Performance Analysis of Differentiated ARQ Scheme for Video Transmission over Wireless Networks

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ABSTRACT

The Advance in video coding and wireless communication techniques has enabled video-based services to be the most important component of many emerging multimedia applications. The critical issue is to develop a quality video transmission system over wireless networks. In this paper, an efficient error control scheme, Differentiated Automatic Repeat reQuest (DARQ), is proposed to enhance the robustness of video transmission over error-prone wireless environments. Analytical and simulation results are given to evaluate the performance of the proposed scheme in terms of discard probability, overflow probability and outage probability.

Categories and Subject Descriptors

H. 1.0 [**Models and Principles**]

General Terms: Performance

Keywords: Differentiated Automatic Repeat reQuest (DARQ), video transmission, discard probability.

1. INTRODUCTION

With the development of video coding techniques and the advance in the wireless communication techniques, the applications employing video streaming services are envisioned to become one of the most important bandwidth consumers in the next-generation networks. Therefore, how to provide the quality video transmission over the wireless networks is becoming a key issue. Video applications typically have stringent delay and delay jitter requirements. At the receiver side, the real-time video must be played out smoothly and continuously. The data arriving after the playout deadline must be discarded at the receiver, resulting in a waste of network resources. On the other hand, wireless networks cannot offer any quality of service (QoS) guarantee to video transmission. Extensive research of mechanisms and protocols for streaming video over wireless networks has been pursued in the past years. However, how to realize high quality video transmission is still a challenging and open issue due to the high bit error rate, time-varying characteristics of wireless channels and the stringent delay and delay jitter requirement of video applications.

Error control schemes are usually used in video streaming systems and have been widely accepted to yield high quality video transmission [1]. In general, error control mechanisms can be classified into two classes: Forward Error Correction (FEC) and Automatic Repeat reQuest (ARQ). FEC works well when the pattern of errors is known, but it cannot adapt to varying conditions of wireless channels. On the other hand, ARQ, as a close-loop error control technique, is more suitable for wireless environments. In order to achieve high quality video transmission, it also needs to consider the characteristics of video streams. A typical MPEG video stream consists of a sequence of I-, B-, and P-frames arranged in a deterministic periodic format called Group of Pictures (GoP) [2]. Due to the inter-frame dependency and error propagation among frames in a GoP, the significance of each frame in the reconstruction of a video stream at clients depends not only on its type but also on its location in a GoP.

Therefore, it is envisioned that by differentiating the retransmission attempts of frames with the corresponding significance in the reconstruction of video at clients, the perceptual video quality can be improved. Based on this design premise, we propose in this paper an error control scheme, called Differentiated Automatic Repeat reQuest (DARQ), in which the specific maximum number of retransmission attempts is assigned to a frame by taking into account both the attribute of the frame and its location in a GoP. In addition, we develop queueing models to evaluate the performance metrics for video transmission such as discard probability, overflow probability, and outage probability. We use numerical and extensive simulation experiments to verify the accuracy of the analytical models and demonstrate the efficiency of the proposed scheme.

The rest of this paper is organized as follows. Section 2 provides a survey on the related work. Section 3 introduces the proposed DARQ scheme and develops the performance models in terms of discard probability, overflow probability, and outage probability. Section 4 gives the simulation results and a comparison with the corresponding analytical results. Finally, we conclude the paper in Section 5.

2. Related Work

Although error-resilient coding techniques such as data partitioning and resynchronization have been employed in video coding standard

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such as the MPEG-4, residual errors are still inevitable. The situation becomes even worse in the presence of error-prone wireless environments. Therefore, the error control scheme is required to reduce the number of residual errors for achieving a higher perceptual video quality at the end users. Forward error correction (FEC) and automatic retransmission request (ARQ) are two widely used error control mechanisms which are detailed in the following subsections.

2.1 Forward Error Correction Schemes

The equal loss protection (ELP) scheme is the simplest of FEC schemes, in which packets are transmitted under the same strength of error protection so as not to be able to address the importance of different messages in the reconstruction of video at end users. In order to overcome the shortage of ELP, the unequal error protection (UEP) scheme is proposed [3][4]. The scheme in [3] varies the error protection strength according to the importance of the bits and the objects to the reconstruction quality of video. The unequal error protection scheme in [4] provides different redundancy for different frames according to their importance for perceptual video quality.

The FEC technique is proved to be efficient when the pattern of errors is known. However, as an open-loop error control scheme, FEC cannot efficiently handle burst errors caused by the unreliability of wireless channels. Without any feedback, the FEC schemes may result in an over-pessimistic channel coding or resource-wasting retransmissions when channel conditions are good or when the error protection is insufficient under a much worse channel condition. Meanwhile, the worst-case design would lead to an intolerably large extent of redundancy, which limits the effectiveness of FEC schemes.

2.2 Automatic Repeat Request Schemes

Automatic repeat request (ARQ), a kind of closed-loop error control techniques, has been shown to be very efficient and successful in wireless environments. Extensive studies have been conducted on ARQ related schemes [5][6][7]. A retransmission scheme aimed to improving the effective channel throughput is introduced by elaborating the number of retransmission attempts for each packet based on the error concealment and channel conditions [7]. The hybrid ARQ scheme proposed in [8] integrates FEC and ARQ mechanisms to improve the performance of multimedia communications over wireless channels. In [9], a delay-constrained hybrid ARQ scheme is given, in which the receiver decides whether or not to issue a retransmission request according to the delay bound of a packet.

In [10], an adaptive priority-based selective retransmission scheme is proposed to increase the chance of successful transmission of packets with higher level of importance. In addition, the characteristics of MPEG video streams are considered in [11], where the I-frames are taken as the most important frames in a video stream. The study concludes that the selective retransmission of I-frames is the most beneficial to improve the quality of received video streams. A further study focusing on the importance of I- and P-frames is presented in [12], where I-frames are allocated to a queue with a higher priority than that of the queue used for P-frames. By employing a priority scheduling scheme, all I-frames get a relatively highly opportunity to be served.

3. Differentiated ARQ Scheme

A Differentiated Automatic Repeat reQuest (DARQ) scheme for video transmission over wireless networks is proposed in this Section to enhance the error resilience of video transmission in wireless environments and improve the perceptual quality at mobile clients. The proposed DARQ considers not only the fact that for a typical video stream different types of frames yield different degree of importance, but also that the significance of a P-frame depends on its position in a GoP. Furthermore, analytical models are developed to evaluate the performance metrics for video transmission such as discard probability, overflow probability, and outage probability.

3.1 The DARQ Scheme

We consider the wireless network environment composed of base station (BS) and mobile clients as shown in Fig. 1. The video packets are transmitted from the streaming server located in the wired network to the mobile clients via the base station. The base station firstly buffers the video packets and then forwards them to the mobile clients through the wireless link.

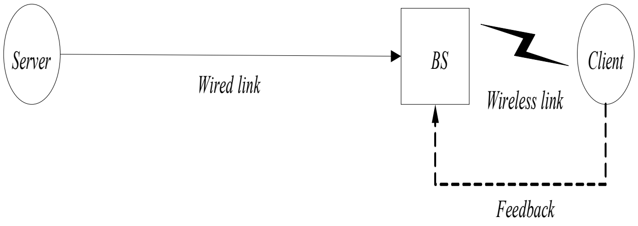

Figure 1. Video streaming over wireless networks.

The principle of DARQ scheme is as follows. At the base station, the link layer entity receives service data units (SDUs) from the upper layer and segments each received SDU into L protocol data units (PDUs) of equal size prior to the delivery over the wireless link. At the receiver side, the received PDUs are placed in the reception buffer until a complete SDU has been successfully received. The receiver acknowledges the successful reception of each PDU or sends a negative acknowledgement back to the base station to trigger the retransmission of lost/corrupted packets if the retransmission is permitted. A SDU is discarded if any of the PDUs constituting this SDU cannot be successfully transmitted after pre-defined maximum number of transmission attempts.

In the DARQ scheme, the pre-defined maximum number of retransmission attempts is assigned to a frame based not only on its frame type but also on the position of the frame in a GoP. Let G(N_P, N_{BP}) denotes a MPEG video stream pattern in which the GoP format is composed of one I-frame, N_P P-frames (represented by P_i ($1 \leqslant i \leqslant N_P$)), and N_{BP} B-frames between an I- or P-frame and its subsequent P-frame (represented by B_{ij} ($0 \leqslant i \leqslant N_P$, $1 \leqslant j \leqslant N_{BP}$)). The parameter N_P denotes the number of P-frames in a GoP, and N_{BP} represents the number of B-frames in an interval between two continuous P-frames or between an I-frame and its succeeding P-frame. For example, $G(3,2)$ denotes a video stream "$IB_{01}B_{02}P_1B_{11}B_{12}P_2B_{21}B_{22}P_3B_{31}B_{32}$ …".

Let S(.) be the function of significance of a particular frame. Thus we have

$$\begin{aligned} &S(B_{ij})<S(P_l)<S(I) \quad \forall i,j,l,\ \ 0\le i\le N_P,\ \ 1\le j\le N_{BP},\ \ 1\le l\le N_P \\ &S(P_{k+1})<S(P_k) \qquad \forall k,\ \ 1\le k<N_P \end{aligned} \tag{1}$$

According to the above relations, the maximum number of transmission attempts can be regulated as follows,

$$
\begin{aligned}
&A_{B_{ij}} \le A_{P_l} \le A_I \quad \forall i,j,l,\ \ 0\le i\le N_P,\ \ 1\le j\le N_{BP},\ \ 1\le l\le N_P \\
&A_{P_{k+1}} < A_{P_k} \qquad \forall k,\ \ 1\le k< N_P
\end{aligned}
\qquad (2)
$$

where A_m denotes the maximum number of transmission attempts for packets belonging to m- frame, $m\in\{\mathrm{I},\mathrm{P_l},\mathrm{B_{ij}}\}$.

By differentiating the significance of each frame in a GoP and assigning the maximum number of transmission attempts accordingly, the proposed differentiated retransmission scheme is capable of manipulating the likelihood of corruption for each frame with different types and position so as to increase the total playable frame rate and improve the perceptual video quality.

3.2 Analytical Model

In this Subsection, the analytical model for the proposed scheme is developed, and key performance metrics for video transmission such as packet discard probability, the overflow probability, and the outage probability are evaluated. The proposed analytical model is based on the following assumptions:

1. A link layer SDU corresponds to an IP packet.
2. At the link layer, each SDU is segmented in *L* PDUs of equal size.
3. Time is slotted, and each time slot is defined as the time it takes for a PDU to travel over the wireless link.
4. A perfect and instantaneous feedback is assumed so that ACKs or NAKs can be sent back immediately, and the unsuccessful PDU is transmitted at the next slot if the retransmission attempt is permitted.
5. For the packet arrival process at the base station, we consider a Bernoulli model. The study [13] concludes that if an equation-based TCP friendly congestion control scheme is adopted at the sender to ensure the fairness and friendly of video traffic with the competing TCP traffic, the arrival process at the base station can be modeled by a Bernoulli process.

3.2.1 Wireless Channel Model

The mobile wireless channels suffer from deep fading that occurs randomly in time and have random duration and depth. Several studies have shown that such a channel can be represented by a Markov model, which can capture the burst error nature of wireless channels [14]. In this paper, we use a Markov model with two states, Good and Bad, to represent the wireless channel as shown in Fig. 2. Let the error probabilities in Good and Bad states be 0 and 1, respectively. The probabilities P_{GB} and P_{GG} represent the transition probabilities from Good state to Bad and Good states, respectively. Similarly, P_{BB} and P_{BG} represent the transition probabilities from Bad state to Bad and Good states, respectively.

With such a model, the transition probability matrix can be expressed as $P=\begin{pmatrix} P_{GG} & P_{GB} \\ P_{BG} & P_{BB}\end{pmatrix}$. The transition probabilities can be calculated from the Eq. (3) with the knowledge of the channel characteristics which are represented by the average PDU-error-rate (PER) ε and the average error burst length (EBL).

$$
\begin{aligned}
p_{BG} &= \frac{1}{EBL}, \\
p_{GB} &= \frac{\varepsilon}{EBL\ (1-\varepsilon)}.
\end{aligned}
\qquad (3)
$$

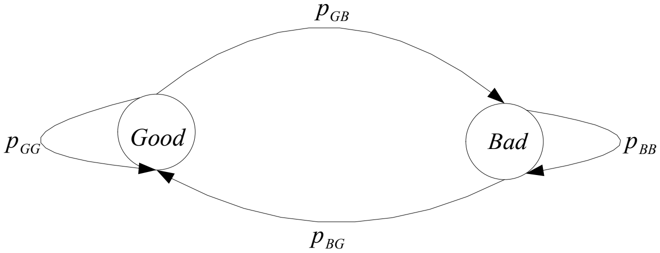

Figure 2. Two-state Markov channel model.

3.2.2 Packet Discard Probability

Based on the above wireless channel model, the transmission of each PDU is modeled with a discrete Markov chain as shown in Fig. 3. The unsuccessful transmission of a PDU will initiate a retransmission, and the number of retransmissions is upper-bounded by the pre-defined maximum number of retransmission attempts for the PDU.

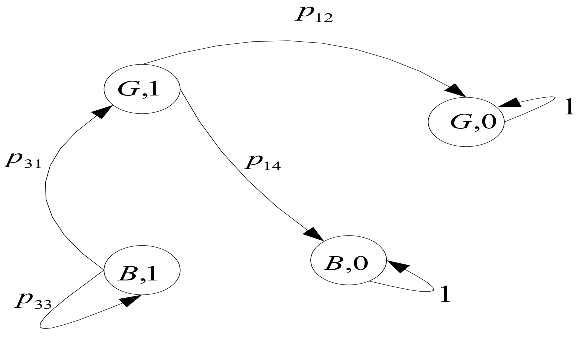

Figure 3. State transition diagram for a PDU.

State (*G,1*) and (*B,1*) indicate that a PDU is not successfully transmitted given that the channel is in Good state and Bad state, respectively. State (*G,0*) and (*B,0*) indicate that a PDU is successfully transmitted given that the channel is in Good and Bad state, respectively. The one step transition probability matrix *Tr* can be expressed as:

$$
Tr = \begin{bmatrix} 0 & p_{12} & 0 & p_{14} \\ 0 & 1 & 0 & 0 \\ p_{31} & 0 & p_{33} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

where $p_{12}=p_{GG}$, $p_{14}=p_{GB}$, $p_{31}=p_{BG}$, and $p_{33}=p_{BB}$.

The state transition diagram, shown in Fig. 3, is an absorbing Markov chain. The residual PDU loss probability given the *n* retransmission attempts can be calculated as follow

$$
F(n) = P\{\eta > n\} = \pi S^n e \qquad (4)
$$

where π denotes the initial state probability vector, $S=\begin{bmatrix}0 & 0\\ p_{31} & p_{33}\end{bmatrix}$, and $e=[1 \quad 1]^T$, respectively. Therefore, the probability of successfully transmitting a PDU given n transmission attempts is $1-F(n)$, the probability of successfully transmitting a packet is $(1-F(n))^L$, and the discard probability of Packets of I-, P- and B Frames are given by

$$p_{discard\_I}=1-(1-\pi S^{A_I}e)^L \tag{5}$$

$$p_{discard\_B}=1-(1-\pi S^{A_B}e)^L \tag{6}$$

$$p_{discard\_P_i}=1-(1-\pi S^{A_{P_i}}e)^L \tag{7}$$

where $\pi=[\pi_G,\pi_B]$, and furthermore, A_I, A_B, and A_{pi} denote respectively the allowed maximum number of transmission attempts for packets belonging to I-, B- and P_i- frames.

3.2.3 Packet Overflow Probability

Under the the condition of finite buffer, besides the packet loss that occurs when the number of unsuccessful transmissions reaches the allowed maximum value, buffer overflow is another reason that causes packet losses. Therefore, it is necessary to analyze the packet overflow probability. A discrete time Markov chain is introduced to evaluate the performance of packet loss due to overflow. Let the capacity of buffer be C in packets. A five dimensional Markov chain is developed using the following parameters.

n is the number of packets in the buffer (n=0,1,2,….C);

s denotes the wireless channel state ($s\in\{g,b\}$);

t represents the type of frame to which the packet in the head of the buffer belongs ($t\in\{I,P_i,B\}$);

m represents the number which indicates the location of the current served PDU in the SDU to which it belongs (m=1,2,3…L);

k is the number of transmissions that the current served PDU has experienced.

Given the state parameters described above, the buffer state can be represented by the state transition diagram shown in Fig. A.1. The steady state probability $\pi(n,s,t,m,k)$ can be derived from the following balance equations

$$\begin{cases}\Pi=\Pi P \\ \sum_{n=0}^{C}\sum_{s\in\{g,b\}}\sum_{m=1}^{L}\sum_{k=0}^{A_I-1}\pi(n,s,I,m,k)+\sum_{n=0}^{C}\sum_{s\in\{g,b\}}\sum_{i=1}^{N_p}\sum_{m=1}^{L}\sum_{k=0}^{A_{Pi}-1}\pi(n,s,P_i,m,k)+\sum_{n=0}^{C}\sum_{s\in\{g,b\}}\sum_{m=1}^{L}\sum_{k=0}^{A_B-1}\pi(n,s,B,m,k)=1\end{cases} \tag{8}$$

where **Π** and **P** denote the steady state probability vector and the one-step transition probability matrix, respectively. From the steady state probability vector **Π** derived from the Eq. (8), the buffer overflow probability can be given by

$$p_{overflow}=\sum_{s\in(g,b)}\sum_{m=1}^{L}\sum_{k=0}^{A_I-1}\pi(C,s,I,m,k)+\sum_{s\in(g,b)}\sum_{i=1}^{N_P}\sum_{m=1}^{L}\sum_{k=0}^{A_{P_i}-1}\pi(C,s,P_i,m,k) \\ +\sum_{s\in(g,b)}\sum_{m=1}^{L}\sum_{k=0}^{A_B-1}\pi(C,s,B,m,k) \tag{9}$$

3.2.4 Packet Outage Probability

For real-time applications, the packets arrived after their playout deadline will be useless and discarded at clients. Therefore, the packet outage probability is also an important metric to evaluate the quality of service for real-time applications. The outage probability is defined as the ratio of the packets arrived beyond the constraint of delay to all arrived packets. In the scenario we discussed, since the wireless link is the bottleneck, the delay jitter stems mainly from the queueing delay at the base station buffer. Therefore, the outage probability can be calculated by setting D (in slots) as the maximum tolerable queueing delay at the base station buffer as follows.

$$\Pr\{Q>D\}=\sum_{n=0}^{C}\sum_{s\in\{g,b\}}\sum_{m=1}^{L}\sum_{k=0}^{A_I-1}\Pr\{Q>D|_{(n,s,I,m,k)}\}\pi(n,s,I,m,k) \\ +\sum_{n=0}^{C}\sum_{s\in\{g,b\}}\sum_{i=1}^{N_p}\sum_{m=1}^{L}\sum_{k=0}^{A_{P_i}-1}\Pr\{Q>D|_{(n,s,P_i,m,k)}\}\pi(n,s,P_i,m,k) \\ +\sum_{n=0}^{C}\sum_{s\in\{g,b\}}\sum_{m=1}^{L}\sum_{k=0}^{A_B-1}\Pr\{Q>D|_{(n,s,B,m,k)}\}\pi(n,s,B,m,k) \tag{10}$$

where $\Pr\{Q>D|_{(n,s,t,m,k)}\}$ is conditional outage probability given that the system is in the state *(n,s,t,m,k)* when a packet arrives at the buffer. In order to formulate the conditional outage probability, we introduce another discrete time Markov chain, as shown in Fig. A.2, to represent the state transition of each packet after it arrives at the base station buffer. Thus, the conditional outage probability can be given by

$$\Pr\{Q>D|_{(n,s,t,m,k)}\}=\frac{\Pr\{Success\ and\ arrival\ beyond\ the\ \mathrm{max}imum\ tolerable\ delay|_{(n,s,t,m,k)}\}}{\Pr\{success|_{(n,s,t,m,k)}\}} \\ =\frac{\Pi_0 Q_2^D e-\Pi_0 Q_2^{nLA_I}e}{1-\Pi_0 Q_2^{nLA_I}e}$$

where $\boldsymbol{Q_2}$ is the one-step transition probability matrix which can be derived from Fig. A.2 , $\boldsymbol{\Pi_0}$ is the state row vector that has all components equal to zero except for the element corresponding to the state $\pi(n,s,t,m,k)$ which is equal to 1, and $\boldsymbol{e}$ is the corresponding column vector with all components equal to 1.

4. Simulation Results

In this Section, the performance of the DARQ scheme is evaluated by using both numerical and simulation results. The simulations are conducted using OPNET [15], in which a popular GoP pattern GoP(3,2) with C=10 (in packets) and L=4 is adopted. We assume that each I-, P-, and B-frame consists of 4, 2, and 1 packets, respectively. The maximum number of transmission attempts for I-, P_1-, P_2-, P_3-, and B-frames are 3, 3, 2, 1, and 1, respectively. The packet arrival probability is 0.25, and the average error burst length of wireless channel is 2.

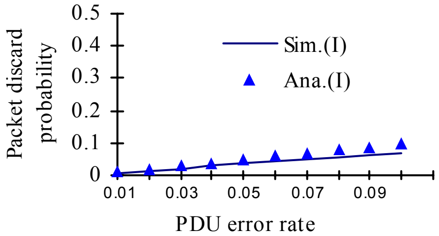

Figure 4. Packet discard probability vs. PDU error rate for I-frames.

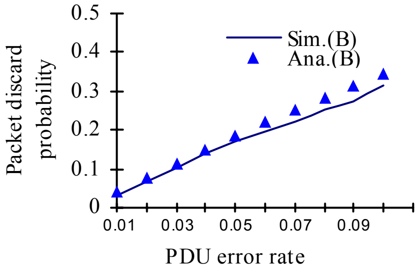

Figure 5. Packet discard probability vs. PDU error rate for B-frames.

Figs. 4 and 5 show the relation between the average PDU error rate of wireless channel and the discard probabilities for packets belonging to I- and B-frames, respectively. It can be observed that the packet discard probability depends on the significance of the frame to which the packet belongs. The likelihood that a packet belonging to I-frame is lost is the lowest due to the assigned largest maximum number of transmission attempts. By providing packets constituting I-frames with the highest probability of successful transmission, the DARQ scheme can alleviate the error propagation due to packet loss and obtain an improved perceptual video quality. The discard probability of packets belonging to B-frames are the highest among all frame types since they are of less important types and are assigned with the smallest number of transmission attempts.

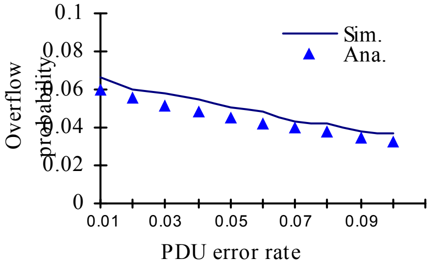

Figure 6. Overflow probability vs. PDU error rate.

Fig. 6 shows how the overflow probability changes with wireless channel conditions. We can see that overflow probability decreases slightly when the wireless channel condition becomes worse. The reason is that increasing PDU error rate results in the increase in the packet discard probability. As a result, more space is left for the arriving packets and the overflow probability decreases slightly.

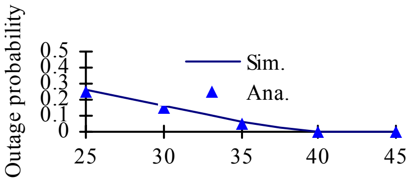

Figure 7. Outage probability vs. maximum tolerable delay.

Fig. 7 shows the relation between outage probability and maximum tolerable delay (in slots) for the average PDU error rate ε=0.05. We can see that the outage probability decreases when the maximum tolerable delay increases. In addition, it is observed that the simulation results approximate the analytical results very well.

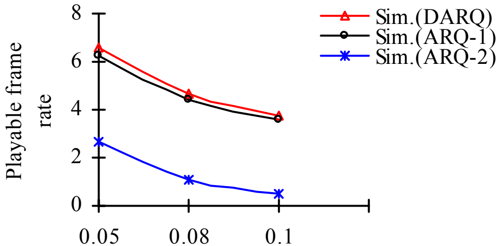

Figure 8. Playable frame rate vs. PDU error rate.

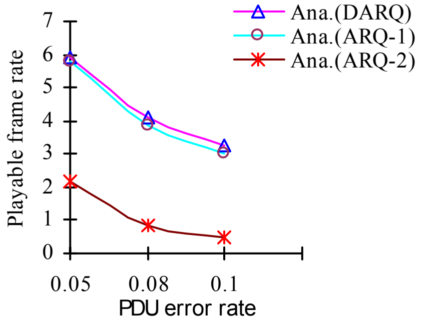

Figure 9. Playable frame rate vs. PDU error rate.

Fig. 8 and 9 show respectively the simulation results and analytical results of the playable frame rate for various error rates of the wireless channel for DARQ and two counterpart schemes, ARQ-1 and ARQ-2. ARQ-1 is devised such that it differentiates the significance of different frames only at the frame level, and assigns the uniform maximum number of transmission attempts to all P-frames, which equals to 2 in our simulation, and ARQ-2 provides no retransmission for all frames. In Figs. 8 and 9, the playable frame rate is used as the metric to evaluate the efficiency of the proposed scheme. However, no detail about the conception and calculation procedure of playable frame rate is given due to the space limitation. Interested readers can refer to [16][17].

From Figs. 8 and 9, it is observed that DARQ scheme provides a higher playable frame rate than its counterpart schemes. That is, the proposed scheme can achieve higher perceptual video quality at mobile clients by efficiently differentiating the significance of frames. The playable frame rate of the scheme ARQ-2 is the lowest since it provides no retransmission for all frames.

5. Conclusion

A differentiated ARQ (DARQ) scheme for MPEG video streaming over wireless networks has been proposed to provide high quality video transmission. The DARQ scheme considers not only the fact that different types of frames yield different levels of importance, but also that the significance of a P-frame depends on its position in the GoP. By assigning the maximum number of retransmission attempts to each frame in a GoP according to its significance, the error propagation due to packet loss is alleviated and a high perceptual quality of the video transmission is achieved. Queueing models have been developed to evaluate the performance of the proposed DARQ scheme in terms of discard probability, overflow probability, and outage probability. The accuracy and efficiency of the proposed scheme have been verified by analytical and simulation results. In addition, the proposed scheme can significantly improve the overall frame playable rate by considering the position of P-frames in assignment of retransmission attempts for video applications.

6. Appendices

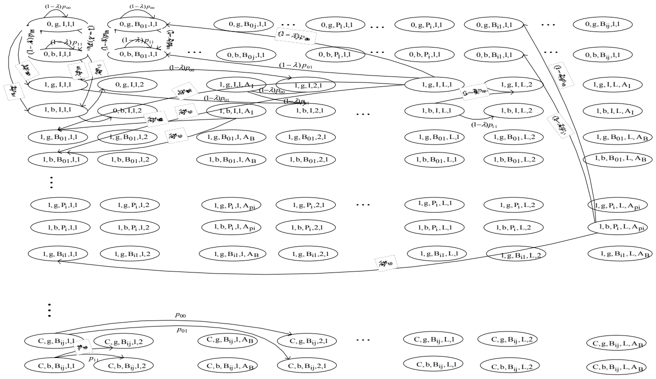

Figure A.1. System state transition diagram.

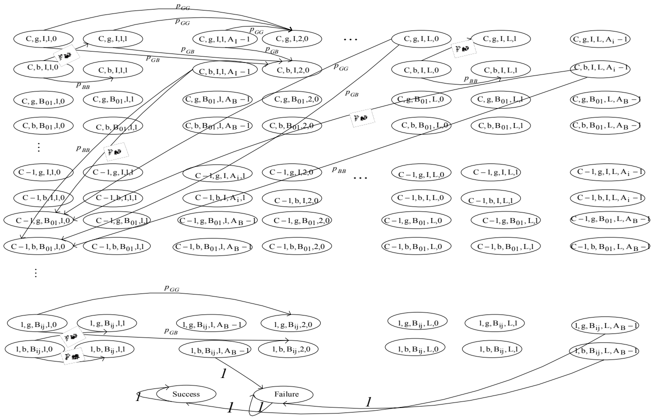

Figure A.2. State transition diagram for each arrival packet.

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