits of the BEFRR scheme are more considerable.

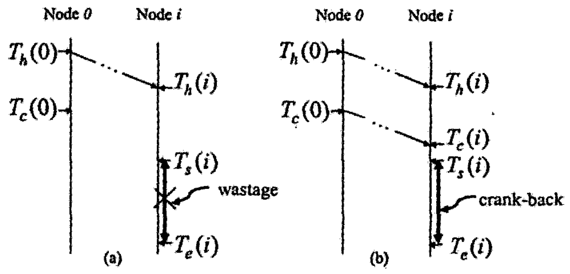

Fig. 2. The comparison between the basic FRR scheme and the BEFRR scheme ($T_h(i)$: A pre-transmitted BHP arrives at the i-th intermediate node; $T_c(i)$: A CLEANUP message arrives at the i-th intermediate node). (a) in the basic FRR scheme, nothing is done with the insufficient pre-reserved resources; (b) in the BEFRR scheme, a crank-back procedure is employed at the intermediate node to release the pre-reserved resources.

B. Theoretical Analysis

The objective of the bandwidth enhancement mechanism is to reduce the potential bandwidth wastage caused by insufficient forward resource reservations in the basic FRR scheme. Therefore, we are interested in the bandwidth savings for a given burst length L_d, and the associated signaling overhead, which is defined as the possibility to transmit the CLEANUP message. For simplicity, we do not consider the effect of θ. We assume that they are negligible as compared to the length of the data burst.

The BEFRR scheme provides bandwidth savings when the pre-reserved resources are insufficient to support the actually assembled data burst. As empirically demonstrated in [1], the prediction residuals delivered by the underlying adaptive filter is approximately Gaussian distributed with mean 0 and variance σ^2, where σ is the standard derivation of the prediction residuals. That is, given a data burst length L_d, the probability distribution function of the predicted value ($\tilde{L}_d$) can be expressed by

$$f(\tilde{L}_d) = \frac{1}{\sqrt{2 \cdot \pi \cdot \sigma}} \cdot e^{-\frac{(\tilde{L}_d - L_d)^2}{2 \cdot \sigma^2}}. \tag{1}$$

Consequently, for a given burst length L_d, the average bandwidth saving (L_s) is

$$\begin{aligned} L_s &= \frac{1}{\sqrt{2 \cdot \pi \cdot \sigma}} \cdot \int_{-\infty}^{L_d - \delta} (x + \delta) \cdot e^{-\frac{(x - L_d)^2}{2 \cdot \sigma^2}} dx \\ &= -e^{-\frac{\delta^2}{2 \cdot \sigma^2}} \cdot \frac{\sigma}{\sqrt{2 \cdot \pi}} + (L_d + \delta) \cdot Q(\frac{\delta}{\sigma}), \end{aligned} \tag{2}$$

where $Q(\cdot)$ is the Q-function [6].

As a CLEANUP message is transmitted as soon as the actual burst length exceeds the reservation value contained in the pre-transmitted BHP, the associated signaling overhead, denoted as S_o, can be expressed as the probability that the forward resource reservation fails, i.e.,

$$\begin{aligned} S_o &= P(L_r = \tilde{L}_d + \delta < L_d) \\ &= \frac{1}{\sqrt{2 \cdot \pi} \cdot \sigma} \cdot \int_{-\infty}^{L_d - \delta} e^{-\frac{(x-L_d)^2}{2 \cdot \sigma^2}} dx \\ &= Q(\frac{\delta}{\sigma}). \end{aligned} \tag{3}$$

Eqs. 2 and 3 represent the upper bounds for the bandwidth savings and the signaling overhead associated with the BEFRR scheme, respectively.

Tighter bounds with respect to L_s and S_o are derivable for the BEFRR scheme, if we consider a more practical and stricter situation that the reservation requirement carried by a pre-transmitted BHP should be no less than 0. In this case, the average bandwidth wastage corresponding to a given data burst of length L_d is

$$\begin{aligned} L_s &= \frac{1}{\sqrt{2 \cdot \pi} \cdot \sigma} \cdot \int_{0}^{L_d - \delta} (x + \delta) \cdot e^{-\frac{(x-L_d)^2}{2 \cdot \sigma^2}} dx \\ &= \frac{\sigma}{\sqrt{2 \cdot \pi}} \cdot (e^{-\frac{L_d^2}{2 \cdot \sigma^2}} - e^{-\frac{\delta^2}{2 \cdot \sigma^2}}) + \\ & \quad (L_d + \delta) \cdot [Q(\frac{\delta}{\sigma}) - Q(\frac{L_d}{\sigma})], \end{aligned} \tag{4}$$

and the potential signaling overhead is given by

$$\begin{aligned} S_o &= P(L_r = \tilde{L}_d + \delta < L_d) \\ &= \frac{1}{\sqrt{2 \cdot \pi} \cdot \sigma} \cdot \int_{0}^{L_d - \delta} e^{-\frac{(x-L_d)^2}{2 \cdot \sigma^2}} dx \\ &= Q(\frac{\delta}{\sigma}) - Q(\frac{L_d}{\sigma}). \end{aligned} \tag{5}$$

IV. SIMULATION RESULTS AND DISCUSSIONS

We also conduct simulations to examine the advantages of the BEFRR scheme as compared to the basic FRR scheme. In our simulations, a 12-order Linear Predictive Filter (LPF) is utilized for data burst length prediction, and the correction value (δ) of the aggressive reservation strategy is determined by the Root Mean Square (RMS)-based method, i.e., $\delta = \alpha \cdot \sigma$, where α is a real-value constant [1]. The traffic flowing into the ingress node is assumed to be a self-similarity process, generated based on the FFT-FGN model [7], with the Hurst parameter of $H = 0.75$ and the average packet size of 2000 bytes. In the rest of the paper, when we normalize the burst assembly duration (τ_a) with respect to the time to transmit one IP packet of 1500 bytes, we will refer to it as τ.

As shown in Fig. 3, the proposed BEFRR scheme improves the bandwidth usage efficiency (ω) as compared to the basic FRR scheme, and the improvement is especially significant when the correction value (δ) is small, whereby the BHP pre-transmission fails at a higher probability. As the proposed BEFRR scheme has no negative impact on the latency reduction performance of the basic FRR scheme (which is determined by the BHP pre-transmission success probability and the ratio between τ_o and τ_a, as described in [1]), we can claim that the BEFRR scheme improves the bandwidth usage efficiency without inducing extra data burst delay.

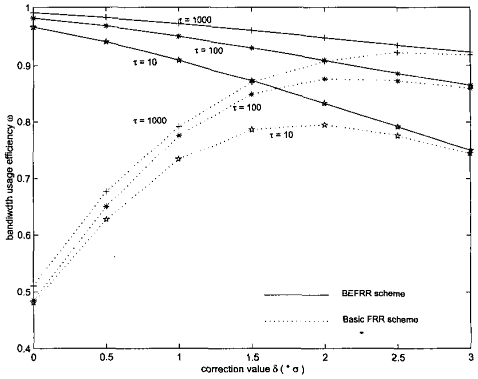

Fig. 3. The bandwidth usage efficiency versus the correction value

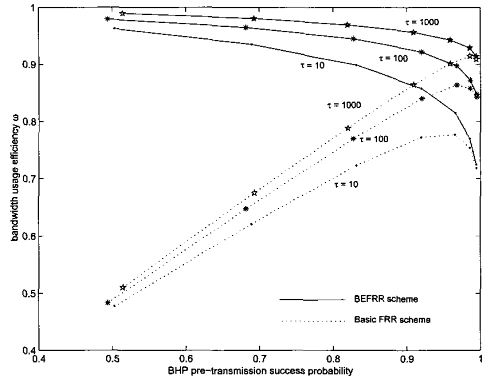

Fig. 4. The bandwidth usage efficiency versus the BHP pre-transmission success probability

It is interesting to see that for any given burst assembly duration τ, the BEFRR scheme delivers similar bandwidth usage efficiency as that in the basic FRR scheme after the optimal correction value (i.e., the correction threshold that delivers the maximum ω for the basic FRR scheme) is reached. This implies that when δ is large, the aggressive reservation strategy becomes the more significant bandwidth wastage contributor, and the BEFRR scheme presents only marginal bandwidth enhancement capability.

The above conclusions also hold in Fig. 4, which plots the relationship between the bandwidth usage efficiency and the BHP pre-transmission success probability (P_s). As observed, both BEFRR scheme and the basic FRR scheme yield similar ω as P_s approaches 100%.

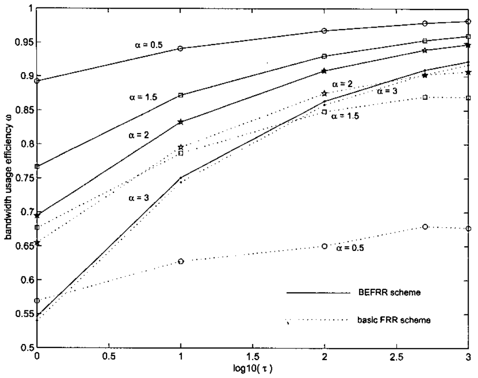

Fig. 5. The bandwidth usage efficiency versus the burstification duration

Another advantage of the BEFRR scheme is that it enables the aggressive strategy to perform more straightforward control on the bandwidth usage efficiency, as illustrated in Fig. 5. Specifically, the BEFRR scheme makes ω to be more proportional to the correction value δ. For example, in the basic FRR scheme, when $\tau = 100$, the bandwidth usage efficiency delivered by $\alpha = 2$ is higher than that both by $\alpha = 1.5$ and $\alpha = 3$ (note that $\delta = \alpha \cdot \sigma$). On the contrary, in the BEFRR scheme, a larger α value (i.e., the larger correction value δ) results in the higher ω value.

The curves in Fig. 5 reinforce our conclusion that the bandwidth enhancement capability of the BEFRR scheme is reduced as δ increases. The bandwidth usage efficiency is largely improved by the BEFRR scheme when $\alpha = 0.5$, while when $\alpha = 3$, both schemes possess similar performance in terms of ω. This indicates that the advantages of the BEFRR scheme is particularly significant when the correction value is relatively small, while as δ increases, a proper plan for δ plays the more important role in the system bandwidth utilization.

V. CONCLUSIONS

In this paper, we have proposed a bandwidth enhancement mechanism for a recently introduced FRR scheme, and subsequently presented the BEFRR scheme which yields better system performance by allowing a CLEANUP message to nullify the pre-reservation requirement and performing the switching matrix configuration just-in-time. Theoretical analysis and simulation results have demonstrated the benefits of the proposed mechanism and the advantages of the BEFRR scheme.

Our major conclusions of this paper include:

1) The BEFRR scheme, in tandem with the VF-scheduling method, reduces the system bandwidth wastage due to the insufficient forward reservations at a low cost of signaling overhead, and enables the correction value to perform more straightforward control on the bandwidth usage efficiency.
2) The benefit of the bandwidth enhancement mechanism is more significant when the correction value is small (whereby the BHP pre-transmission fails with a higher probability), and decreases as the correction value increases. Both the BEFRR scheme and the basic FRR scheme deliver similar bandwidth usage efficiency when the correction value exceeds the optimal value.

Improving the bandwidth usage efficiency of the basic FRR scheme is an on-going research. The optimal solution for the correction value budget remains to be further studied.

REFERENCES

[1] J. Liu and N. Ansari, "Forward Resource Reservation for QoS Provisioning in OBS Systems," *Proc. IEEE Globecome 2002*, Nov. 17-21, 2002.

[2] Y. Xiong, M. Vandenhoute, and H. C. Cankaya, "Control architecture in optical burst-switched WDM networks," *IEEE J. Select. Areas Commun,*, Vol. 18, No. 10, pp.1838-1851, Oct. 2000.

[3] C. Qiao, "Labeled optical burst switching for IP-over-WDM integration," *IEEE Commun. Mag.*, Vol. 38, No. 9, pp. 104-114, Sept. 2000.

[4] L. Tancevski, S. Yegnanarayananm G. Castanon, and L. Tamil, "Optical routing of asynchronous, variable length packets," *IEEE Select. Areas Commun.*, Vol. 18, No. 10, pp. 2084-2093, Oct. 2000.

[5] M. Yoo, C. Qiao, and S. Dixit, "QoS performance of optical burst switching in IP-over-WDM networks," *IEEE J. Select. Areas. Commun.*, Vol. 18, No. 10, pp. 2062-2071, Oct. 2000.

[6] L. G. Alberto, *Probability and random processes for electrical engineering*, Addison-Wesley, 1994.

[7] V. Paxson, "Fast approximation of self-similar network," *Tech. Rep. LBL-36750*, Lawrence Berkeley National Lab, April 1995.