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Adaptive Scheduling for Wireless Video Transmission in High-Speed Networks

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***Abstract*—With the increase of wireless bandwidth, wireless video applications become more and more popular. A high speed core network is needed for large-scale applications to collect video from wireless terminals in a distributed way. It is necessary to guarantee video transmission in wireless networks because video data should be firstly transmitted via wireless channel. Since wireless bandwidth is still limited and fluctuates frequently, it is difficult to protect wireless video transmission. In this paper, we propose an adaptive cross layer scheduling schema to reduce video transmission distortion in IEEE 802.11e networks. Firstly, it is preferred to insert each video frame into the access category (AC) with minimum *relative queuing delay* to reduce transmission delay. Secondly, a *dynamic frame assignment algorithm* (DFAA) is proposed to guarantee the transmission of high priority frames efficiently, with the constraint of limited bandwidth. Finally, each parameter of DFAA is equipped with a fuzzy logic controller which can produce appropriate adjustment to reply quickly to the variation of video data rate, coding structure and network load. Extensive simulation results are presented to validate the effectiveness of our proposed scheme.**

Keywords-Adaptive video transmission; High speed networks; Fuzzy logic; Cross layer; IEEE 802.11e

I. INTRODUCTION

Technical advances in high-speed networks have presented extremely wide bandwidth, encouraging significant increase in Internet traffic. In particular, with the development of wireless access and multimedia compression technologies, great attention has been devoted to wireless video communications. More and more users employed wireless terminals with camera and enjoyed various video applications through wireless access networks and core networks. Since the number of users increases quickly and video applications always have tremendous amount of data, it is required for high speed core networks. For example, a large-scale video surveillance application needs a fairly wide bandwidth to collect video captured by wireless cameras in different places so as to perform analysis in the server. Under such circumstances, video data should firstly be transmitted through wireless networks and then to the server via high speed core networks. Therefore, one of the key technologies of wireless video transmission in high speed networks is to guarantee video transmission quality in wireless access networks.

Up to now, two issues still stand to be resolved in this field. The first problem is how to optimize video communications over wireless links with limited bandwidth. Since video streams require stringent bandwidth, packet loss is inevitable. It is essential to identify the importance of video packets so as to ensure the transmission of high priority packets. Consequently, ideas of cross layer design [1] and unequal protection [2], which pose a bright foreground for video communications, were addressed. At the application layer, packet importance is calculated and packet priority is marked. At the network or MAC layer, unequal packet/frame scheduling is performed to reduce video transmission distortion.

The second problem is how to provide flexibility to the variation of video data rate, coding structure or network load. Solution of this problem requires cooperation between network scheduling algorithm and video encoding algorithm, i.e., cross layer optimization. For example, Navaratnam et al. [3] proposed to control transport layer offered load for multimedia streams based on the degree of medium contention information at MAC layer. Qin et al. [4] proposed a scheme which can adaptively select the number of enhancement layers according to available buffer size, transmission time and other parameters. The second problem is more complicated because capture and fast reply to the variation are difficult to provide.

As for wireless MAC standard, IEEE 802.11 shows its deficiency of not be capable of providing differentiated guarantees for different services. To satisfy the distinct Quality of Service requirements of multimedia service and data service, IEEE 802.11e [5] which is composed of Enhanced Distributed Channel Access (EDCA) and HCF Controlled Channel Access (HCCA) was proposed. Quality of Service support in EDCA is realized with the introduction of four access categories (ACs), among which AC2 is defined for video service. Each AC has its own transmission queue and a set of parameters to contend for transmission opportunities. However, this standard only provides a static mapping between service types and ACs.

To enhance its flexibility, several studies addressed different mapping ways. Ksentini et al. [6] proposed another static mapping algorithm for video streams using H.264 codec. Different types of H.264 video packets are mapped to different ACs. If applied to MPEG-4 codec, I, P and B frames could be

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categorized into AC2, AC1 and AC0 respectively. The performance of static mapping fluctuates as video coding structure and network load vary.

To overcome the deficiency of static mapping, C. H. Lin et al. [7] proposed a dynamic mapping algorithm for MPEG-4 streams, in which video frames are dynamically mapped to the appropriate AC based on the importance of video frame and network load. No matter which type a video frame belongs to, the algorithm always tries to assign it to AC2. A frame will be assigned to a lower priority AC with a dynamic calculated probability when congestion occurs. Obviously, less important video frame has a larger demotion probability. Beside, this work employs two queue length thresholds (*threshold_low* and *threshold_high*) to identify network congestion level and to calculate demotion probability dynamically. Dynamic mapping, compared to EDCA and static mapping, reduces video transmission distortion and improves flexibility of IEEE 802.11e at a certain extent. However, this algorithm is not flexible to the variation of video data rate and coding structure. What is more, rules of choosing optimal parameters are not provided.

In this paper, an adaptive unequal protection scheme for video communications over IEEE 802.11e networks is addressed. Characteristics and contributions of this work are summarized in the following.

(1) We provide a *relative queuing delay* (D_R) based AC selection mechanism. D_R is an approximate value of actual queuing delay. Inserting video frame into the AC with minimum D_R will reduce the transmission delay of each frame as well as overall distortion of the video stream.

(2) We integrate the D_R based AC selection mechanism with a *dynamic frame assignment algorithm* (DFAA). DFAA takes *video frame priority*, D_R and *queue length* (the number of packets in a queue) of each AC as inputs to differentiate frames with different priorities and to provide efficient and dynamic protection of video frames according to the real-time network load. Simulation results show that DFAA reduces video distortion significantly, compared with other reformed schemes.

(3) The fuzzy logic controller (abbr. as "FL controller") is designed to produce appropriate adjustment of DFAA parameter so as to provide flexibility to the variation of environments. An FL controller decides parameter adjustment according to queue length of certain AC and the frame loss rates of certain frame priorities. Experiments validate that DFAA with FL controller could achieve a near optimal performance when the DFAA parameter is initialized with an arbitrary value.

The rest of the paper is organized as follows. System framework and more details of our schema are introduced in Section II. Performance evaluation and discussions are provided in Section III. Finally, Section IV concludes the paper and points out future work.

II. ADAPTIVE VIDEO TRANSMISSION SCHEME

Firstly, abbreviations and symbols frequently used in this paper are presented in Table I and Table II.

A. System Framework

As shown in Fig. 1, the proposed scheme utilizes the capacities of AC1 and AC0 to improve video transmission performance. DFAA is the key component. Congestion level of each AC is recognized by queue length. Video frame priority, D_R and queue length of each AC, and parameter adjustment are collected to help DFAA to be aware of real-time network load so as to decide which AC it should throw the frame in. D_R is calculated to represent actual queuing delay approximately. The FL controller takes statistical information within a time cycle (such as loss rates of video frames with different priorities) and queue length as inputs to determine quantitative adjustment of DFAA parameter for the next cycle.

Generally we use the term "*frame*" to refer to the frame of data link layer unless I, P, and B frames of MPEG-4 codec are discussed.

B. Relative Queuing Delay

To decrease transmission delay, a video frame should be assigned to the AC which has the shortest queuing delay. In IEEE 802.11e multi-queue model, frame queuing delay of an AC is proportional to the amount of queuing bytes and is inversely proportional to the scheduling opportunity of the AC. Although it is impossible to calculate the exact scheduling opportunities, the resulting average throughputs of different ACs within a long period under saturated circumstance can be adopted as their approximations. Let B_i denote the amount of

TABLE I. ABBREVIATION DESCRIPTION

Abbreviation	Description
AC	Access Category
DFAA	Dynamic Frame Assignment Algorithm
EDCA	Enhanced Distributed Channel Access
HCCA	HCF Controlled Channel Access
FL	Fuzzy Logic
ICM, Lin	Proposed scheme in [6] and [7]
avgPSNR	Average PNSR

TABLE II. SYMBOL DEFINITIONS

Symbols	Description
D_R	Relative queuing delay
T_2:T_1:T_0	Ratio of average throughputs of AC2, AC1, AC0
AC_{min}	The AC with the minimum D_R
AC_{mid}	The AC with the middle D_R
AC_{max}	The AC with the maximum D_R
$k_1, k_2, \ldots, k_n$	Queue length thresholds of AC_{min} and AC_{mid}
C_j	FL controller for k_j
l_j	Loss rate of the *j*th frame priority
R_2, R_1, R_0	Rate of traffic entering AC2, AC1 and AC0
R_v, R_{be}, R_{bg}	Rate of voice, best effort and background streams
R_I, R_P, R_B	Rate of I, P, B video frames
P_I, P_P, P_B	Dropping probability of I, P, B frames

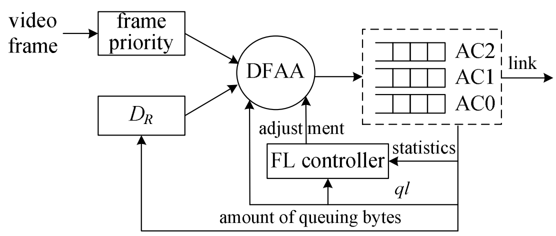


Figure 1. System framework of proposed scheme

queuing bytes in ACi and let T_2:T_1:T_0 denote the ratio of average throughputs of AC2, AC1 and AC0, D_R can be calculated as equation (1):

$$D_{Ri} = B_i / T_i, \tag{1}$$

where D_{Ri} denotes D_R of ACi. Notice that B_i is a real-time parameter while T_2:T_1:T_0 could be determined in advance. Let AC$_{min}$, AC$_{mid}$ and AC$_{max}$ denote the AC with the minimum, the middle and the maximum D_R among three ACs respectively. Notice that AC$_{min}$, AC$_{mid}$ and AC$_{max}$ vary in time.

C. Dynamic Frame Assignment

If we do not consider frame priority and try to insert each frame into AC$_{min}$, different types of video frame will have the same dropping probability. Since distortion caused by the absence of high priority frames is more significant, DFAA performs unequal protection for different types of video frames to decrease the dropping probability of high priority frames. In DFAA the frame priority, D_R and queue length of each AC are considered as scheduling parameters. The basic ideas are as follows: (1) Let D_R identify the priority of an AC. AC priority is inversely proportional to D_R. If congestion level is not high, try to insert each video frame into the AC with the highest priority. (2) Let queue length denote the congestion level of an AC. Define several thresholds for queue length of AC$_{min}$ and AC$_{mid}$, and match each threshold with a video frame priority. If real-time queue length is larger than the threshold correspondent to the frame priority, the video frame will be inserted into the AC with a lower priority.

DFAA scans AC$_{min}$ and AC$_{mid}$ in turn and determines whether a video frame could be inserted into one of them according to frame priority and real-time queue length of AC$_{min}$ and AC$_{mid}$. If both ACs are congested, the frame will be assigned to AC$_{max}$. DFAA is suitable for those video codecs who have limited priorities. To decrease the number of thresholds, AC$_{min}$ and AC$_{mid}$ can share thresholds. Assume a codec has n+1 priorities, then n thresholds (denoted as k_1, k_2, …, k_n; and k_1>k_2>...>k_n) are required. Algorithm I describes the details of DFAA.

D. Analysis of DFAA Parameters

Predetermined parameters of DFAA include T_2:T_1:T_0 and queue length thresholds. T_2:T_1:T_0 can be determined through experiment approximately. In this experiment, standard EDCA is employed. We set the bandwidth of IEEE 802.11e wireless link to 1Mbps. Data rate of voice is 64kbps (a rate commonly used) and data rates of the other three service types are 1Mbps respectively to produce a saturated link. The source, destination and packet length of various service types are uniform. From Table III we can find that the difference among various packet length settings is not distinct. We set T_2:T_1:T_0 to 9:3:1, a near optimal value.

In DFAA the protection level of a certain frame priority is mainly determined by its opportunity of entering AC$_{min}$. Thus the protection level of the highest priority is inversely proportional to the difference between the upper bound of queue length and k_1. And the protection level of the jth priority is proportional to the difference between k_j and k_{j+1}. Therefore, k_1 should be set to the upper bound of queue length to ensure the transmission of video frames with the highest priority. The optimal setting of k_j (j>1) depends on the coding structure and the network load. For example, if the proportion of the jth priority frames is large, it is necessary to increase k_j-k_{j+1} and to decrease k_{j-1}-k_j. If the network load is very heavy, k_2, k_3, ..., k_n should be set to a value near zero because maybe only the transmission of video frames with the highest priority could be ensured. On the contrary, k_2, k_3, ..., k_n should be set to a value near the upper bound of queue length to take full advantage of available bandwidth.

During the transmission of VBR video streams over IEEE 802.11e networks, video data rate, coding structure and network load may vary dramatically, i.e. the optimal settings of k_2, ..., k_n are dynamic. To find a near optimal setting, we address a fuzzy logic based self-adjusting scheme.

E. FL Controller

Each queue length threshold can be equipped with an FL controller. Since k_1 is always set to the upper bound of queue length, n-1 FL controllers (C_2, ..., C_n) are required. C_j is responsible for dynamic adjustment of k_j. Thus C_j influences the transmission of video frames with the j-1th and the jth priorities. Since the bandwidth of wireless links is limited, one controller will compete with the other controllers. To ensure the

Algorithm I: Dynamic Frame Assignment Algorithm (DFAA)

```
Input:
B_i, i=0,1,2; T2:T1:T0; queue length of AC_min and AC_mid
Priority of the video frame
Output:
AC assignment of the video frame
Procedure DynamicFrameAssignment
for (i=0;i<2;i++)
  D_Ri = B_i / T_i.
Determine AC_min, AC_mid and AC_max according to D_Ri
switch{priority} {
  case 1:
    if (queue length of AC_min < k1)         insert into AC_min;
    else if (queue length of AC_mid <k1)     insert into AC_mid;
    else                                     insert into AC_max;
    break;
  …………
  case j:  // 1<j<n+1
    if (queue length of AC_min < kj)         insert into AC_min;
    else if (queue length of AC_mid <kj-1)   insert into AC_mid;
    else                                     insert into AC_max;
    break;
  …………
  case n+1:
    if (queue length of AC_min < kn)         insert into AC_min;
    else if (queue length of AC_mid < kn)    insert into AC_mid;
    else                                     insert into AC_max;
    break;
  default:
   break;
}
```

TABLE III. EXPERIMENT RESULT OF T_2:T_1:T_0

Packet length(bytes)	T_2 (kbps)	T_1 (kbps)	T_0 (kbps)	T_2/T_1	T_1/T_0
200	410.76	136.31	48.06	3.01	2.84
500	532.59	161.15	64.30	3.31	2.51
1000	581.94	188.42	66.38	3.09	2.84

transmission of high priority frame, it is notable that FL controllers also have priorities. C_j will not be activated unless (C_2, …., C_{j-1}) work well, i.e. the loss rates of the former j-1 frame priorities are decreased to zero. As for a specified controller C_j, there are three inputs and one output.

(1) Input 1: loss rate of the j-1th priority, denoted as l_{j-1}.
(2) Input 2: loss rate of the jth priority, denoted as l_j.
(3) Input 3: real-time queue length of AC_{min}.
(4) Output: k_j adjustment.

Considering implementation of C_j, triangular membership functions are employed for inputs. Both l_{j-1} and l_j have five levels (*Low*, *Medium*, *High*, *Very high* and *Extremely high*). Value ranges of l_{j-1} and l_j are divided unequally (level "*Low*" has the smallest range) to decrease loss rate more quickly. Queue length of AC_{min} has three levels, called *Low*, *Medium* and *High*. The output uses singleton membership function and has seven levels including three positive, zero and three negative adjustments. To raise the protection level of the j-1th priority, step size of negative adjustments is set to a larger value than that of positive adjustments.

Principles for setting fuzzy rules are as follows:

(1) Try to decrease l_{j-1} and then try to decrease l_j under the circumstance of l_{j-1}=0.
(2) The k_j reduction is proportional to l_{j-1} and the k_j increment is proportional to l_j.
(3) The k_j reduction is proportional to queue length of AC_{min} and the k_j increment is inversely proportional to queue length of AC_{min}.

III. PERFORMANCE EVALUATION

Simulations are based on the integrated platform of ns-2 [8] and Evalvid [9], implemented by Chih-Heng Ke [10]. Network topology is presented in Fig. 2, in which wireless nodes $w0$~$w3$ are connected to AP via IEEE 802.11e link. Foreman (300 frames, 10 seconds) and football (176 frames, 6 seconds) with MPEG-4 codec and CIF resolution are adopted as test sequences. The frame rate is set to 30 frames per second. As Table IV shows, data rates of two sequences at each second are quite different. From Table V we can also find the difference of coding structures between these two sequences, i.e. foreman has more I frames and B frames with respect to football. Since there are three types of video frames, two queue length thresholds and one FL controller should be deployed accordingly. The FL controller is responsible for adjusting k_2 to reduce dropping probability of both I frames and P frames. Bandwidth of IEEE 802.11e link is set to 4Mbps.

In the first experiment, the performance of four schemes is studied: (1) standard EDCA; (2) static mapping [6], denoted by ICM; (3) dynamic mapping proposed by C. H. Lin [7], denoted by Lin; and (4) DFAA without FL controller. Two queue length thresholds of DFAA and Lin are both set to 50 and 25. *Prob_I*, *Prob_P*, *Prob_B* of Lin are set to 0, 0.3 and 0.6 respectively. To make a comprehensive comparison, video sequences are transmitted under the following three scenarios.

(1) Streams of four service types are transmitted from $w0$~$w3$ to B respectively.

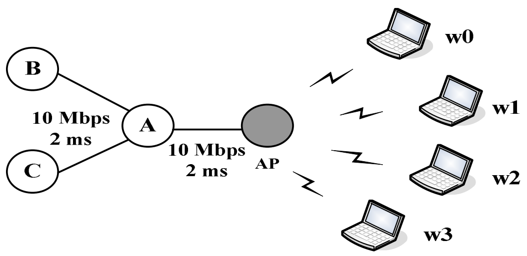


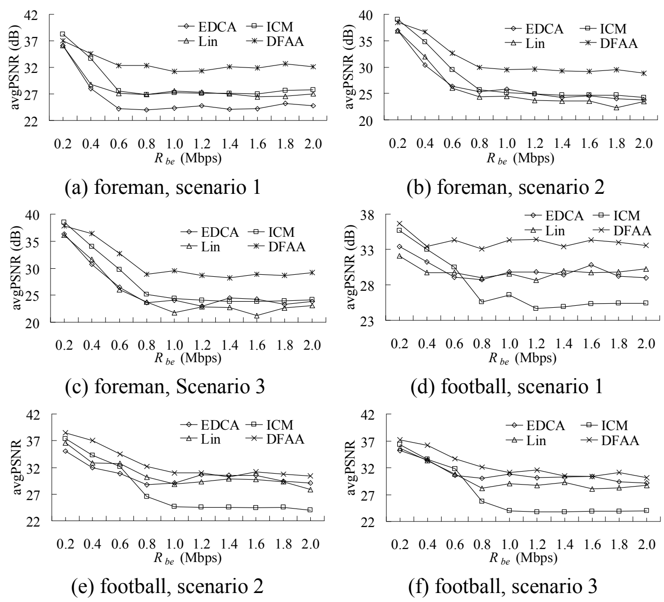
Figure 2. Simulation topology

TABLE IV. DATA RATES OF TWO SEQUENCES AT EACH SECOND

Second No.	Data rate (foreman)	Data rate (football)	Second No.	Data rate (foreman)
1	2209.54	3368.70	7	2573.90
2	1997.00	3342.50	8	2594.45
3	2102.40	1727.28	9	2924.42
4	2111.65	1713.87	10	2723.00
5	2181.50	2448.97		
6	2322.80	2669.00		

TABLE V. TOTAL BYTES OF I/P/B FRAMES

type	foreman	football
I frames	1094951	472474
P frames	1318951	1313338
B frames	583988	4367



(a) foreman, scenario 1 (b) foreman, scenario 2 (c) foreman, Scenario 3 (d) football, scenario 1 (e) football, scenario 2 (f) football, scenario 3

Figure 3. Average PSNR comparison of two sequences in three scenarios

(2) Four streams are uniformly transmitted from $w1$ to B.
(3) Streams are transmitted from B to $w0$~$w3$ respectively.

Since the decoding effects of I, P and B frames are quite different, the overall frame loss rate can not reflect video transmission distortion. Thus average PSNR is employed as the unique metrics in our evaluation.

Fig. 3 shows the average PSNR (avgPSNR) variation as data rates of best effort (R_{be}) and background traffic (R_{bg}) increase. Notice that R_{be}:R_{bg} remains to 2. From this figure we can find that avgPSNR of four schemes go down dramatically at first and then turn steady as R_{be} and R_{bg} increase in every case. As we know video frames will occupy scheduling opportunities of BE and BG streams especially when R_{be} and R_{bg} are low. Thus the number of video frames entering AC1 and AC0 reduces as R_{be} and R_{bg} increase. However, effect of increasing R_{be} and R_{bg} continuously after they reach the capacity of AC1 and AC0 is not notable because almost all increasing frames are dropped.

Table VI gives the average avgPSNR improvements of DFAA compared to other schemes in each case, in which we can find that DFAA reduces the transmission distortions of both sequences greatly. Fig. 3 and Table VI verify the analysis that existing schemes are not adaptive to the variation of environments. EDCA has a good performance when R_I is low (football) and ICM is suitable for the case in which R_I is high (foreman). Also the performance of ICM with football sequence is not bad when R_{be} and R_{bg} are relatively low. On the other hand, it is difficult for Lin to achieve better performance with respect to EDCA and ICM. Table VII-VIII, which depict packet loss numbers of different frame type in two cases when R_{be}=1Mbps, presents the reason. Lin always has the lowest overall packet loss rate, but significant P_I increment degrades its performance. Although P_I of ICM in both cases are 0, too many P and B frames are dropped. DFAA achieves a good balance between P_I and P_P/P_B.

Experiments below are all performed in scenario 1. From Fig. 4 we can find that k_2=25 is not suitable for every case. To achieve better performance, k_2 should be set to 10 when foreman is transmitted in a 3Mbps wireless link while it should be set to 45 for football in a 4Mbps link. The results verify the analysis that fixed parameter is not flexible to the variation of data rate, coding structure and network load. Furthermore, despite the issue of which value should k_2 be set to, the performance difference when applying various k_2 is remarkable. The maximum differences between two k_2 settings when R_{be}=2Mbps in four cases are 2.25, 0.74, 4.25 and 4.23.

Then we pay attention to the performance of DFAA with FL controller (abbr. as "DFAA-FL"). Since DFAA-FL could adjust k_2 according to the variation of environments, it is expected to provide the following advantages: (1) Achieve a near optimal performance; (2) Have a steady performance no matter which initial value is employed for k_2, so that k_2 can be initialized with an arbitrary value.

In this experiment, the adjustment cycle is set to 0.5 second while R_{be} is set to 2Mbps. Table IX shows the avgPSNR variation of DFAA-FL when k_2 is initialized with different values. Unlike the results of Fig. 4, the performance of DFAA-FL keeps relatively steady in each case as initial value of k_2 varies. It is notable that in some cases (case 1 and case 2) the performance of DFAA-FL may be better than any solution with fixed k_2 in Fig. 4. Also the performance may be close to the best one among DFAA-10, DFAA-25 and DFAA-45 in other cases (case 3 and case 4), indicating that DFAA-FL can achieve a near optimal performance.

Finally, Fig. 5 shows the adjustment details of k_2 as the simulation goes on when deployed with different initial value. From the figure we find that the variation of k_2 depends on link congestion greatly. When video sequences are transmitted in 3Mbps wireless links, frame loss rate remains relatively high. The FL controller has to adjust k_2 continually to find an optimal value, leading to performance degradation. It is shown that the values of k_2 in three schemes with different initial values go closer as the simulation goes on. On the contrary, most I frames and P frames are transmitted successfully when the link

TABLE VI. AVERAGE AVGPSNR IMPROVEMENT OF DFAA

	foreman scenario 1	foreman scenario 2	foreman scenario 3	football scenario 1	football scenario 2	football scenario 3
EDCA	6.791392	4.721894	4.893259	4.086974	2.070394	1.458251
ICM	3.73179	3.610254	3.734626	6.448081	4.945693	5.311563
Lin	4.67666	5.575557	5.724116	4.28027	1.936427	2.392729

TABLE VII. PACKET LOSS OF FOREMAN, SCENARIO 2

	avg PSNR	overall loss	I loss	P loss	B loss
EDCA	25.80	625	311	22	292
ICM	25.17	1279	0	885	394
Lin	24.49	616	212	109	295
DFAA	29.45	705	0	265	440

TABLE VIII. PACKET LOSS OF FOOTBALL, SCENARIO 2

	avg PSNR	overall loss	I loss	P loss	B loss
EDCA	29.09	496	182	280	34
ICM	24.67	909	0	909	0
Lin	28.85	461	161	272	28
DFAA	30.99	508	5	465	38

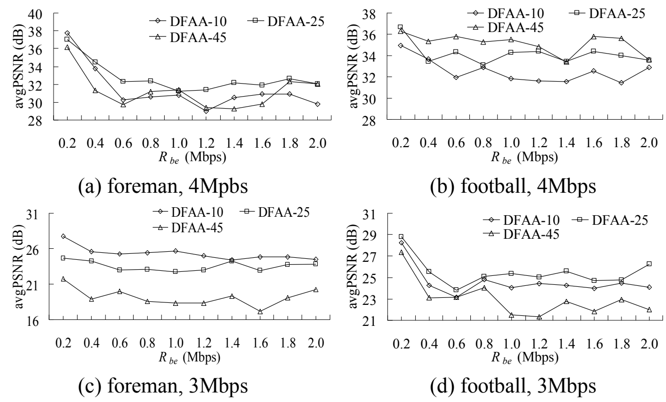


Figure 4. Performance comparison of DFAA with different k_2

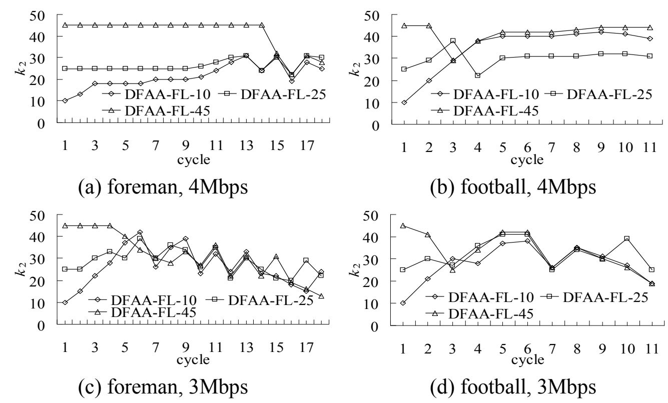


Figure 5. Adjustment details of k_2

TABLE IX. AVERAGE PSNR VARIATION OF DFAA-FL WITH DIFFERENT INITIAL K_2

	5	10	15	20	25	30	35	40	45
foreman-4M	32.065091	32.878719	33.161832	32.556565	32.231595	32.246726	32.611982	33.189742	33.266999
football-4M	35.680533	35.704185	35.099334	34.895166	34.800419	34.909711	35.390898	35.933422	35.740335
foreman-3M	23.452098	23.441892	23.133167	23.465348	23.578261	23.233329	25.082089	24.082125	24.099737
football-3M	25.076173	25.056241	24.436718	24.659746	25.524935	25.936345	23.997507	23.865539	25.307283

load is not heavy (4Mbps links), resulting in slight adjustment of k_2. In Fig. 5(a) after the 15th cycles and in Fig. 5(b) before the 5th cycles, the adjustment of k_2 are remarkable because data rate of video sequence at that time produces heavy congestion.

IV. CONCLUSIONS

In this paper we address an adaptive video scheduling scheme through wireless access networks and high speed core networks. To minimize video transmission distortion from wireless terminal to the server, adaptive scheduling mechanism should be deployed at the wireless channel for its limited bandwidth. Our proposed scheme is based on the ideas of cross layer design and unequal protection. Three enhancements are proposed in this novel scheme: (1) D_R is defined to identify the priority of AC so as to reduce transmission delay of video frame; (2) *DFAA* which considers both frame priority and network load is addressed to provide efficient unequal protection; (3) *FL controllers* are deployed to provide flexibility to video data rate, coding structure and network load. Simulation results show that the average PSNR of DFAA is much higher than those of EDCA, ICM and Lin in different scenarios. Moreover, FL controller can produce appropriate adjustment of DFAA parameter so that a random initialization of DFAA parameter becomes possible.

DFAA-FL is not limited to video communications over IEEE 802.11e networks. DFAA is suitable for any video codec which has limited priorities; the idea of DFAA could be used in any priority based multi-queue or single-queue unequal scheduling problem at network or MAC layer; similar FL controller(s) may be applied to other scheduling algorithms having one or more parameters to provide flexibility to environments.

For future work, we plan to consider the region-of-interest coding method to improve subjective video quality and combine multi-path routing with DFAA-FL to further enhance the performance of unequal protection.

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