Cross-layer Design of Rate and Quality Adaptation Schemes for Wireless Video Streaming

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Abstract

Video streaming service over wireless networks is a challenging task because of the changes in the wireless channel conditions that can occur due to interference, fading, and station mobility. To provide an efficient wireless video streaming service, the rate adaptation scheme should improve wireless node performance and channel utilization. Moreover, the quality adaptation scheme should be considered at the streaming application. To meet these requirements, we propose a new cross-layer design for video streaming over wireless networks. This design includes the rate and quality adaptation schemes. The rate adaptation scheme selects the optimal transmission mode and resolves the performance anomaly problem. Based on performance improvement by the proposed rate adaptation scheme, our quality adaptation scheme improves the quality of video streaming. Through performance evaluations, we prove that our cross-layer design improves the wireless channel utilization and the quality of video streaming.

Keywords: Cross-layer design, rate adaptation, quality adaptation, video streaming

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1. Introduction

The Internet has recently been experiencing an explosive growth of the use of multimedia streaming applications. Moreover end users increasingly seek mobility, and thus paving the way for extensive deployment of wireless technologies like IEEE 802.11. However, multimedia streaming over a wireless network is a challenging task because the wireless channel characteristics such as shadowing, multipath fading, and interference still limit the available bandwidth of the Wireless Local Area Network (WLAN).

Since multimedia streaming applications are very sensitive to network bandwidth, WLAN performance directly affects the quality of wireless streaming service. To improve WLAN performance, a scheme referred to as rate adaptation is being employed at the Medium Access Control (MAC) and physical (PHY) layers. Basically, the rate adaptation scheme is a process of automatically switching the data transmission mode to match the wireless channel conditions with the goal of selecting the transmission mode that will achieve the optimal quality for the given wireless channel conditions [1][2]. Here, optimal quality means maximizing the wireless node throughput as much as possible.

With the performance improvement caused the rate adaptation scheme, streaming applications should be quality-adaptive. That is, streaming application should adjust the quality of video streaming such that the required bandwidth matches the throughput of the wireless node; this is the essence of quality adaptation. The quality adaptation scheme maximizes the perceptual video quality within the rate limit of the wireless node. Adaptive video streaming is not a new topic. Much research has been conducted in this area and various approaches have been proposed. By jointly considering various aspects over different communication layers, the adaptation schemes can further improve the quality of video streaming [3][4][5][6].

In this paper, we propose a new cross-layer design for video streaming over wireless networks. First, we consider the rate adaptation scheme at the MAC and PHY layers because it improves the wireless node throughput by adapting the data transmission mode to the current wireless channel conditions. We also consider the quality adaptation scheme because it matches the quality of video streaming to the wireless node throughput. Our proposed design explicitly includes a quality adaptation scheme and a new rate adaptation scheme. To adjust the quality of video streaming, the quality adaptation scheme utilizes the rate limit which is provided from the rate adaptation schem at the MAC and PHY layers.

The rest of this paper is organized as follows: the rate adaptation scheme and related works are discussed in the next section. In Section 3, we describe the rate and quality adaptation algorithms introduced in our cross-layer design. Simulation environments and performance evaluations are described in Section 4. Finally, Section 5 concludes the paper and discusses some of our future work.

2. Related Work

2.1 Rate Adaptation Scheme

The IEEE 802.11 standard defines specifications for the MAC layer and PHY layers. In the MAC layer, two channel access functions are specified. The mandatory contention-based channel access function is called the Distributed Coordination Function (DCF) which is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). The optional polling-based Point Coordination Function (PCF) is also specified in the standard, but it is rarely implemented in IEEE 802.11-compliant products [8][9].

The IEEE 802.11 PHY provides multiple data transmission modes. A higher data rate does not necessarily yield a higher throughput. Only when the channel conditions are good, a higher data rate gives a higher throughput. The rate adaptation scheme is commonly employed to accommodate different wireless channel conditions, due to fading, interference, and mobility, etc. This is realized by dynamically adjusting the modulation and coding levels to optimize performance over time-variant wireless channel conditions [1][2]. Since the IEEE 802.11 standard does not specify any mechanism or protocol to efficiently utilize multiple data transmission modes, many rate adaptation schemes have been proposed and some have been used in real WLAN products [1][2][9][10][11][12]. The basic idea of the rate adaptation scheme is to estimate the wireless channel quality and to adjust the data transmission mode accordingly. This is typically achieved by using a few metrics collected at the sender and the associated design rules. The widely used metrics include probe packets, consecutive successes or losses, PHY metrics such as Signal to Noise Ratio (SNR) or Received Signal Strength Indicator (RSSI), and short-term/long-term statistics.

The rate adaptation schemes are categorized into two different approaches which are the statistics-based and channel quality-based approaches. The statistics-based approach estimates the channel quality based on the successful data transmissions or failures. According to this estimation, the statistics-based approach gradually adjusts its data transmission mode. An easy way to obtain the necessary information about the wireless channel conditions is to maintain statistics about the data delivery such as the Packet Error Rate/Bit Error Rate (PER/BER), the retry ratio, and the achieved short-term/long-term average throughputs. Among the existing statistics-based rate adaptation schemes, the earliest and the most widely used on is Auto Rate Fallback (ARF) which was used in Lucent's WaveLAN-II product. In the ARF scheme, a discrete set of data rates are used. If the ACK frames for two consecutive data frames are not received by the sender, then the sender drops the transmission mode to the next lower data rate and a timer is started. If ten consecutive data frames are successfully received or the timer expires, then the transmission mode is raised to the next higher data rate and the timer is stopped [1]. The channel quality-based approach estimates the channel quality based on the measured SNR or SSI instead of the statistics and it adjusts the data transmission mode by using the pre-defined threshold lookup table. A typical example is the Receiver-Based Auto Rate (RBAR) scheme that performs the rate adaptation at the receiver instead of at the sender. The RBAR mandates the use of a Request To Send/Clear To Send (RTS/CTS) exchange. The receiver of an RTS frame selects the transmission mode to be used by the sender based on the measured SNR from the received RTS frame and on a set of SNR thresholds calculated with an a priori wireless channel model [2].

2.2 Performance Anomaly Problem

The rate adaptation scheme improves the wireless nodes' performance by adjusting the data transmission mode based on the changes in the wireless channel conditions. In a typical WLAN environment, some wireless nodes may be far away from their Access Point (AP) so that the quality of their radio transmissions is low. In this case, the rate adaptation schemes decrease the data transmission mode when a wireless node detects repeated unsuccessful frame transmissions. If there is at least one wireless node with a lower mode, then a WLAN system presents a performance anomaly: the throughput of all wireless nodes transmitting at the higher transmission mode is degraded below the level of the lower mode. Such behavior penalizes fast wireless nodes and rewards the slow one. As depicted in **Fig. 1**, the throughput of a fast node (11Mbps) is limited to that of the competing slow nodes (5.5 or 1 Mbps) and the wireless channel is under-utilized [13][14].

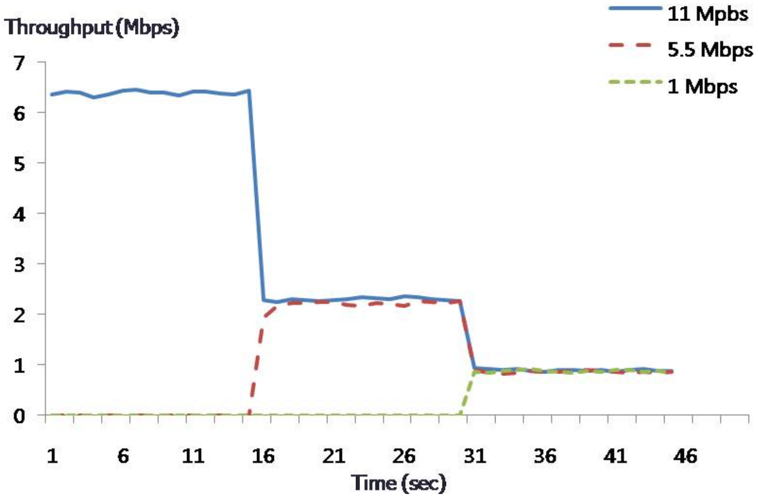


Fig. 1. Performance anomaly problem

The reason for this anomaly problem is the DCF channel access mechanism that guarantees that the long-term channel access probability is equal for all wireless nodes. When a node captures the channel for a long time because its transmission mode is low, it penalizes other nodes that use the higher transmission mode. When the same-sized packets are used and channel conditions are similar, each competing node, regardless of its data transmission mode, achieves roughly the same throughput. This is defined as the throughput-based fairness.

To improve the WLAN system performance by resolving the performance anomaly problem, the channel access mechanism should provide the time-based fairness instead of the throughput-based fairness [14]. Each competing wireless node achieves an equal share of the wireless channel occupancy time under the time-based fairness. Compared to the throughput-based fairness, the time-based fairness improves the wireless channel utilization because the faster nodes have more transmission opportunities than the slower nodes.

Some mechanisms have been proposed to resolve this anomaly problem [14][15][16][17]. G. Tan et al. proposed a new scheduling mechanism that runs on the AP and works with any MAC protocol to provide time-based fairness by regulating frames [14]. Under the throughput-based fairness scheme, the wireless nodes with slower data transmission modes occupy the channel much longer than those with higher transmission modes. The proposed Time-Based Regulator (TBR) scheme allocates equal channel occupancy time to all competing wireless nodes regardless of their transmission modes. Moreover TBR defines the baseline property as “The long-term throughput of a node competing against any number of nodes running at different transmission modes is equal to the throughput that the node would achieve in all competing nodes that are running at the same data transmission mode”. This property signifies that the performance improvement of the faster nodes under the time-based fairness scheme comes from the higher wireless channel utilization but is not caused by the throughput degradation of the slower nodes. However, the TBR scheme only schedules data frames based on the selected data transmission mode; it does not consider the rate adaptation that is operated independently at each wireless node.

S. Yoo et al. proposed a time-based fairness scheme that proportionally adjusts the Maximum Transmission Unit (MTU) size depending on the data transmission mode [15]. If the ratio of the fast node transmission mode to the slow node mode is *X*, then the fast node transmits *X* times longer frame. Therefore the fast node achieves *X* times higher average throughput than the slow node. This MTU-based scheme guarantees the time-based fairness and eliminates performance anomaly by adjusting the frame size based on the selected data transmission mode. However, the MTU-based scheme overlooks the fact that BER is increased as the frame size is longer [18].

Recently, a Quality of Service (QoS) differentiation scheme based on the controlling minimum Contention Window (CWmin) has been proposed [16][17]. In this scheme, the performance anomaly problem can be cleanly resolved through configuring the initial contention window size for each transmission mode inversely proportional to the data transmission mode. The fast node with the highest transmission mode retains the current default value, i.e., CWmin=32 slots. The CWmin of other slow nodes is then set as shown in (1). Fast nodes with smaller CWmin values more frequently access the wireless channel and transmit more data frames compared to the slower nodes. Therefore, the performance anomaly can be resolved through the CWmin differentiation. However, this CWmin-based scheme does not guarantee accurate time-based fairness because the back-off time is randomly selected within the limits of the CW value. Moreover, CWmin-based wastes wireless channel resources due to channel access overhead such as DIFS and back-off time.

$$CW_{\min}^{Tx.Mode} = CW_{\min}^{11Mbps} \times \frac{11Mbps}{Tx.Mode}\left(CW_{\min}^{11Mbps} = 32slots\right) \qquad (1)$$

3. The proposed Cross-layer Design

3.1 Overview

Fig. 2 shows the proposed cross-layer architecture for wireless video streaming. The cross-layer design includes the rate adaptation module at the MAC and PHY layers and the quality adaptation module. **Fig. 2** also illustrates the function blocks and data flows related to the proposed cross-layer design as well. The rate adaptation module selects the optimal transmission mode based on the wireless channel conditions and transmits this information to the quality adaptation module. The quality adaptation module then adjusts the video stream quality and delivers a controlled video stream to the receiver through wireless networks.

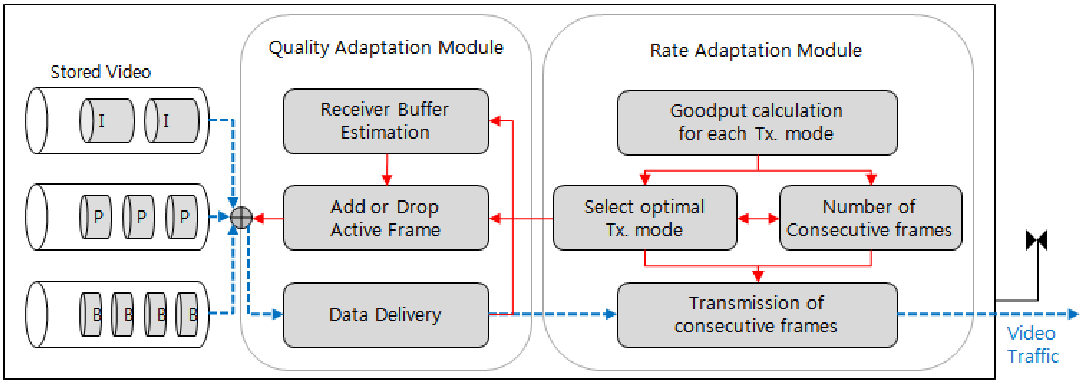


Fig. 2. Cross-layer architecture

In the rate adaptation module, we propose a new rate adaptation scheme, called Goodput-enhanced Rate Adaptation (GeRA). The proposed GeRA scheme provides a time-based fairness to improve wireless channel utilization. GeRA efficiently resolves the performance anomaly problem by transmitting consecutive data frames. The number of consecutive frames is calculated based on the ratio of the optimal transmission mode to the basic rate. To select the optimal transmission mode for the given wireless channel conditions, the GeRA scheme calculates the expected goodputs for each transmission mode. The data transmission mode with the highest goodput is selected as optimal and the wireless node transmits consecutive data frames when it captures the wireless channel. Details of the proposed rate adaptation scheme are described in Section 3.2.

Normally, a video stream consists of three types of frames; I-, P-, and B-frames. The frame is the basic unit of video data and is equivalent to the picture. A sequence of frames beginning with an I-frame is called a Group Of Picture (GOP) and is defined by two parameters: the number of P-frames between two I-frames and the number of B-frames between two P-frames. In this paper, we assume that each frame type has the same data size. This is unlikely in a real codec, but it simplifies the analysis.

The streamed video data is limited by the selected optimal transmission mode that is determined by the rate adaptation module. The streaming server can only transmit the video stream up to this boundary. The quality adaptation scheme is required when the data rate of an originally stored video stream is higher than the selected data transmission mode. When the quality adaptation scheme is applied, some frames of a GOP are activated and transmitted to the receiver but the others are not. In Section 3.3, we describe our quality adaptation scheme in a cross-layer design.

3.2 The rate Adaptation Scheme of Our Design

To improve WLAN system performance by resolving the performance anomaly problem, a channel access mechanism should provide a time-based fairness scheme instead of a throughput-based one. Some time-based fairness schemes have been proposed for this purpose. However, they have some limitations as described in Section 2.3 and do not consider the rate adaptation scheme. In this paper, we propose the GeRA scheme that is a statistics-based rate adaptation scheme. GeRA scheme also provides time-based fairness to improve the wireless channel utilization by resolving the performance anomaly problem.

To improve wireless channel utilization and resolve the performance anomaly problem, our GeRA scheme transmits consecutive data frames when a wireless node captures the wireless channel. The Number of Consecutive data Frames (NCF) is calculated based on the ratio of each data transmission mode to the basic rate. If the selected transmission mode is twice the basic rate (*BasicRate*), then the node consecutively transmits two data frames when it captures the wireless channel. The time-based fairness is guaranteed by transmitting the consecutive data frames. The transmission of consecutive data frames in the GeRA scheme efficiently utilizes the wireless channel resources and improves wireless channel utilization because it has no channel access overhead.

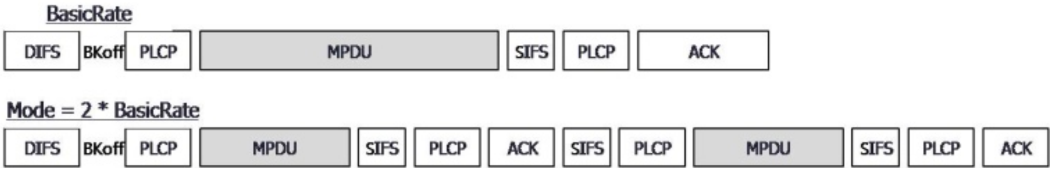


Fig. 3. Transmission of consecutive data frames in the GeRA scheme

The GeRA scheme selects a data transmission mode as optimal which has higher goodput than other transmission modes. Therefore, the NCF is an important parameter for selecting the optimal transmission mode because the goodputs of each transmission mode are calculated based on it. The goodput means a useful throughput. In the GeRA scheme, the goodputs of each transmission mode can be calculated by:

$$G_{Tx.Mode} = \frac{L_{MPDU} \times 8bits}{T_{NCF}^{Tx.Mode}} \times NCF \times P_{Success}^{Tx.Mode} \tag{2}$$

$$T_{NCF}^{Tx.Mode} = T_{DIFS} + T_{Backoff} + T_{MPDU}^{Tx.Mode} + T_{ACK}^{BasicRate} + SIFS \times (1 + NCF) \tag{3}$$

where T_{NCF} is the time taken by a wireless node to transmit NCF data frames and *PSuccess* is the probability of successful data transmission at *Tx.Mode*. The probability of successful data transmission can be calculated as shown in (4) because a successfully transmitted data frame is retransmitted when an ACK frame has failed. An ACK frame is transmitted at the basic rate in general and is 14 bytes long, which is usually much shorter than the data frame. Therefore, the probability of successful data transmission can be approximated as shown in (5) because the error probability of the ACK frame is very low compared to that of the data frame.

$$P_{Success}^{Tx.Mode} = \left\{\left(1 - P_{Error\_MPDU}^{Tx.Mode}\right) \times \left(1 - P_{Error\_ACK}^{BasicRate}\right)\right\} \tag{4}$$

$$P_{Success}^{Tx.Mode} \cong \left(1 - P_{Error\_MPDU}^{Tx.Mode}\right) \tag{5}$$

The proposed GeRA scheme can estimate goodputs for each transmission mode for the given wireless channel conditions. After estimating the goodputs, the GeRA scheme selects the optimal transmission mode with the highest goodput as shown in (6). Therefore GeRA scheme can improve the wireless channel utilization as well as the wireless node throughput.

$$Tx.Mode_{Opt.} = MAX\,(G_{BasicRate}, \ldots, G_{Tx.Mode}) \tag{6}$$

Wireless channel conditions possibly change over the course of NCF transmission. This situation has to be considered in the GeRA scheme because it transmits consecutive data frames when a node captures the wireless channel. The GeRA scheme thinks of two frame errors back-to-back as changes in the wireless channel conditions occur and it adjusts the data transmission mode. Among transmission modes that are slower than the current optimal, the mode with the highest goodput is selected to be the new optimal. After changing the optimal transmission mode, the NCF has to be re-calculated. New NCF data frames will be transmitted at the new optimal transmission mode during the remaining channel occupancy time. The NCF can be updated as shown in (7) where *P_Tx.Mode* and *N_Tx.Mode* are the previous and new optimal transmission modes respectively. *m* means the number of data frames that have already been transmitted at the previous transmission mode.

$$NCF_{N\_Tx.Mode} = \left(\frac{P\_Tx.Mode}{BasicRate} - m\right) \times \frac{N\_Tx.Mode}{P\_Tx.Mode} \tag{7}$$

A wireless node under the GeRA scheme transmits consecutive data frames when it captures the wireless channel. Therefore, the collision avoidance mechanism of the 802.11 DCF should be modified to prevent frame collision. This modified collision avoidance mechanism includes updating the contention window and setting the Network Allocation Vector (NAV).

The 802.11 DCF reduces the collision probability by adjusting the contention window based on the successful data frame delivery. In our GeRA scheme, the contention window is adjusted based on the delivery of the last NCF data frame. If the last data NCF data frame is unsuccessfully transmitted, then the contention window is exponentially increased as shown in (8), similar to the 802.11 DCF.

$$CW_{\min}^{n} = CW_{\min}^{n-1} \times 2 \tag{8}$$

With the contention window algorithm, the GeRA scheme provides the modified NAV algorithm to reduce frame collision. In the 802.11 DCF, the NAV is set to the time that is necessary to complete a data frame transmission. All competing nodes overhearing the RTS/CTS frame set their NAV in order to defer their data transmissions during this time. Therefore, the wireless nodes are guaranteed to have contention-free data frame delivery.

In the GeRA scheme, the NAV is set to enough time to complete transmitting consecutive data frames. This NAV is easily calculated by using the basic concepts of the time-based fairness. Under the time-based fairness, each competing wireless node receives a fair share of the wireless channel occupancy time. The modified NAV is calculated as shown in (9). This equation can be divided into two factors (*T1* and *T2*). *T1* is the overall time of a data frame transmission at the rate *BasicRate*. *T2* is the additional overhead for transmitting the consecutive data frames at the rate *Tx.Mode*. The wireless node under the GeRA scheme tries to transmit consecutive data frames during the (*T1*+*T2*) when it accesses the wireless channel. Therefore, our GeRA scheme avoids frame collision and can successfully transmit consecutive data frames.

$$\begin{aligned} NAV_{NCF} = {} & \left(2\frac{PLCP}{BasicRate} + \frac{MPDU}{Tx.Mode} + \frac{ACK}{BasicRate} + SIFS \right) \times NCF \\ & + SIFS \times (NCF - 1) + \rho(P\,ropagation\_delay) \end{aligned} \tag{9}$$

$$NAV_{NCF} = T1 + T2 \tag{10}$$

$$T1 = 2\frac{PLCP}{BasicRate} + \frac{MPDU}{BasicRate} + \frac{ACK}{BasicRate} + SIFS + \rho^{'} \tag{11}$$

$$T2 = (NCF - 1) \times \left(2\frac{PLCP}{BasicRate} + 2SIFS + \frac{ACK}{BasicRate} \right) + \rho^{''} \tag{12}$$

3.3 The quality Adaptation Scheme of Our Design

To improve WLAN system performance by resolving the performance anomaly problem, a channel access mechanism should provide a time-based fairness scheme instead of a throughput-based one. Some time-based fairness schemes have been proposed for this purpose. However, those schemes have some limitations as described in Section 2.3 and they do not consider the rate adaptation scheme. In this paper, we propose the GeRA scheme that is a statistics-based rate adaptation scheme. GeRA scheme also provides time-based fairness to improve the wireless channel utilization by resolving the performance anomaly problem.

To provide a quality-adaptive video streaming service, the GeRA scheme informs its transportable rate limit to the streaming application via cross-layering. Depending on the optimal transmission mode, rate limit is periodically transmitted to the quality adaptation module; then, it is used to adapt the quality of video streaming by adjusting the number of active frames.

Our quality adaptation scheme utilizes the temporal scalability that is generally introduced in the MPEG standards. In our previous work, we proposed the quality adaptation scheme for wired video streaming that adjusts the quality of video stream based on the estimated receiver buffer occupancy and available bandwidth [4]. In our cross-layer design, the quality adaptation scheme is derived from the previous work except that the available bandwidth is replaced by the rate limit.

A new frame can be added as soon as the rate limit exceeds the consumption rate of the active frames (α, β, and γ) are the numbers of active frames for I-, P-, and B-frames, respectively). A more practical approach is to start sending a new frame when the rate limit exceeds the consumption rate of the active frames plus the newly added frame. A newly added frame (K) is selected according to the type of current active frames and the rate limit.

$$Condition\_1: RateLimits \geq Consumption\_rate(\alpha, \beta, \gamma, K)$$

This bandwidth constraint for adding frames is still not sufficiently conservative. Some excess bandwidth leads to more buffered data at the receiver and can induce buffer overflow. If the receiver buffer is expected to overflow, then the sender improves video quality by increasing the frame rate. Then, the receiver buffer occupancy may be lowered because the buffered active frames are more rapidly consumed by the decoder. Although the network condition is more congested transiently, the buffer overflow is nevertheless efficiently prevented.

$$Condition\_2: Number\ of\ buffered\ GOP \geq Threshold\_Overflow$$

An active frame can be dropped when the consumption rate of the active frames exceeds the current rate limit. However, to provide higher quality for as long as possible, a frame should be slowly dropped. If the receiver buffer is expected to underflow, then the sender degrades the video quality by decreasing the frame rate. Dropping an active frame leads to a lower consumption rate at the receiver and delivers more GOPs per unit time because the sending rate remains the same.

$$Condition\_3: Number\ of\ buffered\ GOP \leq Threshold\_Underflow$$

The quality adaptation scheme deactivates and discards an excess of data frames over the rate limit when the encoding rate of the original video stream is higher than the rate limit. However, all data frames are activated and transmitted to the receiver when the encoding rate is lower than the rate limit. If the data rate of the active frames exceeds the current rate limit, then some active frames are deactivated and discarded because the MAC and PHY layers cannot transmit these frames. On the other hand, some frames can be activated as soon as the rate limit exceeds the data rate of the current active frames. Newly activated or deactivated frames are selected according to the type of the current active frame and the level of the rate limit. The number of active I-frames in a GOP is regularly maintained because it has the highest data importance and no frame rate control. Also, the B-frames are deactivated earlier and activated later than the P-frames because of their lower data importance. If these three conditions are not satisfied, then the quality adaptation module keeps up the current active frames and transmits them by order of frame importance.

4. Performance Evaluation

4.1 Simulation Environment

In this section, we present our simulation environments and results. The GeRA scheme performance has been measured using the ns-2 simulator [19]. **Fig. 4** shows the network topology of the performance evaluations. All of our experiments are done in the BSS mode of IEEE 802.11b. A BSS includes an AP and two wireless nodes. To performance evaluate the proposed GeRA scheme, we generate the Constant Bit Rate (CBR) traffic at a rate of 4 or 8Mbps. In the simulation environments, we consider the two-ray ground model as the fading model of the wireless channel. We assume that the transmission power of each wireless node is configured to be 15dBm.

Each simulation lasts of about 50 seconds. During the simulation time, the wireless nodes (sender or receiver) are continuously moved to change the wireless channel conditions. From the 0 to 10 second mark, the nodes are fixed and from the 10 to 30 second mark, the nodes are moved away from the AP at a low speed, i.e. 1m/s. From the 30 to 40 second mark, they are moved up to the AP at a medium speed, i.e. 2m/s. Finally, from the 40 to 50 second mark, they are moved away from the AP again at a high speed, i.e. 3m/s.

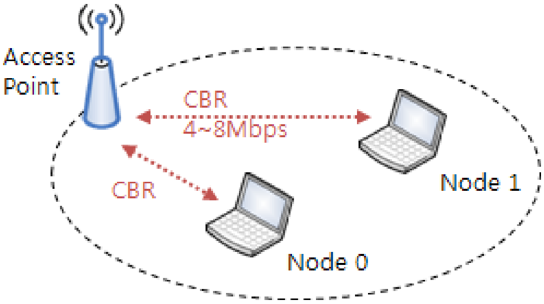


Fig. 4. Simulation environment for performance evaluation

4.2 The Rate Adaptation Scheme Performance

We checked the time-based fairness of our GeRA scheme and compared it to the previous CWmin-based scheme. **Fig. 5** shows the average throughput and aggregate throughput changes of these schemes during a 50 second span. For each time-based fairness scheme, the data transmission modes of node 0 and node 1 are set to 11Mbps and 5.5Mbps respectively. Our GeRA scheme and the CWmin-based scheme provide time-based fairness. However, our GeRA scheme reduces the channel access overhead and uses the wireless chennel resources more efficiently compared to the CWmin-based scheme. The GeRA scheme transmits consecutive data frames while CWmin-based scheme only transmits a data frame when the node captures the wireless channel. Therefore our proposed scheme improves the wireless channel utilization. Approximately, the aggregate throughput of the GeRA scheme is about 5.63Mbps and the CWmin-based scheme achieves about 5.21Mbps.

Under the same simulation environments, the estimated goodputs for each transmission mode are depicted in **Fig 6**. With the changes in the wireless channel conditions, the estimated goodputs of each transmission mode are oscillated because of the variable error rates. Normally, the oscillation of higher transmission modes is larger than that of slower transmission modes because the error rate is rapidly increased when the wireless channel conditions are bad. From the 10 to 30 second mark, the wireless node is moved away from the AP. The goodput of the 11Mbps mode is gradually oscillated because of the bad wireless channel conditions. From the 30 to 40 second mark, the wireless node is moved up to the AP and the goodput of the 11Mbps mode is higher than those of others. From the 40 to 50 second mark, the goodput of the 11Mbps mode is decreased considerably because the wireless node is moved away from the AP and the wireless channel conditions are rapidly degraded. During this period, the goodputs of the slower transmission modes are higher than the 11Mbps mode because they are more robust to the wireless channel errors.

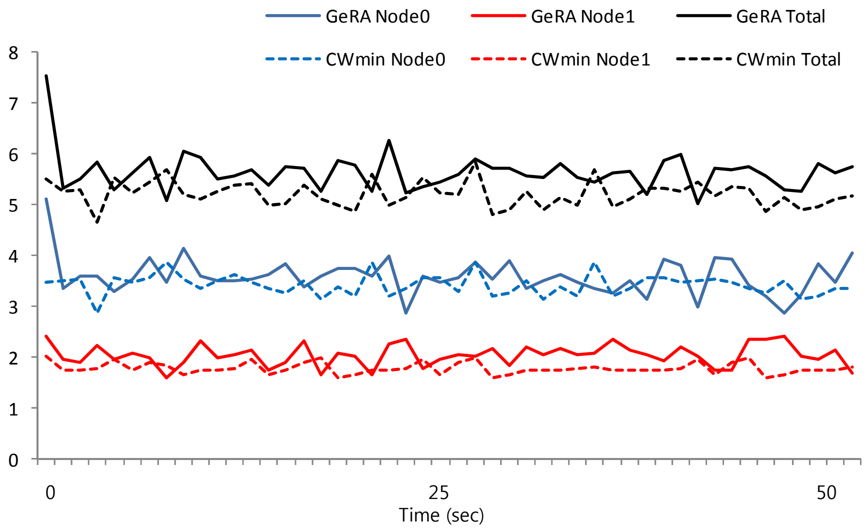


Fig. 5. Performance comparison between the GeRA scheme and the CWmin-based scheme

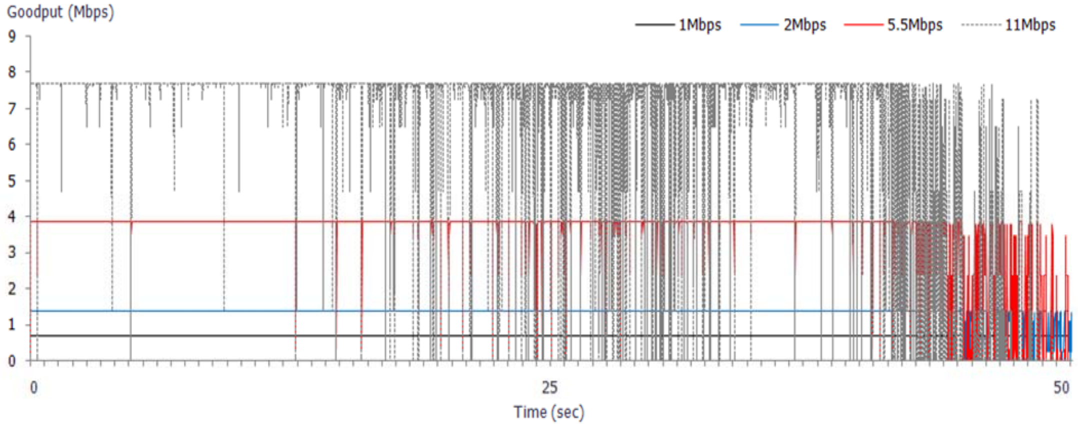


Fig. 6. Goodput changes for each transmission mode

Based on the estimated goodputs for each transmission mode as shown in **Fig. 6**, our GeRA scheme selects the optimal transmission mode with the highest goodput. **Fig. 7** shows the optimal transmission mode changes of the GeRA scheme. For the most part, the 11Mbps mode is selected as the optimal transmission mode. However, in case of the bad wireless channel conditions especially from the 40 to 50 second mark, the 5.5Mbps mode is frequently selected to be the optimal transmission mode because of its robustness. Sometimes we showed that the 2Mbps mode, even the 1Mbps one, is selected as the optimal mode when the wireless channel conditions reach the worst. From this result, we prove that the GeRA scheme reacts to the changes in wireless channel conditions and appropriately selects the optimal transmission mode.

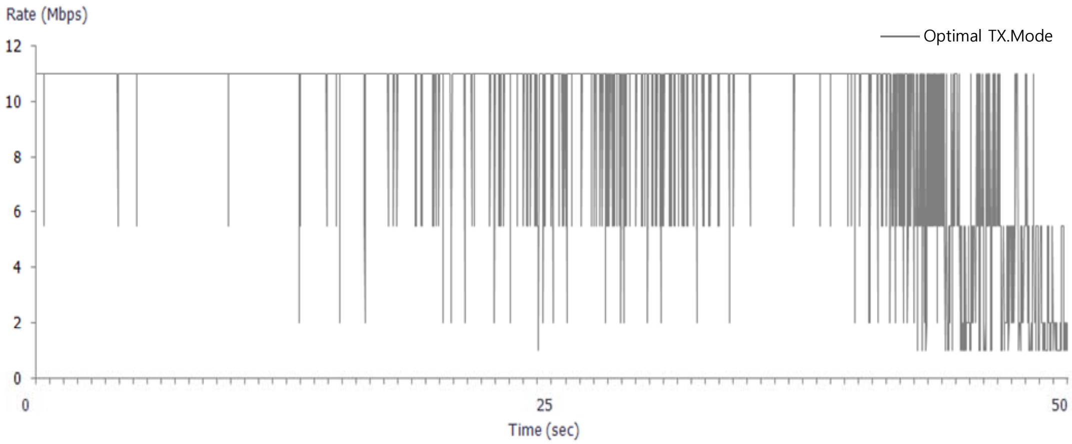
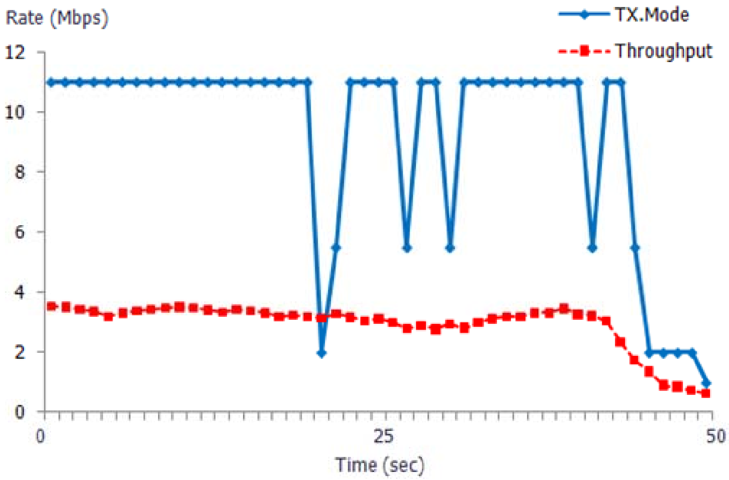
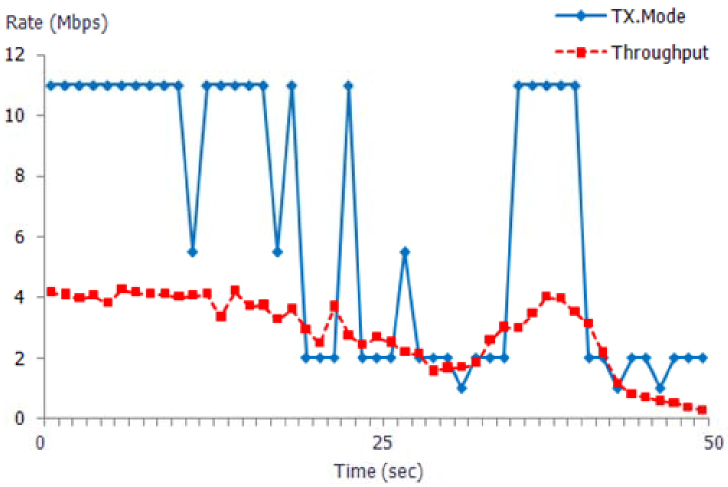


Fig. 7. Transmission mode changes

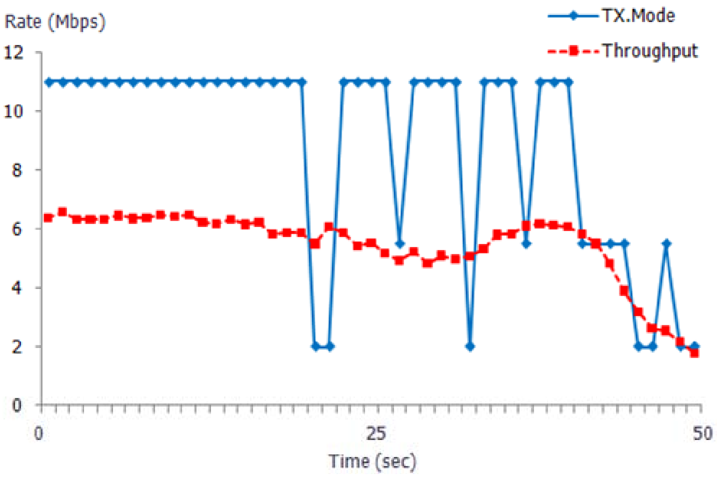
We check the performances of the RBAR and ARF schemes to compare them with our GeRA scheme. **Fig. 8** shows the transmission mode changes of these schemes with the throughput changes over the simulation time. The RBAR scheme rapidly reacts to the changes in the wireless channel conditions because it adjusts the transmission mode based on the measured channel quality. However, the ARF scheme does not react as well because it gradullay adjusts the transmission mode based on the successful or failed data frame delivery. Our GeRA scheme can be classified into the statistics-based approaches because it is based on the estimated goodput and error rate. However, our scheme can react rapidly to the changes in the wireless channel conditions just like the RBAR scheme because it chooses the optimal transmission mode with the highest goodput among the modes supported by the wireless node.



(a) RBAR scheme



(b) ARF scheme



(c) GeRA scheme

Fig. 8. Changes of the transmission modes and average throughputs

The number of total transmitted frames and wireless channel utilization are recorded in **Table 1** to compare the performance of the rate adaptation schemes in detail. To make the contending channel conditions, the simulation environment is extended by increasing the number of wireless nodes. The RBAR scheme rapidly responses to the changes in the wireless channel conditions and provides reliable data transmission by using the RTS/CTS exchange for every data frame. However, the RBAR scheme wastes wireless channel resources by using this RTS/CTS exchange that is enabled in every data frame and transmitted at the basic rate (i.e. 1Mbps). The ARF scheme cannot adjust the data transmission mode appropriately under the unstable channel conditions. Sometimes, it discards the data frame because of an excess of the retry limits and timeout. Our GeRA scheme transmits more data frames compared to the RBAR and ARF schemes because it selects the optimal transmission mode with the highest goodput and transmits the consecutive data frames to resolve the performance anomaly problem. Therefore, our scheme improves each wireless node throughput and channel utilization.

Table 1. Performance comparison

	Node	**Number of transmitted frames**	**Number of total transmitted frames**	**System throughput (Channel utilization)**
RBAR	0	8,717	18,321	2.93 Mbps
	1	9,604		
ARF	0	5,866	11,993	1.92 Mbps
	1	6,127		
GeRA	0	16,081	35,100	5.62 Mbps
	1	19,019		

4.3 The Quality Adaptation Scheme Performance

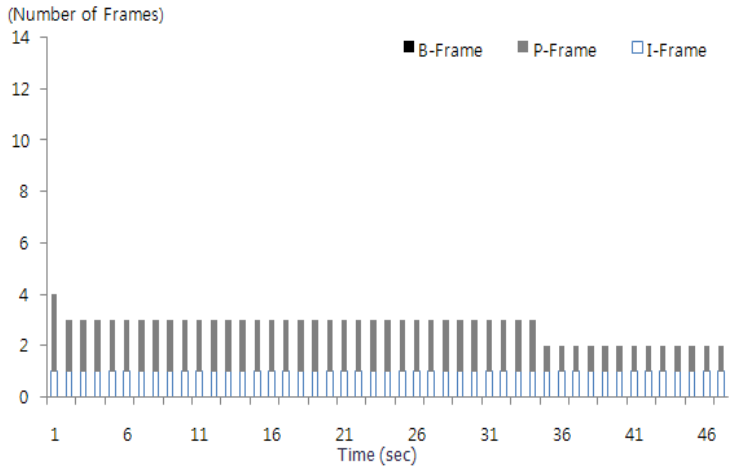
We use a video sample to evaluate the performance of ous quality adaptation scheme in a cross-layer design. The video sample characteristics are described in **Table 2**. We assume that the video stream has been encoded at 3.2 Mbps with 24 frames per second. The video sample also has three types of frames, I, P and B-frames, with different data sizes.

Table 2. The video sample characteristics

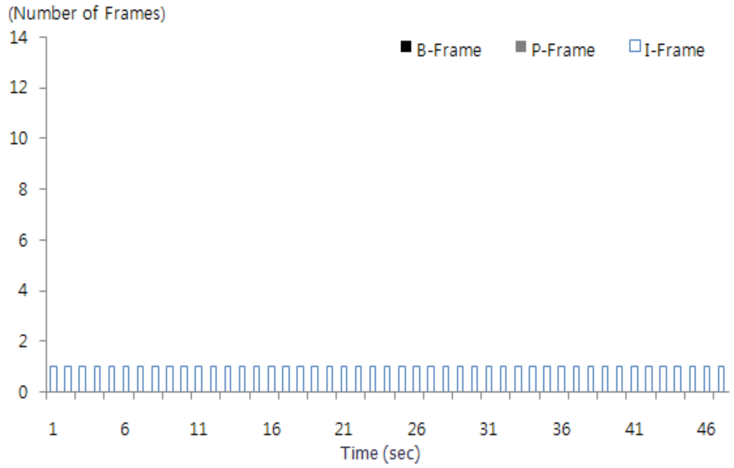
GOP Sequence	I-B-B-P-B-B-P-B-B-P-B-B		
Frame Rate	24 fps		
Encoded Rate	3.2 Mbps		
Frame Types	I	P	B
Number of Frames in a GOP	1	3	8
Size of Each Frame (bytes)	60 K	20 K	10 K

In the proposed cross-layer design, the GeRA scheme transmits the rate limit to the quality adaptation module. Those rate limit is transmitted to the quality adaptation module with one second intervals because the frequent quality changes of the video stream degrade the perceived quality of video streaming. After receiving the rate limit from the GeRA scheme, the quality adaptation scheme controls the quality of the video stream by adjusting the number of active frames. This quality adaptation is performed with one second intervals similar to the reporting interval of the rate limit.

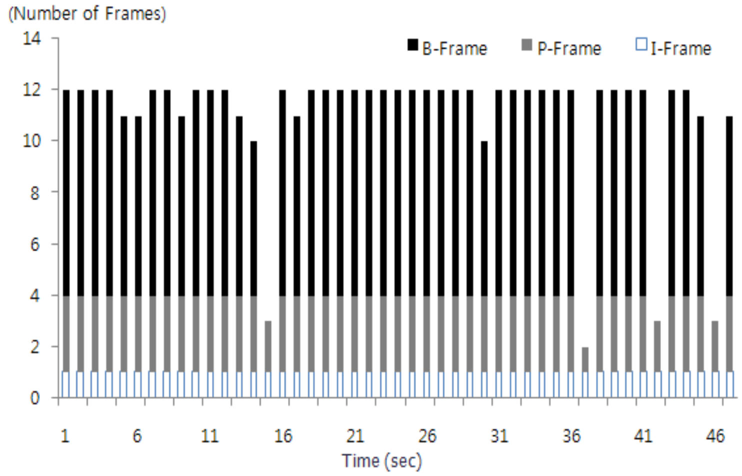
The simulation environment shown in **Fig. 4** is used to evaluate the quality adaptation scheme performance. If the rate limit is lower than the data rate of the video stream, then the quality adaptation scheme controls the number of active frames. **Fig. 9** shows that our quality adaptation mechanism appropriately controls the number of active frames within the rate limit. Based on the rate limit, the quality adaptation scheme activates or deactivates the data frames. The type of activated or deactivated frame is selected according to the frame's importance (I > P > B). Therefore, B-frames are deactivated earlier and activated later than P- and I-frames because of their lower frame importance. Compared with the ARF-based and RBAR-based schemes, our GeRA-based quality adaptation scheme improves the quality of video streaming with more P- and B-frames. From the simulation results, we prove that our quality adaptation scheme efficiently adjusts and improves the quality of video streaming with the help of the GeRA scheme.



(a) RBAR-based quality adaptation



(b) ARF-based quality adaptation



(c) GeRA-based quality adaptation

Fig. 9. The quality adaptation scheme performance

5. Conclusions

In this paper, we propose a new cross-layer design for video streaming over wireless networks. The proposed design combines the quality adaptation scheme with the rate adaptation scheme to improve video streaming quality. The GeRA scheme, a proposed rate adaptation scheme in our cross-layer design, selects the optimal transmission mode based on the estimated goodputs and calculates the number of consecutive data frames. Therefore, the GeRA scheme can improve the wireless channel utilization as well as the performance of each wireless node. The GeRA scheme of our cross-layer design transmits the rate limit to the quality adaptation module. The quality adaptation scheme utilizes this information to adjust the quality of video streaming.

Through the performance evaluations, we have proven that the proposed rate adaptation scheme improves the performance of the each wireless node and wireless channel utilization. Our cross-layer design properly combines the rate adaptation with the quality adaptation and improves the quality of wireless video streaming.

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