Adaptive Significance Classification for Streaming Video over Differentiated Service Networks

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Abstract. Although a Differentiated Service (DiffServ) network provides the Class of Service (CoS) delivery quality to real-time video data, the received picture quality may still be seriously degraded if it lacks an effective significance classification scheme for video packets. Moreover, even with a significance classification scheme, the performance could still be limited due to the use of a fixed set of parameters for videos with various coding characteristics. To solve above problems, this paper proposes an Adaptive Significance Classification mechanism in Temporal and Spatial domains (ASC-TS) for video data over DiffServ networks. ASC-TS determines the video packet significance simultaneously in temporal and spatial domains. From the temporal domain, ASC-TS evaluates the packet significance based on the estimated error propagation if a packet is lost. From the spatial domain, ASC-TS computes the packet significance based on the content complexity belonging to a packet. Moreover, ASC-TS is adapted to various video sequences with a self-learning mechanism. Compared with traditional significance classification schemes, simulation results show that the proposed mechanism can significantly improve the accuracy of signification determination up to 15% and effectively improve the received video quality up to 0.7dB in PSNR.

Keywords: Video service, differentiated service, video significance classification.

1 Introduction

With the advances in compression technology and network infrastructure, rich multimedia services have been dramatically boosted to users [1, 2]. The compressed Variable Bit Rate (VBR) video, one of the major components of most multimedia contents, is extremely vulnerable against packet loss, because the decoding error propagation will produce significant degradation in the quality of the following video frames. When a video packet that belongs to an I-frame is lost due to network congestion, all frames belonging to the same Group of Picture (GOP) are hurt due to error propagation in the decoding process. This phenomenon causes significant degradation of received picture quality. Moreover, all succeeding frames belonging to the same GOP are also hurt if a video packet that belongs to P-frame is lost, as shown in Fig. 1.

To deliver real time video data, many venders provide robust core/access routers and Layer 3 switches where the DiffServ [2, 3, 4, 5] framework was popularly implemented in this equipment. However, the fact that every video packet has various significance and different picture quality influence in the video decoding process generally complicates DiffServ operations. The congestion loss of video packets is possible in the DiffServ network if too many packets with the same class [6, 7] simultaneously arrive at an output port of router/switch. Those video packets that have high influence to receive picture quality must be well protected. Therefore, an effective significance classification mechanism for video packets at the sender side is required to prevent the unexpected packet loss to significant video packets in the DiffServ network [7, 8, 9, 10, 11, 12, 13].

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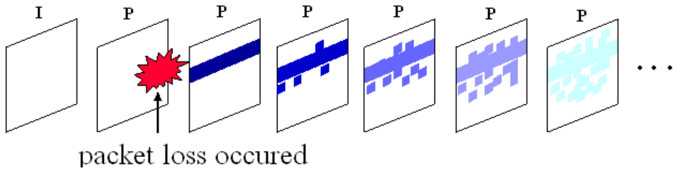

Fig. 1. Error propagation effect if a video packet of P-frame is lost

2 Related Works

In this area, many research results were developed in past years. In [10, 14, 15, 16], the frame type (I-/P-/B-frame) was used directly to classify the priorities of video packets. Video packets that belong to I-frames and B-frames always have the highest and the lowest priorities. However, the significance classification of packets in the same video frame is not considered. In [17], the error propagation influence of each video frame is estimated at the sender side according to its temporal position in a GOP. However, the method in [17] still ignored the significance diversity among packets in the same frame. In [18], the intra-refreshed MacroBlock (MB) technique is used to alleviate the error propagation. In the spatial domain, the content of each packet is evaluated to determine the packet significance, according to the ratio of the number of intra-refreshed MBs to the total number of MBs in a packet. However, the error propagation effect of each packet in the temporal domain is not examined in [18]. In [8], the authors analyzed the distortion effect of each lost MB and utilized a fixed model to approximate the statistic results. Nevertheless, a fixed model cannot satisfy the varied properties of video sequences. In [19], the authors determined the priority of a video packet according to the evaluation from temporal and spatial domains simultaneously. A weighting factor α ($0 \le \alpha \le 1$) was used to decide the proportion of spatial domain and temporal domain considerations. However, the value of α is not easy to decide since it depends on the complexity of video sequence. In [20, 21], the video frames were reconstructed before transmission under the assumption of a packet loss. This method can accurately evaluate the significance of video packets. However, the computational complexity and memory requirement are large.

To solve the above-mentioned problems, this paper proposes an Adaptive Significance Classification mechanism in Temporal and Spatial domains (ASC-TS) for video data over the DiffServ network. In contrast to conventional temporal-based or spatial-based priority assignment methods, the proposed method determines the video packet significance simultaneously in temporal and spatial domains. From the temporal domain, ASC-TS evaluates the packet significance based on the temporal position of the packet and the estimated error propagation if the packet is lost. From the spatial domain, ASC-TS computes the packet significance based on its content complexity, where the ratio of pixels referred by the next video frame to total pixels of current packet is used. More importantly, ASC-TS is adaptive to various video sequences with a self-learning mechanism. By learning the parameter *r* (error propagation ratio) for next GOP from current and previous GOPs, ASC-TS can estimate the error propagation property of each GOP in a video sequence dynamically. The remainder of this paper is organized as follows. The detailed process of the proposed scheme is presented in Section 3. Simulation environment and results are discussed in Section 4. Finally, Section 5 concludes this paper.

3 Significance Classification of Video Packets

3.1 Previous Work

The scheme in [17], in which we refer to it as Frame Based Classification (FBC) in this paper, is intended to evaluate the influence of lost video packets. In [17], while the *i*-th video packet of *k*-th video frame is lost, a distortion $D_{k,i}$ is computed at the decoder side, where $D_{k,i}$ is called the initial distortion of *i*-th packet of *k*-th frame. The total initial distortion of *k*-th frame is then computed by

$$D_k = \sum_{i=1}^{P} D_{k,i} \tag{1}$$

where D_k is the summation of initial distortion of each packet in the *k*-th frame and *P* is the total packet number of a frame. Obviously, such a distortion is propagated to the following frames. FBC assumed that the error propagation effect exhibits a nearly linear relationship to the following frames, as presented in (2). Therefore, the total error distortion *D* due to packet loss in the *k*-th frame would be expressed by (3).

$$D_k \approx D_{k+1} \approx D_j \ , k+1 < j \le N \tag{2}$$

$$D \approx (N-k) \cdot D_k \tag{3}$$

where D includes the initial distortion and the induced distortion due to error propagation and N is the GOP size in a video sequence. In [17], the Loss Impact (LI) of a given packet in the k-th frame is defined as:

$$LI_k = \sqrt{(N-k) \cdot D_k} \tag{4}$$

Note that each packet of the k-th frame has the same LI, which is independent of i-th packet, $i = 1,2,...,P$, and (4) cannot be appropriately used to wide video sequences because of fixed error propagation effect.

3.2 Analysis of Error Propagation Effect

Generally, various video sequences have different encoding properties, including motion vector and content complexity. To verify the efficiency of (4) in cases of video sequences with different characteristics, this work defines the video Quality Degradation of the k-th frame, QD_k. As shown in (5), QD_k represents the actual total distortion due to packet loss in the k-th frame,

$$QD_k = \sum_{n=k}^{N} \sum_{i=1}^{P} \Delta PSNR_{n,i} \tag{5}$$

where $\Delta PSNR_{n,i} = PSNR\left(f_{n,i}, f_{n,i}^{*}\right) - PSNR\left(f_{n,i}, f_{n,i}^{**}\right)$. $PSNR\left(f_{n,i}, f_{n,i}^{*}\right)$ is the reconstructed video quality while the i-th packet of n-th frame is accurately received and decoded. When the packet cannot be correctly decoded due to loss or error propagation, the resulted video quality is represented as $PSNR\left(f_{n,i}, f_{n,i}^{**}\right)$.

According to (5), this work further defines the Quality Degradation Ratio (QDR), as shown in (6). The QDR_k represents the degree of error propagation when packets of k-th frame are lost. A large value of QDR_k means that the distortion due to error propagation is serious. In case of $QDR_k = 1$, it represents that no error propagation occurs to the following frames when the packets in k-th frame are lost.

$$QDR_k = \frac{QD_k}{D_k} = \frac{\sum_{n=k}^{N} \sum_{i=1}^{P} \Delta PSNR_{n,i}}{\sum_{i=1}^{P} \Delta PSNR_{k,i}} \tag{6}$$

Since the variation of QDR among different GOPs is wide, this work defines the Normalized Quality Degradation (NQD) obtained from normalizing (6), as shown in (7). Here the basis of GOP is used.

$$NQD_k = \frac{QDR_k}{\underset{k}{Max}(QDR_k)} \tag{7}$$

Utilizing (7), this work can obtain the actual NQD value of each frame in a GOP and then obtain the NQD distribution of each GOP. Note that the distribution of NQD is over a GOP with size N, the same as in (6), because the error propagation effect is terminated by the I frame of the next GOP. Considering an example as shown in Fig. 2, we draw the NQD distributions of the first GOP of Stefan, News, and Akiyo video sequences, respectively. The horizontal axis represents the frame number that video packet loss happened. Each slice is packetized to a video packet in this paper. In Fig. 2, this work observes that all NQD distributions of three video sequences do not exhibit a linear relationship. Moreover, this work finds that different video sequences have various distortion distributions. Therefore, traditional classification schemes such as [17] that uses linear and fixed mathematics model cannot accurately describe the behaviors of error propagation, which may result in mistaken classification of packet significance (so-called QoS mapping [22]) for different video sequences. To solve the above problem, this paper proposes a model that can flexibly adjust a curve to approximate the NQD distribution of a video sequence in the following section.

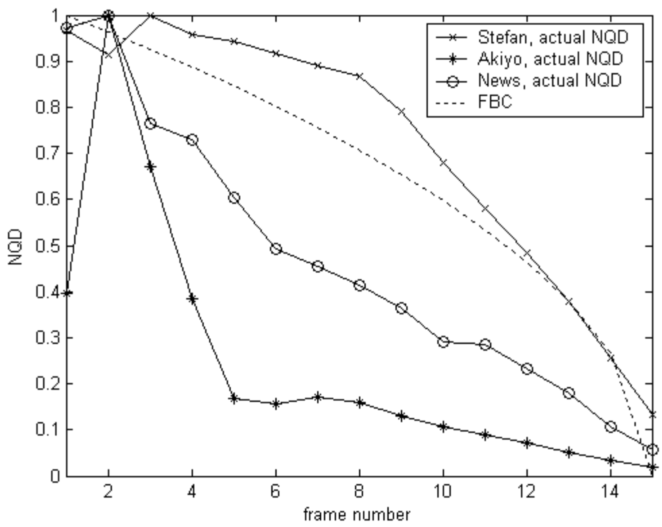

Fig. 2. Actual NQD distributions of different video sequences

To further classify the significance difference among packets in the same frame and enhance the approximation accuracy, SC-TS always buffers the current (k-th) and next ($k+1$-th) frames and computes the reference ratio (ref_pixel_j) of the j-th packet of $k+1$-th frame to the i-th packet of current k-th frame, as present at (11). $ref\_pixel_j = 1$ means that all pixels of i-th packet of current k-th frame are referred by j-th packet of next $k+1$-th frame.

$$ref\_pixel_j = \frac{\text{Number of pixels in i-th packet refered by j-th packet of k+1-th frame}}{\text{Total number of pixels in i-th packet of k-th frame}} \tag{11}$$

Therefore, the estimated QD_k^*, QDR_k^*, and NQD_k^* are further refined to (12)-(14) respectively and the basis to examine the quality degradation is packet instead of video frame.

$$QD_{k,i}^{**} = D_{k,i} + \sum_{j=1}^{P} \frac{\left(r^{NP_j} - 1\right)}{r-1} \cdot r \cdot D_{k,i} \cdot ref\_pixel_j, 0 \le NP_j \le N-k \tag{12}$$

$$QDR_{k,i}^{**} = \frac{QD_{k,i}^{**}}{D_{k,i}} = 1 + \sum_{j=1}^{P} \frac{\left(r^{NP_j} - 1\right)}{r-1} \cdot r \cdot ref\_pixel_j, 0 \le NP_j \le N-k \tag{13}$$

$$NQD_{k,i}^{**} = \frac{QDR_{k,i}^{**}}{\underset{k,i}{Max}(QDR_{k,i}^{**})} = \frac{(r-1)}{r^N - 1} + \sum_{j=1}^{P} \left(\frac{r^{NP_j} - 1}{r^N - 1}\right) \cdot r \cdot ref\_pixel_j, 0 \le NP_j \le N-k \tag{14}$$

Note that in (12)-(14) a new notation NP_j is used. Regarding the H.264 error resilient operations, the Cyclic Intra Refresh (CIR) and the Random Intra Refresh (RIR) mechanisms are provided. This work uses the CIR method and computes the Number of Propagated frames (NP) between the frame having a packet loss and the frame enabling the intra refresh coding operation in the same vertical position of the lost packet.

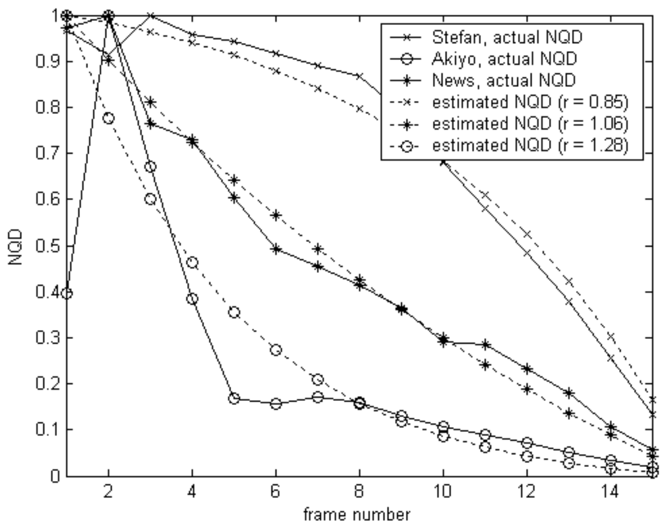

Fig. 3. Flexible significance of frame position

Given (14), the approximated QD value for the *i*-th packet of *k*-th frame, which is called *Significance Index* (SI) in this paper, can be easily obtained by

$$\begin{aligned} SI^{**}_{k,i} &= NQD^{**}_{k,i} \cdot D_{k,i} \\ &= \frac{D_{k,i} \cdot (r-1)}{r^N - 1} + \sum_{j=1}^{P} \left(\frac{r^{NP_j} - 1}{r^N - 1}\right) \cdot r \cdot D_{k,i} \cdot ref\_pixel_j, 0 \le NP_j \le N-k \end{aligned} \tag{15}$$

While computing the *SI* value with (15), no reconstruction work such as (5) is required. Obviously, employing (15) to obtain the $SI^{**}_{k,i}$ of *i*-th packet of *k*-th frame can efficiently reduce the computational complexity, buffer requirement, and additional computing delay, if the value of *r* is determined in advance based on the complexity of video sequence.

To verify the performance of SC-TS, this work examines the actual and estimated QD values of first 60 frames in Container sequence. We denote the *i*-th packet of *k*-th frame in a GOP as $VP_{k,i}$ and estimate the *SI* value of $VP_{k,i}$ by (15), where r =1.01 is used. On the other hand, the *LI* value of $VP_{k,i}$ is also estimated by (4) of FBC, and the actual QD value of $VP_{k,i}$ is computed at decoder side here. As shown in Fig. 4, the estimated QD values generated from the proposed SC-TS is more accurate than that of FBC, where three curves are normalized for comparison.

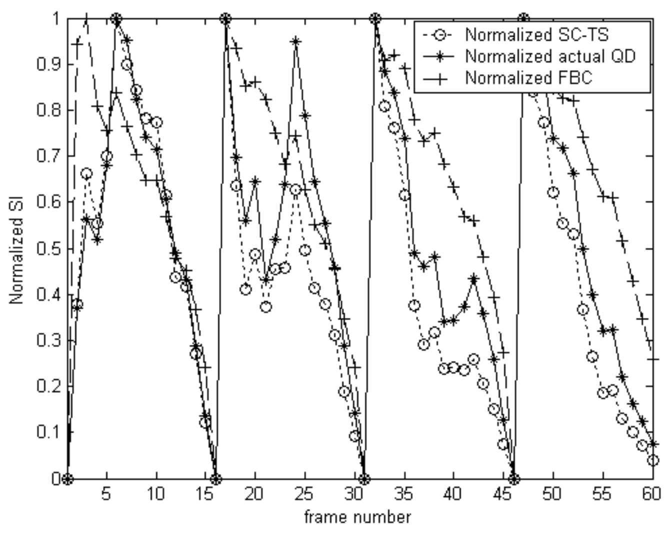

Fig. 4. Performance comparison of the proposed SC-TS method to FBC scheme

3.4 Adaptive Significance Classification in Temporal and Spatial Domains (ASC-TS)

Although SC-TS can provide the estimated QD value to each packet of a video sequence effectively, the current proposed method still requires selecting the suitable value of r for a given video sequence by complicated manual process. Therefore, this work further proposes the Adaptive Significance Classification in Temporal and Spatial domains (ASC-TS) mechanism to solve the above problem, where a self-learning algorithm is involved. The operation of ASC-TS is independent of the video sequence type and the value of r is automatically adjusted while each GOP begins in a video sequence.

The flowchart of the self-learning algorithm is shown in Fig. 5. Each GOP has two values of r in ASC-TS. One is the estimated r and the other is the actual r, which are expressed as r_{next} and r_{new}, respectively. The value of r_{next} is given when a GOP begins and is used to calculate the SI value of each packet in the GOP. On the other hand, the value of r_{new} is automatically computed whenever the encoding process for the GOP is finished. In general, the computed r_{new} of GOP_i will be the r_{next} of GOP_{i+1} directly. However, to reduce the undesirable oscillation phenomenon of r_{next}, a smoothing process is utilized in ASC-TS. If the difference between the r_{new} computed from current GOP_i and the mean value calculated from previous r_{new} is less than a threshold, the r_{new} computed from GOP_i will be the r_{next} of GOP_{i+1} directly. In contrast, if the above condition violates, ASC-TS will average the computed r_{new} of GOP_i to the mean of previous r_{new} values and the result is as the r_{next} of next GOP. In ASC-TS, the initial r_{next} and "Mean" are set to 0.99 for the first GOP of a video sequence and the current used r is denoted as $r_{current}$ in Fig. 5. Note that the initial value of 0.99 is determined by averaging the values of r of video sequences that belong to the Class B video type. In addition, to decrease the computational complexity for obtaining r_{new}, ASC-TS uses four frames, including the 2nd, 6th, 9th, and 13th frames of a GOP, to determine the value of r_{new}, where the positions of four frames are located to front, center, and rear of GOP. Moreover, for computing r_{new} value, extra memory with the size of GOP is required.

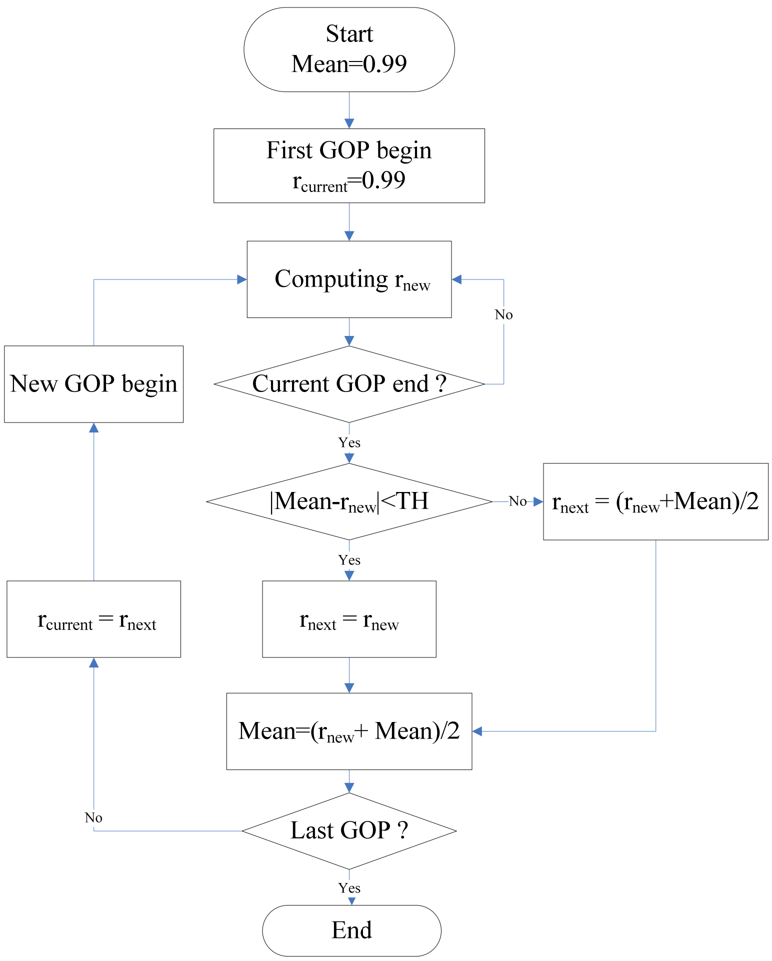

Fig. 5. The flowchart of ASC-TS

The robustness of ASC-TS is verified in Fig. 6, where three methods are compared with each other. Regarding the ASC-TS-upbound method, GOP_i is buffered at first, and the r_{new} of GOP_i is calculated and then assigned to the $r_{current}$ of GOP_i. Although the current GOP_i can use the most suitable value of r to estimate the QD values of packets, extra delay and additional computation complexity are generated in ASC-TS-upbound method. However, the results of ASC-TS-upbound can act as the upper bound in this simulation scenario. The second method is the ASC-TS-directly mechanism that the smoothing operations for avoiding oscillation of r_{next} are inhibited, where this work intends to examine the influence of oscillation of r_{next}. In Fig. 6, we observe that ASC-TS-directly method generates obvious oscillation of r in the range of 6^{th} - 9^{th} GOPs in Stefan sequence and the difference between ASC-TS-upbound and ASC-TS-directly methods is explicit. Similar situation results also happen in the case of Akiyo. In contrast to ASC-TS-directly method, the proposed ASC-TS algorithm decreases the oscillation effectively and the generated results of r are close to that of ASC-TS-upbound method. Even though some scene changes happen, the proposed ASC-TS algorithm still works well.

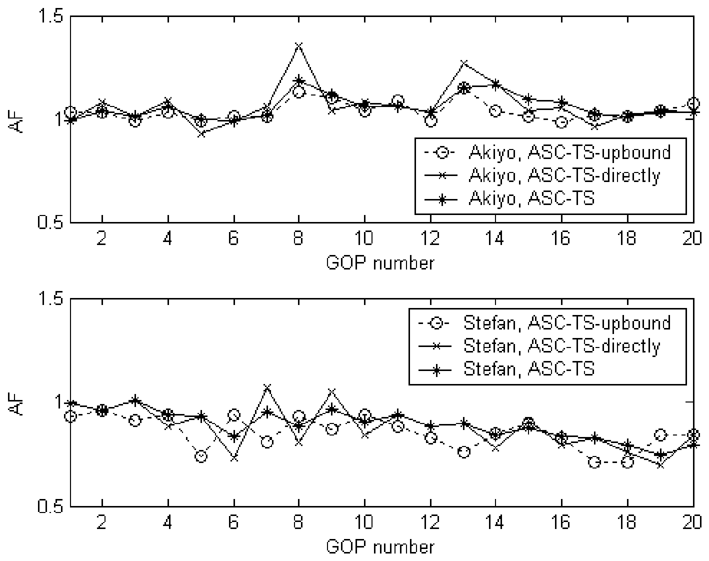

Fig. 6. Comparison of ASC-TS performance

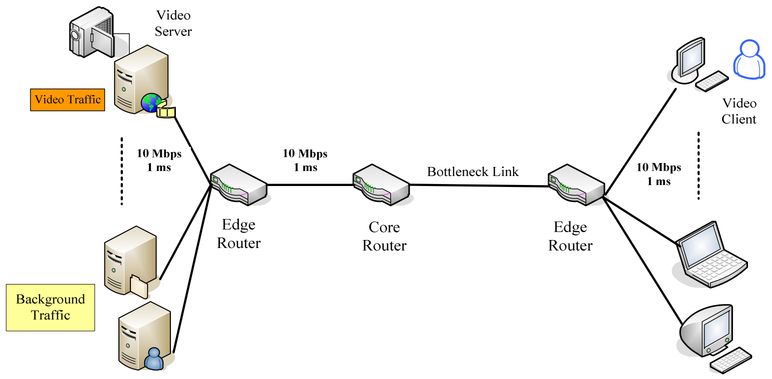

Fig. 7. Simulation architecture using NS-2

4.2 Simulation Environment

In this section, this paper uses Network Simulator version 2 (NS-2) to simulate the Diffserv network, and evaluates the performance of our proposed ASC-TS and FBC mechanisms. In these simulation cases, this work uses the H.264 JM10.2 codec and compresses videos at a target rate of 1M bps. The video format is CIF, the frame rate is 30 frames per second, and the length of video sequence is 300 frames. In addition, the length of GOP is set to 15 frames, IPPP video format is encoded, p frame only refer previous one frame, and the CIR mechanism is activated. The simulation architecture is shown in Fig. 7. Video flows have to compete with background flows, and three DiffServ levels are provided in the simulated network. A Weighted Round Robin (WRR) is also utilized here and Random Early Discard (RED) operation is activated for queue management.

4.3 Simulation Results

Using (16), Table 1, Table 2, and Table 3 first show the accuracy comparison of packet classification between the proposed ASC-TS mechanism and traditional FBC method in cases of LAB, MAB, and HAB, respectively. In these tables, two additional ASC-TS-directly and ASC-TS-upbound methods defined in Section 3.3 are used for comparison. In these simulation results, we observe that the accuracy of packet classification using ASC-TS is better than that of FBC up to 15%. Moreover, as mentioned in Section 3.3, the computational complexity of the proposed ASC-TS is less than that of ASC-TS-directly method. However, the accuracy of packet classification using ASC-TS is better than that of ASC-TS-directly method up to 1%.

Table 1. Accuracy of packet classification in case of LAB (%)

	FBC	ASC-TS-directly	ASC-TS	ASC-TS-upbound
Akiyo	85.78	93.57	93.91	94.89
Container	85.07	93.78	94.17	95.33
Foreman	76.61	88.54	89.11	90.98
News	88.13	93.41	93.7	94.67
Stefan	80.7	91.81	92.78	94.67
Bus	78.38	91.67	92.13	93.98

Table 2. Accuracy of packet classification in case of MAB (%)

	FBC	ASC-TS-directly	ASC-TS	ASC-TS-upbound
Akiyo	84.39	93.65	94.13	95.56
Container	84.67	93.33	93.56	94.87
Foreman	75.44	89.76	90.13	91.54
News	90.2	94.39	95.17	96.15
Stefan	80.07	91.31	91.78	94.41
Bus	75.79	91.85	91.94	93.29

Table 3. Accuracy of packet classification in case of HAB (%)

	FBC	ASC-TS-directly	ASC-TS	ASC-TS-upbound
Akiyo	84.57	93.96	94.37	95.41
Container	85.46	92.33	93.07	94.52
Foreman	76.94	90.28	90.93	93.02
News	91.76	93.72	94.65	96.06
Stefan	82	92.56	93.19	95.22
Bus	75.37	92.18	92.27	93.7

In the second simulation scenario, the classified packets by means of ASC-TS and FBC are delivered individually to the simulated DiffServ network and the received PSNR values are examined. Four network conditions with Packet Loss Rate (PLR) 5%, 10%, 15%, and 20% are considered in this scenario and two video sequences, Akiyo and News, are used. Observing in Fig. 8, the received video quality of Akiyo using ASC-TS is better than that of FBC up to 0.7 dB in LAB condition. Similarly, ASC-TS outperforms FBC up to 0.41 dB in case of News sequence. In Fig. 9, ASC-TS mechanism improves the received video quality up to 0.61 dB in Akiyo video sequence and up to 0.41 dB in News video sequence, where both are in the case of MAB condition. The same received PSNR improvement because of ASC-TS also occurs in the case of HAB condition as shown in Fig. 10.

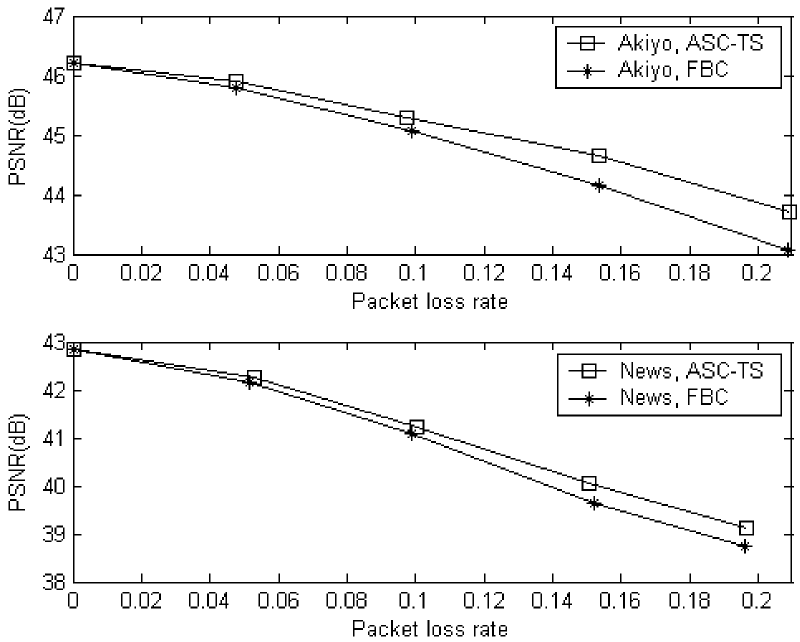

Fig. 8. Performance comparison of ASC-TS to FBC in LAB

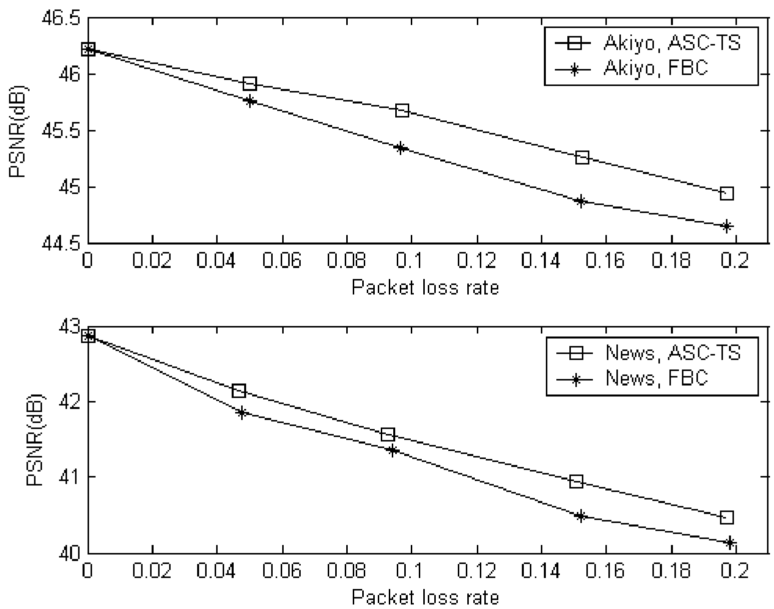

Fig. 9. Performance comparison of ASC-TS to FBC in MAB

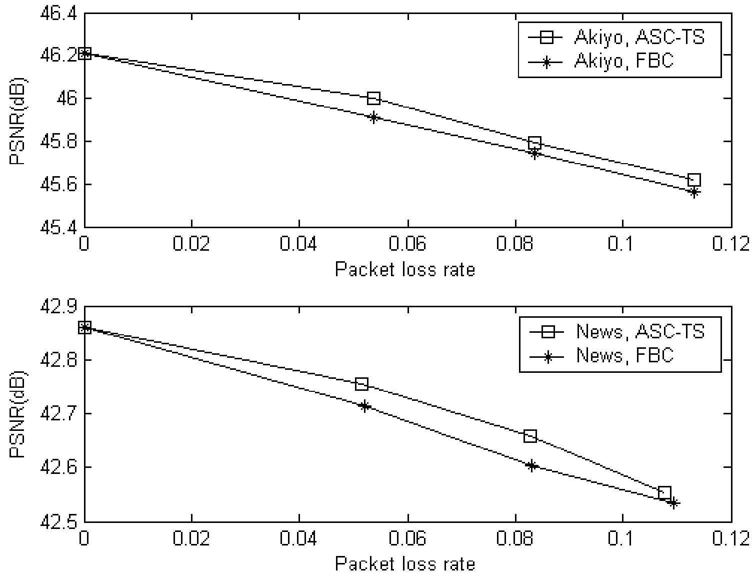

Fig. 10. Performance comparison of ASC-TS to FBC in HAB

5 Conclusions

The data of various video sequences always exhibits different significances and different error propagation characteristics because of various video-coding tools applied. Using a fixed model to classify the priorities of video data for various sequences is ineffective and thus degrades the received video quality due to undesirable loss of important video packets. The proposed ASC-TS mechanism adaptively and effectively solves above problems by evaluating the significance of video packets in temporal and spatial domains simultaneously with a self-learning process. Compared with traditional FBC scheme, the proposed mechanism can significantly improve the accuracy of significance classification up to 15%. Moreover, delivering video data with ASC-TS on DiffServ network outperforms FBC priority strategy up to 0.7dB in PSNR.

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