A Feedback-Controlled EDF Scheduling Algorithm for Real-time Multimedia Transmission

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Abstract. Real-time communication is important for time-critical multimedia applications. However, conventional real-time schedulers such as EDF (Earliest Deadline First) and RM (Rate Monotonic) are designed for task sets with sophisticated characteristics. They can perform well in the idea network with precise workloads. But, in a realistic network with shared bandwidth and unpredictable workloads, their performances may be poor. In this paper, a control-theoretical approach of EDF called BC-EDF (Buffer-Controlled EDF) is proposed to resolve the real-time scheduling problem in multimedia communications. Based on the feedback control ideas (that have been used successfully in systems with unpredictable workloads), BC-EDF utilizes the feedback of buffer-occupancy to prevent packet loss from buffer's overflow/underflow (whether its occupancy is prevented to run above/below the watermark). It can tolerate diverse system behaviors to provide reliable multimedia communications and playback quality. Experiments show that BC-EDF outperforms other schedule mechanisms that don't reflect on the changes of buffer-occupancy.

***Keywords*:** feedback control, buffer-occupancy, EDF, real-time, multimedia communications.

1. Introduction

Multimedia applications such as digital library, home shopping, distance learning, VOD (video-on-demand), and VC (video-conferencing) are attracting great attentions. Different from conventional text/image applications, end-to-end quality-of-service (QoS) is necessary for multimedia application to provide jitter-free playback of audio and video. In such time-critical applications, real-time communication is one of the most important parts for transporting media data from server to clients. For achieving QoS-guaranteed communications, real-time protocols and real-time networks are necessary. In past years, many real-time protocols have been proposed [7]. EDF (Earliest Deadline First) is one of the best-known real-time scheduling algorithms for these protocols. In EDF, the task priorities depend on the closeness of their deadlines. Theoretically, it can guarantee optimal delay performance if a deterministic real-time network is provided [9]. In definition, a reliable real-time network should display bounded and known message delivery delay in the presence of distributing factors such as overload or faults. To achieve such a bounded delivery delay, a lots of points must be taken into account: traffic pattern, latency classes, LAN sizing/parameterizing, and application-level load/flow control [8].

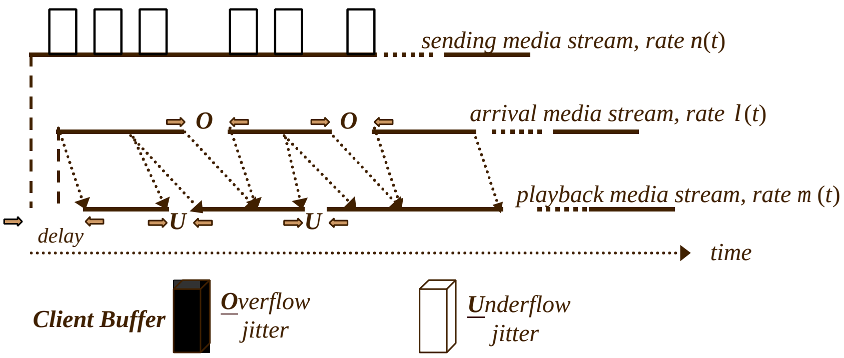

Fig. 1. A simple example to show that traffic jitter is related to buffer overflow and underflow..

Modern network environments are open and unpredictable. Under the consideration of cost-effectiveness, the bandwidth of the public network backbone is shared by all kinds of applications to achieve the statistical multiplexing gain. It introduces considerable uncertainty in workload and resource requirements. While delivering a packet through the network, the delay and jitter is unpredictable even if the packet is not lost. Although conventional algorithms can perform effectively under accurate workload/resource requirements [6], they may not be good for the load sharing networks as shown in Figure 1. Though some mechanisms [11][12] are introduced to smooth the traffic flow as a pre-specified transport function to reduce the jitter impact, they assume the deterministic of network/client behaviors. Due to the dynamics of the multimedia communication system, we indeed need a new real-time scheduling mechanism to formulate the dynamic behaviors of network/client for preventing the degradation of playback quality.

Feedback control ideas, those gain momentum as a promising foundation to control the uncertainty, have been used successfully in computer systems with complex and unpredictable workloads. Recently, some literatures [4][5] tried to apply the feedback control mechanism to the real-time scheduling problem. Their experiments demonstrated the effectiveness of the feedback control mechanisms in achieving predictable system performance without precise knowledge of worst-case load patterns. However, they did not consider the influence of buffer and its occupancy for client and network congestion control in real-world multimedia applications. Different from CPU scheduling [5], the dynamic of buffer-occupancy plays an important role in network scheduling. As the buffer size is limited, the client has to stop decoding and displaying while playback running out of packet in the buffer to decode. Likewise, the incoming packet will be discarded if it is flooding the buffer. Therefore, the underflow and overflow of client buffer introduced by the delay and jitter in transporting packets also reflect respectively delay and jitter while playback decoding. They may jeopardize seriously the playback quality; especially, while the clients preserve very limited buffer resources (such as set-top box, wireless PDA and cellular phone).

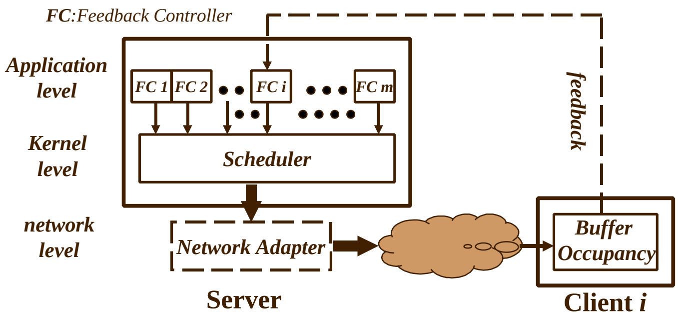

Fig. 2. Architecture of BC-EDF.

In this paper, a control-theoretical approach of EDF called BC-EDF (Buffer-Controlled EDF) is proposed to resolve the real-time scheduling problem for multimedia communications. Note that the schedulers are usually deployed on the kernel space in operating systems. They are designed to schedule all tasks in CPU, cache/memory and disk to achieve optimal performance in all aspects. However, the non-PD-control feedback control of buffer occupancy is deployed in applications [3][15]. To fit system implementation, we decompose the proposed BC-EDF scheduler into two components: application-level feedback controller and conventional EDF scheduler, as shown in Figure 2. Note that the separation of application-level control policy and the system-level schedule method can let controller and scheduler work independently. It will allow arbitrary combinations of control and schedule mechanisms in system implementation. In BC-EDF, we utilize the feedback of buffer-occupancy to predict buffer's overflow/underflow and to prevent the degradation of playback quality. By evaluating the changes of buffer-occupancy, the controller (that related to each transport stream) decreases/increases packets' *transport deadlines* to adjust stream's sending rate up/down[3]. (Such a kind of feedback controller is called *deadline-modifier* in this paper.) After modifying packets' deadlines, an EDF scheduler is then applied to select the most suitable packet for delivery to prevent buffer's overflow/underflow. It can tolerate unpredictable system behaviors to provide reliable multimedia applications.

Note that at the initial time, the priority queue of the EDF scheduler (it is a heap data structure) can be constructed in O($m$log$m$) time where m is the number of active media streams in the server system. The actions of extraction (to select the packet with closest deadline) and insertion (to schedule a packet into the queue) cost only O(log$m$) time. In this paper, our problem objective is to achieve the best playback quality. We need to successfully transport as many data packets as possible through the non-deterministic network. Experiments show that our BC-EDF approach successfully applies elements of control theory to real-time multimedia systems operating in uncertain environments. It outperforms other schedule mechanisms that don't reflect on the changes of buffer-occupancy. In Section 2, we introduce the feedback control mechanism and the proposed BC-EDF algorithm. The impact from the real-world dynamic environments to our system is also presented. The experiments and performance results of our proposed method are shown in section 3. In section 4, we analyze the proposed algorithm by mathematical proof. The last section is our conclusions.

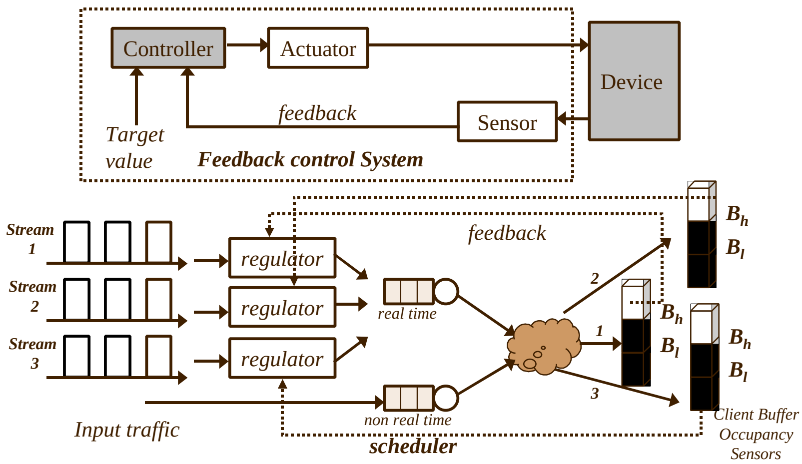

Fig. 3. A feedback control approach of multimedia communications..

[3] The communication flow control can be rate-based or window-based. In time-critical multimedia applications, it should be rate-based rather than window-based.

2. Buffer-Controlled EDF scheduler

In this section, firstly we describe the system components of the proposed buffer-controlled EDF scheduler: kernel-level network scheduler and application-level feedback controller. Secondly, we present the applied control theories in the feedback controller for multimedia communication. The proposed algorithm for BC-EDF is described lastly in this section.

2.1 Network Scheduler and Feedback Controller

The basic architecture of a multimedia communication system is shown in the lower diagram of Figure 3. For each media stream, there is a sequence of data packets waited to be transported. As they are already in an EDF order, the regulator needs only consider the first un-transported packet in the media stream to assign it a suitable *transport deadline*. Basically, the transport deadline should be the *playback deadline* minus the time of workload needed for delivery (called *relative deadline*). It depends on the network dynamics in doing transportation. However, in the network cloud, the system dynamics that come from such as packet lost or packet out-of-sequence are unpredictable. We need feedback information that provides network dynamics to predict the workloads and to support a good regulator. As shown in the upper diagram of Figure 3, The feedback control system can be described by a device to be controlled, a actuator and a sensor. Timely, the system monitors and compares the error between the current value and the target value of the sensor. If necessary, the controller will perform a feedback function to the system based on this error. An adaptive algorithm is introduced to support applications in dynamic uncertain environments.

Note that in multimedia communications, each client has only a limited buffer. The incoming packets will be discarded while they are flooding the buffer and delayed to playback while buffer running underflow. They introduce complex system dynamics. In this paper, we regard the scheduler as a controller, and use buffer's occupancy to predict its overflow/underflow. The target value of sensor is just a threshold of buffer-occupancy. In this paper, we use the low threshold b_l and the high threshold b_h of buffer-occupancy to foresee the chance of buffer overflow and underflow. Let the target value of buffer-occupancy be b_m where b_m is defined as the middle point of b_l and b_h. Based on the feedback control theory, at any time t, our algorithm controls the buffer-occupancy $b(t)$ to be running close to b_m. Therefore, the scheduler can prevent buffer overflow/underflow to achieve satisfactory playback quality.

2.2 Control Theory for the Multimedia Communication

Note that the running position of buffer-occupancy depends on not only its current value $b(t)$ but also the rate-difference $r(t)$ between packet arrival rate $l(t)$ and packet playback rate $m(t)$. We can define

$r(t) = \frac{db(t)}{dt} = l(t) - m(t)$. In this paper, by deploying the control theoretic concept, we pick up the function of PD (Proportional-Derivative) control as follows.

$$\frac{dr(t)}{dt} = -\left(b(t) + \frac{db(t)}{dt} - b_m\right) \times \frac{R_M}{b_m} \quad \textbf{(1)}$$

The given constant R_M represents the maximum rate-difference which the system can tolerate for the traffic burst while delivering packets to prevent the jitters and congestion in the network. The mathematical results conducted from Appendix show that, even $b(t_0)>b_h$ or $b(t_0)<b_l$, there exists a time period T let $b(t_0+T) \cong b_m$. We can control $b(t)$ starting at any $b(t_0)$ and finally converge close to the target value b_m in a short time period. Note that in real world applications, all the functions described above should be considered in discrete cases. The control function for discrete case should be rewritten as follows.

$$\Delta r(t) = -\left(b(t) + \frac{b(t) - b(t - \Delta t)}{\Delta t} - b_m\right)\frac{R_M}{b_m} \quad \textbf{(2)}$$

Without loss of generality, the proposed mechanism primarily focuses on the PD control model in this paper. However, it is not difficult to extend the proposed idea to the PID (Proportional-Integration-Derivation) control model. While considering the noise term, the control function can be updated as follows.

$$\Delta r(t) = -\left(b(t) + \frac{b(t) - b(t - \Delta t)}{\Delta t} + \sum_{\Delta t}(b(t) - b_m) - b_m\right)\frac{R_M}{b_m} \quad \textbf{(3)}$$

In Appendix, we have shown that the PD control model is good enough for our problem. Additionally, we have also proved that only proportional feedback (the P control model) can not prevent the oscillation condition. In a network system, the sending rate $n(t)$ can be defined as $n(t) = l(t) + q(t)$ where $q(t)$ represents the jitters or the packet loss. By applying the same idea, we can calculate the adaptation of sending rate $n(t+1) = n(t) + \Delta r(t) + \Delta q(t)$ where $\Delta q(t)$ is the picked up control function. For example, $\Delta q(t) = -(n(t) - l(t))* \varepsilon$ where $0 < \varepsilon < 1$ is a small constant.

2.3 Buffer-Controlled EDF Algorithm

As illustrated in Figure 2, in the proposed BC-EDF mechanism, the deadline-modifier will regulate the server's packet sending rate $n(t)$ by the timely feedback from the sensor. For example, the client sends server a feedback message indicated that the client buffer running below the low threshold b_l (or above high threshold b_h). The application at server side will update the sending rate for packets delivering from $n(t)$ to $n(t+1) = n(t) + \Delta r(t) + \Delta q(t)$. Without loss of generality, we assume all the packets among the streams are the same size 1. The relative deadline for the first un-transported packet in the stream will be changed from $1/n(t)$ to $1/n(t+1)$. (As packets in the same stream are already in the

EDF order, we can simply consider the first packet in the stream for scheduling.) Then, the EDF scheduler will set the packet j with the transport deadline $d_j(t) = D_j - 1/n(t)$ where D_j is the playback deadline of packet j. A step-by-step description of the proposed deadline-modifier is shown as follows.

Algorithm: Deadline-Modifier

Listen the feedback from the controller.

if (a new feedback is obtained) **then begin**

Calculate Δr(t-1) and Δq(t-1) by following the proposed control functions.

Calculate ν(t) = ν(t-1) + Δr(t-1) + Δq(t-1);

Modify the deadline of packet $d_j(t) = D_j - 1/n(t)$;

end

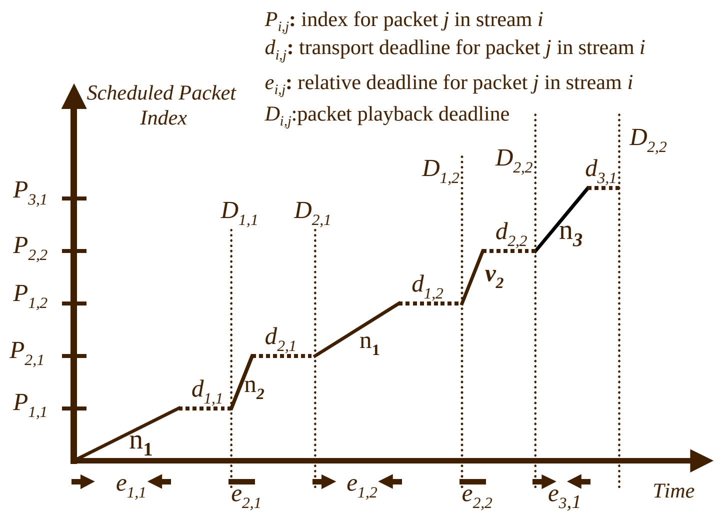

Fig. 4. Trace of packet deadline in deadline-modifier.

Note that, while m multimedia streams are served in the system, there are m packets (the first un-transported packet in each stream) falling into the EDF scheduler and asking scheduler to server them. The EDF scheduler will select the packet with the closest deadline for delivery. Note that at the initial time, the priority queue of the EDF scheduler (it is a heap data structure) can be constructed in O($m$log$m$) time. Then, we can simply perform the extraction function provided by the heap data structure to select the packet with closest deadline in deadline-driver priority queue. It requires only O (logm) computations time. Figure 4 illustrates an example of the trace of packet deadlines modified by the feedback controller. It can be found that every stream can be logically considered as a periodic task. In each time period, the transport deadlines of packets just represented its sending rate.

3. Experiments and Performance Results

In the following, we describe the details of the experiments, performance and evaluation for proposed BC-EDF. Besides, the related simulation results for the control function for BC-EDF in the Appendix are also discussed at the last subsection.

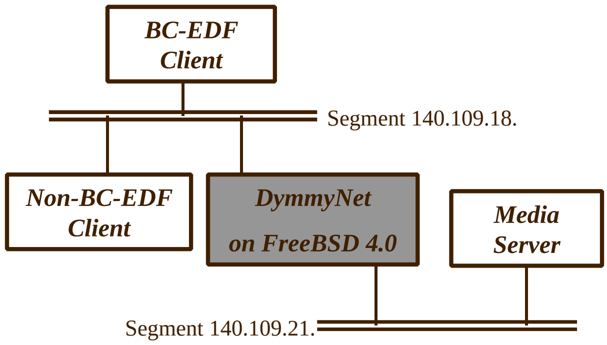

Fig. 5. The test bed applied.

3.1 Experiments for BC-EDF

In this paper, our test bed is based on the one proposed in our previous work [3]. As shown in Figure 5, in this test bed, the server system provides reliable true VOD (Video-on-Demand) services by applying application-level network control mechanisms with the feedback of client's buffer-occupancy. There are two clients are running in the test bed. The BC-EDF client is the client running our proposed PD-feedback-control mechanism with the server. The server will perform the discrete PD control function while receiving the buffer-occupancy feedback control from the BC-EDF client. Non-BC-EDF client's timely buffer-occupancy feedback control will request only the server to update the sending rate by just increasing or decreasing a constant (i.e. Δr equals 1K byte per second always). Note that both the BC-EDF and non-BC-EDF clients will send out the feedback control to server while the instance of the buffer occupancy running either above the high threshold b_h or below the low watermark b_l because considering the overhead of communication overhead for frequently feedback information to the server. Considering the network jitter and packet loss will introduce the noise term $q(t)$ from the difference between sending rate $n(t)$ and arrival rate $l(t)$ described in section 2, we assume the $q(t)$ remains constant most of time and then $\Delta q(t)$ is very close to zero (will be discussed in detail in the following section). Therefore, the algorithm of buffer-occupancy feedback controller should be rewritten for the experiments. Besides, considering the different rate control policies required on BC-EDF and non-BC-EDF clients in the experiments and their feedback controls sending to the same server, the revised algorithm of buffer-occupancy feedback rate controller running at server is presented as following.

Algorithm: Feedback Rate Controller

Declare c is a constant of rate adjustment for the non-BC-EDF client.

Declare ν_M is a constant of maximum sending rate for $\nu(t)$.

Program begin

Listen the feedback controller from the client.

if (a new feedback of latest instance of buffer occupancy b(t)is from BC-EDF client) then

$$\Delta r(t) = -\left(b(t) + \frac{b(t) - b(t - \Delta t)}{\Delta t} - b_m \right) \frac{R_M}{b_m}$$

else begin /* non-BC-EDF client */

if (b(t) is higher than b_h) **then** $\Delta r(t)=-c$

if (b(t) is below than b_l) **then** $\Delta r(t)=c$

end

if ($\nu(t-1)+\Delta r(t)$ is less than ν_M) **then begin**

$\nu(t)= \nu(t-1)+\Delta r(t)$

update the packet-sending rate to ν (t)

end

Program end

Assume that clients are running on a different network segment with the server. A router in which a Dummynet simulation tool [16] is running then connects these network segments. By applying this tool, we can approximate the network model to simulate different effects of finite routing queue, bandwidth limitation, communication delay and packet drop rate.

Note that the system dynamic may be changed at any time. For fair comparisons, we need to make sure the system dynamics applied in different tests are the same. In our experiments, we first assume that the same media stream is requested. The media content applied is a MPEG-1 file. It is a 30 minutes length of video with 292 MB in the file size. The packet size segmented for delivery is 1K byte. The arrival packet will be accommodated in a buffer unit at client. In the testing period, we record the variances of the sending rate according the response for the feedback control of buffer-occupancy. Additionally, the variations of running buffer-occupancy for each client are also recorded. In our experiments, the feedback controller is invoked every 500ms (i.e. $\ll T$, a short period T let $b(t_0+T) \cong b_m$, defined in section 2.2) to timely monitor and control the running buffer occupancy. The maximum sending rate of the VOD server is 183024 bytes/s (it is measured from the 1.5 Mbps bandwidth of the ADSL downstream that simulated by the Dummynet). Both of the BC-EDF and non-BC-EDF clients are set-top box machines with the same limited buffer size of b and b equals 200 buffer units (i.e. 200K bytes). The low watermark b_l is $b/4$ and the high watermark b_h is $3b/4$ in our experiments. The middle point of b_l and b_h is b_m and b_m is also aimed to the middle of buffer. Besides, the distances from overflow and underflow position on the buffer to b_h and b_l are the same. In statistics, the chance of overflow and underflow for these thresholds will also be the same in the long term.

To prevent the congestion on the path in the network clouds, media stream i of the applications will preserve itself a maximum sending rate constant n_M. The constant n_M for each stream will limit the possible non-decreasing sending rate updating for the aggregation of $n(t)+\sum\Delta r(t)$ while the obtained $\Delta r(t)$ remains positive for a long period without making the possible congestion condition worse in the network.

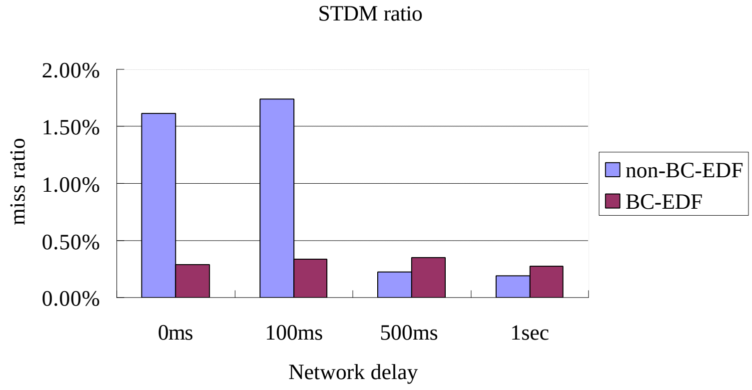

Fig. 6. Soft Transport Deadline Miss Ratio.

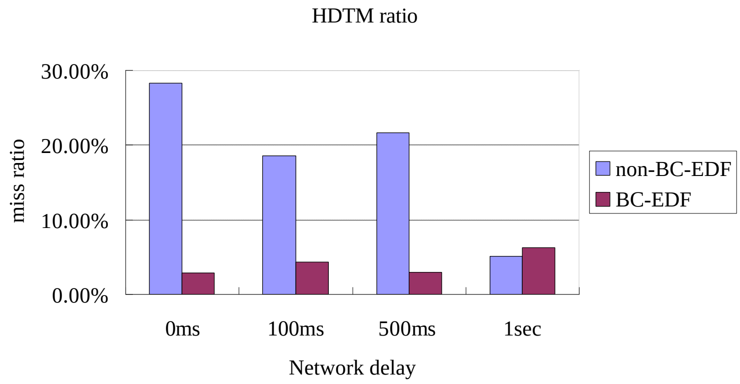

Fig. 7. Hard Transport Deadline Miss Ratio.

3.2 Performance Results and Evaluation

To measure the performance of our proposed BC-EDF mechanism, we first define the *soft transport deadline miss* ratio (STDM) as the ratio of buffer-occupancy flooding or draining the client buffer in the buffer-occupancy records. The *hard transport deadline miss* ratio (HTDM) is defined as the ratio of the buffer-occupancy running above the high watermark b_h or below the low watermark b_l respectively as the feedback controller are expected to maintain. We want to show that the buffer-occupancy of BC-

EDF are controlled to run within b_h and b_l in the best effort. Both STDM and HTDM obtained are smaller in BC-EDF in our experimental result. For showing STDM of buffer feedback is a kind of index of playback quality, we define the *hard playback deadline miss* ratio (HPDM) as the ratio of packets that miss their playback deadlines. While HPDM is reduced as STDM is decreased, we can apply the feedback control of buffer-occupancy to achieve better playback quality.

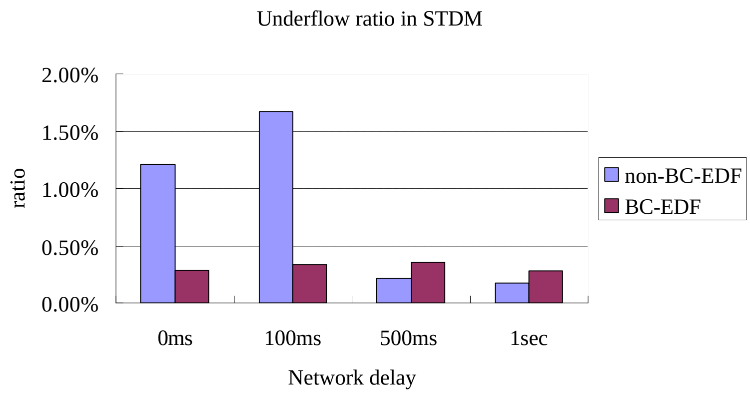

Fig. 8. Underflow Ratio.

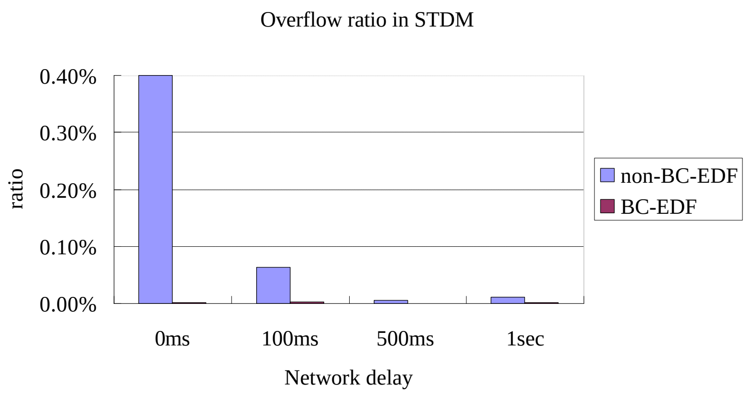

Fig. 9. Overflow Ratio.

Figure 6 and figure 7 show the experimental results of STDM and HTDM ratios while both the BC-EDF and non-BC-EDF client experience the delays for none, 100ms, 500ms and 1 second simulated by the Dummynet tool. The results show that the STDM ratios of BC-EDF for different lengths of delay are all less than 0.5% and are all very close to zero while no packet loss in the network. Again, while study the figure 8 and figure 9 for the underflow and overflow ratios in STDM ratios for BC-EDF and non-BC-EDF clients, we can find out most of the soft transport deadline misses in BC-EDF clients are conducted by underflow. According to our observation on the running buffer occupancies of the records in our experiments, most the buffer underflows are introduced at the beginning of the service while the feedback control system is not yet stable, non-BC-EDF is not stable either at that time. However, non-BC-EDF client suffers much more overflow than BC-EDF does. Therefore, the BC-EDF client should outperform the non-BC-EDF client under all the measurement criterions proposed in the experiments.

The experimental results indicate that the predictive BC-EDF mechanism of buffer-occupancy feedback control maintains low SPDM to prevent the hard playback deadline miss (HPDM) for playback QoS. Moreover, though FC^2-EDF [4] adds one more PID control to FC-EDF [5] to improve both the deadline miss ratio and CPU utilization, they did not consider the running buffer occupancies of the clients for multimedia communications to guarantee the real-time playback quality like BC-EDF.

3.3 The Simulation Results for PD control function

Note that the convergent function $b(t)$ obtained from the formulas in Appendix by Laplace transform on the proposed PD control function. The locus of the $b(t)$ indicates the running buffer-occupancy while start at $b(0)$. We apply different values for $b(0)$ starting at buffer unit 0, 50, 100 and 150 of buffer occupancy respectively and draw the curves of $b(t)$ respectively in the Appendix. Considering not to incur burst of packet sending while rate controller update the sending rate, the maximum rate difference R_M is limited to 2K bytes per second (i.e. 2 buffer units per second). Though the larger value of R_M indicates the faster the time to converge for buffer occupancy, it's not practical to apply large value of R_M in the network of sharing bandwidth. The large value of Δr derived from the large value of R_M in the PD control formula and consequently it may introduce huge traffic to worse the traffic burst or congest the network. In the experiment, different from the Appendix, we merely apply R_M with 2K bytes to keep the traffic smooth in spite of the consequence of the slow speed to converge. The initial rate difference r_0 sets zero for the assumption of packet arrival rate $\lambda(0)$ equals to playback rate $\mu(0)$ at the beginning. b_m is the target value of the adaptive control function and it equals 100 buffer units, so ideally all the loci of the $b(t)$ for different initial $b(0)$ will finally converge to b_m (as shown in the Appendix) and will be bounded in between the low watermark b_l=50 and high watermark b_h =150 in 90 second even if the worst case while buffer underflow or overflow at the beginning(i.e. $b(0)$=0 or 200). In the experiments for BC-EDF and non-BC-EDF, the server won't not update the rate as the buffer occupancy running within the interval $[b_l, b_h]$.

4. Advanced Analysis for BC-EDF

In this section, we present the analysis of BC-EDF scheduler, Network dynamic impact and the reliable communication issues for BC-EDF.

4.1 Analysis of BC-EDF Scheduler

The packet delivering in multimedia application provides a periodical task scheduling discipline. Theoretically, periodical task with period e_i can be feasibly scheduled by EDF if $\sum_{i=1}^{m}(x_i/e_i) \le 1$ [7] where x_i is the execution time for the packet scheduling task in stream i. That is to say, the BC-EDF scheduling system can provide EDF scheduler with schedulable task set all time under condition of $\sum_{i=1}^{m}(n_i \times x_i) \le 1$. In the real world multimedia server, the execution time x_i should be much smaller than the task period (i.e. $x_i \ll e_i$) and bounded to a constant (i.e. $x_i \le x_c$) since system always preserves the sufficient workload. Consequently we can find out the inequality $\sum_{i=1}^{m}(n_i \times x_i) \le x_c \sum_{i=1}^{m} n_i$. Now we rewrite the condition of scheduling feasibility for BC-EDF to $\sum_{i=1}^{m} n_i \le \frac{1}{x_c}$ regardless of the packet size. Moreover, $1/x_c$ can be represented as the minimum throughput to delivering the media packets for the server while system loaded. Therefore, we can conclude that the periodic task set is schedulable if the total sending rate for all media streams is less the minimum throughput while system loaded.

However, while all the real-time scheduling packets go beyond the public network and arrive at the client buffer, the playback quality can still not be guaranteed. Fortunately, via the experience of the buffer-occupancy control in the previous work [3], we the intuit the basics of both the applied feedback control theoretic function for buffer-occupancy $b(t)$ in section 2.2 and the sending rate control of deadline-modifier in section 2.3. The modified real-time task period e_i (i.e. $1/\nu_i$) will effect the sending rate; The revised rate for sending packet will effect the buffer occupancy; The feedback of buffer occupancy will again effect the deadline of the real-time task. Such an adaptive real-time scheduling life cycle will target to perform the playback QoS for multimedia communications. Therefore, though under uncertain network behaviors such as delay, jitter and loss may seriously degrade the performance of real-time scheduling and the playback QoS for multimedia clients, our proposed adaptive buffer-occupancy feedback control function can prevent these serious degradations as shown in the experimental results in the previous section.

4.2 Analysis of Network Dynamics

As mentioned before, open-loop EDF scheduler perform poorly in non-deterministic network because of the dynamics in the network clouds and clients. The dynamics include delay jitter, variations of running buffer occupancy and packet loss. The delay jitter is introduced by multiplexing gain on shared networks. The variation of running buffer occupancy is introduced by the rate difference between the buffering arrival rate l_i and the playback rate m_i (i.e. decoding rate) at client i. Actually the buffering arrival rate l_i is effected by the server sending rate ν_i. In the proposed algorithm of deadline-modifier in section 2.3, the sending rate $\nu_i(t)$ is ideally calculated by the summation of $\nu_i(t\text{-}1)$ and two delta functions obtained (i.e. $\Delta r(t\text{-}1)$ and $\Delta q(t\text{-}1)$) from the proposed control functions. But in the experiments for BC-EDF mechanism, the $\Delta q(t)$ is considered to be zero for the assumption of the network noise $q(t)$ remains invariant most of the time in the formula $n(t) = l(t) + q(t)$. In the following, we will show the reason why the $\Delta q(t)$ can be discarded in the proposed feedback rate control algorithm in the experiments.

$$r(t) = l(t-\Delta t) - m(t-\Delta t) + r(t-\Delta t) = n(t-\Delta t) - q(t-\Delta t) - m(t-\Delta t)$$

$$r(t+\Delta t) = n(t) - q(t) - m(t)$$

$$b(t+\Delta t) = b(t) + r(t) \times \Delta t$$

$$\therefore \Delta r = r(t+\Delta t) - r(t) = n(t) - n(t-\Delta t) - (q(t) - q(t-\Delta t)) - (m(t) - m(t-\Delta t)) = \Delta n - \Delta q - \Delta m$$

In our proposed BC-EDF mechanism, most of the time Δn is zero while the packet delivering task period is the same value $n(t)$ and $n(t\text{-}\Delta t)$. Δt is the period smaller than the period T of the feedback control. Δm represents the error of the playback rate and it should be close to zero for a reliable decoder providing a constant decoding rate. Therefore the Δr will equal to $-\Delta q$ while Δm and Δn are all zero. Then the next instance of running buffer occupancy will also compensate the $-\Delta q$ without violating the single feedback control function deployed in the experiments. Therefore, the control function for $\Delta q(t)$ can be approximately associated into a single $\Delta r(t)$ control function for the coming instance of buffer occupancy $b(t+T)$ will be partly reflected by the accumulated network noise $\sum_T \Delta q(t)$.

Both of the proposed rate control service discipline without feedback control by [11] and the feedback control mechanism FC-EDF by [4] did not consider the importance and dynamic of playback QoS at client side in the multimedia applications. Though literatures have provided evidences that control theoretic close-loop feedback control can adaptively achieve high performance in many aspects of application, they can not provide a unique solution for all kinds of applications. [11] proposes an idea to decompose the rate-controlled service discipline into rate-controller and scheduler without feedback control of QoS from client side. [4] provides a general feedback control to real-time scheduler for minimize the local deadline task miss ratio and maximize the CPU utilization. Their miss ratio can not represent the degradation of QoS such as buffer overflow and underflow. Event if they redefined the miss ration equals playback deadline, they still could not prevent the degradation in advance like our proposed BC-EDF. Our rate-based deadline modifier with buffer-occupancy will perform the adaptive job to fine-tune the rate-based deadline in the best effort. Therefore, proposed BC-EDF performs better playback QoS than other schedule mechanisms that they don’t reflect on the changes of buffer occupancy.

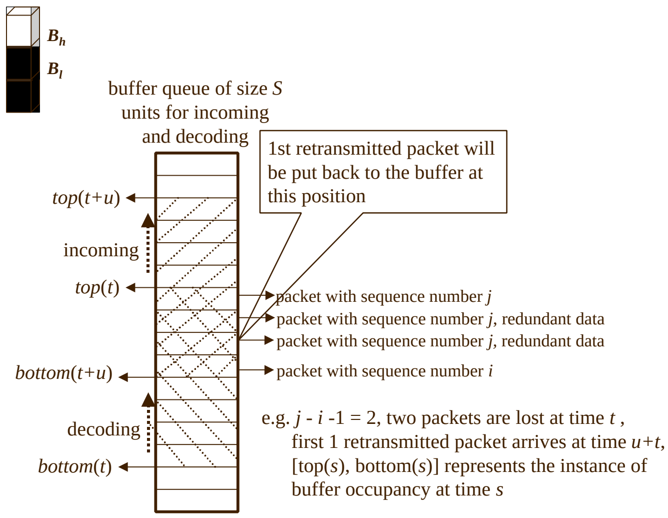

Fig. 10. Buffer-occupancy Control.

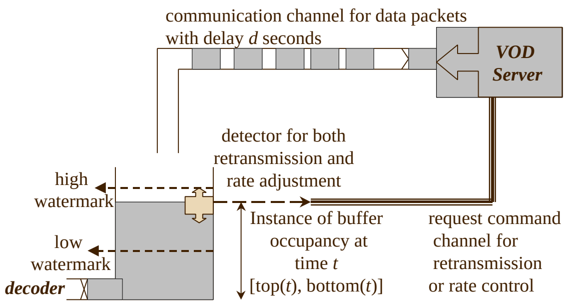

Fig. 11. Microscopic of buffer-occupancy control.

4.3 Reliable Communications in BC-EDF

Considering the deployment of the error control mechanism for packet loss in the reliable multimedia communications without violating the real-time constraints. The buffer-occupancy feedback deadline-modifier in our proposed real time multimedia service discipline will also help to achieve the reliable feature of error control. In Figure 10 and Figure 11, the diagram simply depicts the retransmission mechanism in the buffer occupancy mechanism for error control. Because the decoder will consume the buffer content in a FIFO manner, the retransmission packet should be sent out from server to client as soon as possible before client can not playback the retransmitted packet. Therefore, we reset the relative deadline of the retransmission packet to zero and it will be immediately scheduled to network by the scheduler right after the decoder receives the retransmission request. The higher the buffer-occupancy running higher more valid retransmission will be received at client. Valid retransmission is defined as a retransmission packet can be decoded in time while server retransmit the packet upon client's retransmission request. Invalid retransmission will also indicate overhead of network bandwidth and error control. The running buffer-occupancy can help to indicate if the client is too late to send the retransmission request to prevent the redundant traffic in the network. Moreover, we duplicate the latest received packet and insert into the buffer position where the lost packets should be put back. Even if these packets can not be put back in time, most of current decoder can tolerate such playback noise without fatal error and continues to decode and playback normally.

5. Conclusions

In this paper, we have proposed an end-to-end network scheduling mechanism BC-EDF by a control theoretic buffer-occupancy feedback control in real-time scheduling to achieve reliable real-time multimedia communications. The guideline of the schedule feasibility in BC-EDF is also proposed while system is loaded. Though EDF is an optimal uni-processor scheduling algorithm, the proposed two-tier mechanism allow to apply arbitrary combinations of control and schedule mechanisms in the required implementation for different kinds of applications.

The experimental results show that the proposed PD control function can highly control running the buffer occupancy on a very limited-size buffer in a real multimedia application sustaining different length of delay, one of the network dynamics. These results also show the improvement of playback QoS on client running while deploying the control theoretic feedback control function with real-time scheduler for real-time multimedia applications. The controllable of running buffer occupancy also support the stability showed in the simulation results for the proposed PD control function formula. Besides, the proposed error control mechanism would help to achieve a reliable real-time multimedia communication for BC-EDF.

Our proposed mechanism not only considers the real-time issue for providing reliable multimedia service by the rate-based BC-EDF scheduler and error control, but also the most important playback QoS at client side by buffer-occupancy feedback control.

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Appendix:

1. Proportional Control (P control):

$$\frac{db(t)}{dt} = r(t)$$
$$\frac{dr(t)}{dt} = -(b(t) - b_m)\frac{R_M}{b_m}$$

$$sB(s) - b_0 = R(s)$$
$$sR(s) - r_0 = \frac{-R_M \times B(s)}{b_m} + \frac{R_M}{s}$$
$$s^2B(s) - sb_0 - r_0 = \frac{-R_M \times B(s)}{b_m} + \frac{R_M}{s}$$
$$s^3B(s) - s^2b_0 - sr_0 = \frac{-sR_M \times B(s)}{b_m} + R_M$$
$$B(s) = \frac{s^2b_0 + sr_0 + R_M}{s^3 + \frac{sR_M}{b_m}}$$

$$\therefore b(t) = \frac{b_m\sqrt{R_M} + (b_0 - b_m)\sqrt{R_M}\cos(\sqrt{\frac{R_M}{b_m}}t) + r_0\sqrt{b_m}\sin(\sqrt{\frac{R_M}{b_m}}t)}{\sqrt{R_M}}$$

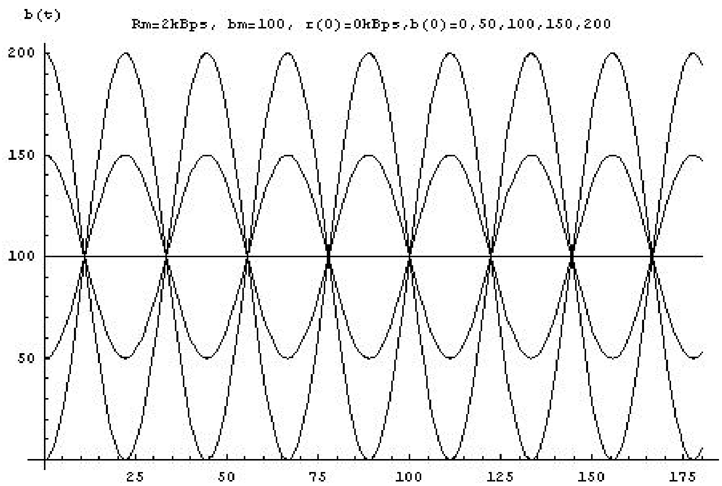

Fig. A12. ideal curves of $b(t)$ for P control only.

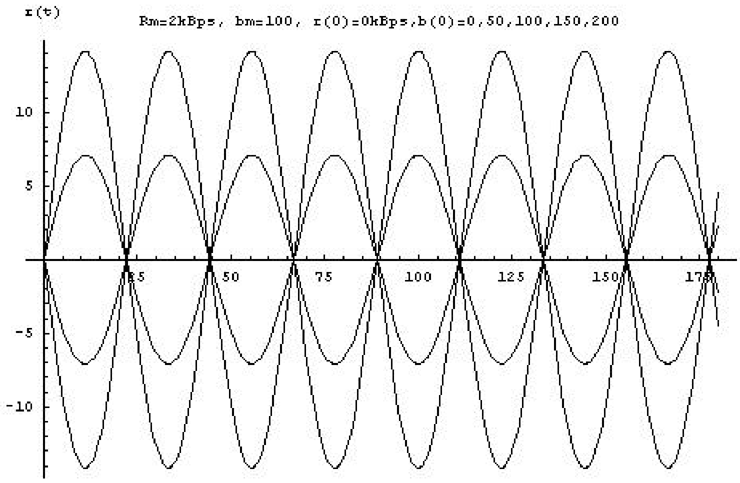

Fig. A2. ideal curves of $r(t)$ for P control only.

2. Proportional plus Derivation Control (PD control):

$$\frac{db(t)}{dt} = r(t)$$

$$\frac{dr(t)}{dt} = -\left(b(t) + \frac{db(t)}{dt} - b_m\right)\frac{R_M}{b_m}$$

$$sB(s) - b_0 = R(s)$$

$$sR(s) - r_0 = \frac{-R_M \times B(s)}{b_m} - \frac{R_M(sB(s) - b_0)}{b_m} + \frac{R_M}{s}$$

$$s^2B(s) - sb_0 - r_0 = \frac{-R_M \times B(s)}{b_m} - \frac{R_M(sB(s) - b_0)}{b_m} + \frac{R_M}{s}$$

$$s^3B(s) - s^2b_0 - sr_0 = \frac{-sR_M \times B(s)}{b_m} - \frac{s^2R_MB(s)}{b_m} + \frac{sb_0R_M}{b_m} + R_M$$

$$B(s) = \frac{s^2b_0 + sr_0 + \dfrac{sb_0R_M}{b_m} + R_M}{s^3 + \dfrac{s^2R_M}{b_m} + \dfrac{sR_M}{b_m}}$$

$$\therefore b(t) = b_m\left\{\begin{array}{l} 1 + (\dfrac{e^{\frac{-R_M+\sqrt{R_M(-4b_m+R_M)}}{2b_m}t}\left[-2b_0R_M + 2b_mR_M + \left(-R_M + \sqrt{R_M(-4b_m+R_M)}\right)r_0\right]}{R_M(-4b_m + R_M - \sqrt{R_M(-4b_m+R_M)})} + \\ \dfrac{e^{-\frac{R_M+\sqrt{R_M(-4b_m+R_M)}}{2b_m}t}\left[2b_0R_M - 2b_mR_M + \left(R_M + \sqrt{R_M(-4b_m+R_M)}\right)r_0\right]}{R_M(-4b_m + R_M + \sqrt{R_M(-4b_m+R_M)})} \end{array}\right\}$$

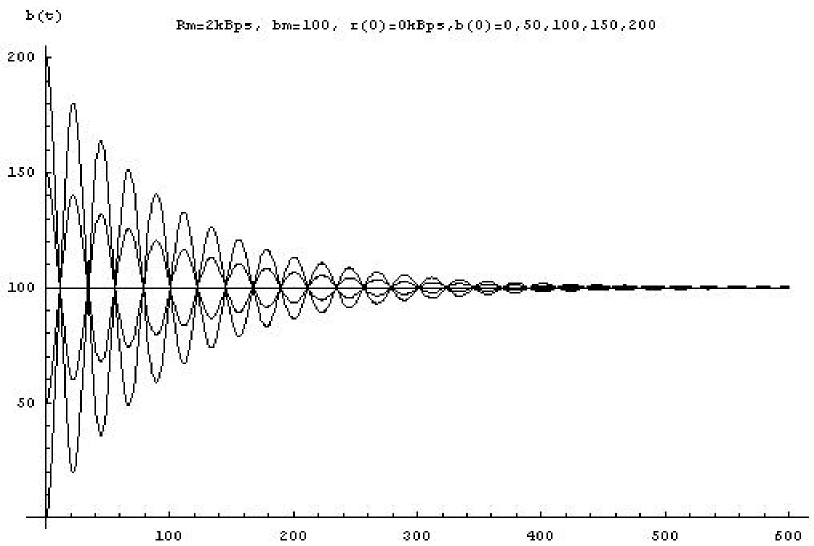

Fig. A3. ideal curves of $b(t)$ for PD control.

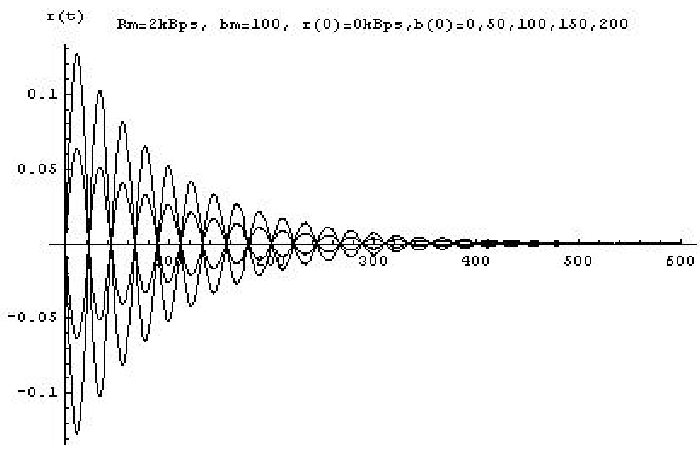

Fig. A4. ideal curves of $r(t)$ for PD control.