COMBINED LINK ADAPTATION AND TRAFFIC CONTROL SCHEME FOR MGS H.264/AVC VIDEO TRANSMISSION

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ABSTRACT

In this paper, we propose a joint link-adaptation and traffic control algorithm that efficiently allocates network resources to support multiple scalable video users over a capacity constrained wireless channel. Multi-rate networks, such as IEEE 802.16 or IEEE 802.11 use a link adaptation mechanism in the physical layer (PHY) and adjust the coding and modulation schemes to maintain the reliability of transmission under varying channel conditions. We consider Medium Grain Scalable (MGS) H.264/AVC video and employ a traffic control module that selectively drops individual video packets based on the packet dependencies in MGS. We present a framework that jointly optimizes the operation of the link adaptation and packet drop modules to achieve the highest video quality, while satisfying bandwidth/capacity constraints. Performance evaluations show that our proposed framework results in significant gains over existing schemes in terms of average video PSNR that can reach 3dB in some cases for different channel SNRs and different bandwidth budgets.

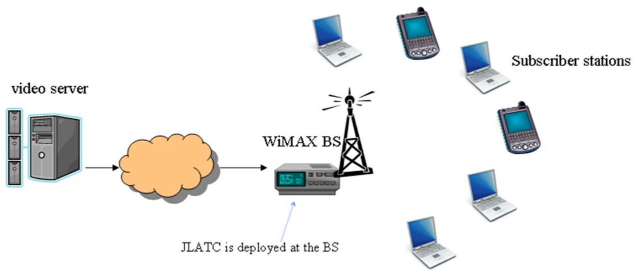


Fig. 1. General diagram of the wireless video streaming system in which a transmitter (base-station or access-point) serves multiple video users/clients. The video streaming service is allocated a fixed share of the bandwidth that the transmitter can support, such that all video users compete for a portion of the allocated bandwidth share.

1. INTRODUCTION

Broadband wireless services have witnessed a rapid growth that has accompanied a major advancement in video compression technology to enable future high quality digital video broadcast and telephony applications. However, there remain several challenges to be addressed before such applications are efficiently deployed.

The variation in wireless channel quality is usually handled using a link adaptation scheme that maintains a certain level of link reliability under varying channel conditions. The use of link adaptation results in multi-rate operation, where lower physical layer (PHY) transmission rates are used to achieve higher reliability under bad channel conditions. To counter this situation scalable video coding is used, where a single video sequence is encoded into a base layer and several enhancement layers. When the available throughput decreases, a traffic control module drops the higher enhancement layers. This method is the conventional solution for handling capacity variation using scalable video.

Several recent works have studied the transmission of scalable video over different types of wireless networks [1, 2, 3, 4]. The work in [1] presents an optimal solution for transmission of scalable video traffic over MIMO systems, through optimizing quantization parameters, GOP (Group of Picture) size and channel coding and symbol constellation for a simplified MIMO system. In the work presented in [2], a cross layer optimization scheme is provided that jointly optimizes MAC and application layer operations to improve the quality of delivered scalable video under delay constraints. The work presented in [3]] focuses on employing spatial multiplexing feature of a MIMO system to better deliver scalable video. This method proposes an adaptive channel selection for scalable video transmission over MIMO channels where partial channel information is derived and used to improve the system performance. In another relevant work, [4] proposes a rate distortion optimized method for transmission of scalable video over CDMA networks.

In this paper, we offer a new traffic control algorithm as well as an optimization framework that achieve the maximum possible video quality for multiple stations that are using Medium Grain Scalable (MGS) video [5, 6]. Our proposed solution differs from existing works in that it offers a combined link adaptation and MAC/Network layer packet drop scheme that maximizes the collective quality of the delivered video to multiple users. The methods presented in this paper are applicable to all packet based multirate networks such as IEEE 802.11 or IEEE 802.16 [7]. For demonstration purposes we consider the physical layer of the IEEE 802.11 Wireless Local Area Network (WLAN). The general system overview can be seen in Fig. 1.

The remainder of this paper is organized as follows: In section 2 we formalize the resource allocation problem. Section 3 proposes the joint link-adaptation and traffic-control optimization problem. The performance of the proposed joint resource allocation scheme is analyzed in Section 4, and finally we present our conclusions in Section 5.

2. GENERAL OVERVIEW OF THE RESOURCE ALLOCATION PROBLEM

In this section, we describe the different components of the video streaming system, formalize the problem at hand and discuss the existing solutions and their limitations. We consider a wireless video streaming system in which a transmitter (base-station or access-point) serves multiple video users/clients (Fig. 1). The video streaming service is allocated a fixed share of the bandwidth that the transmitter can support, such that all video users compete for a portion of the allocated bandwidth share.

2.1. Problem Description

Link adaptation and dynamic variation of capacity in wireless networks necessitates dynamic traffic control, which in turn requires the applications to be tolerant of variable throughput. For video applications, scalable video will be used to adapt the video bit-rate to the variable available throughput. With SVC, the simplest solution to adapt to decreased throughput is to drop the higher enhancement layers.

Let u be the video user index and let $l \in \{0, 1, ...L\}$ be the scalable video layer index, such that, layer 0 corresponds to the base layer and layer L the highest (lowest priority) enhancement layer. Let r_l^u be the estimated video bit-rate required by layer l of user u, and let C_l^u be the PHY transmission rate allocated for layer l of user u. We define the temporal share τ_l^u occupied by video layer l of user u as follows:

$$\tau_l^u = \frac{r_l^u}{C_l^u}. \tag{1}$$

In this paper, we assume that the scheduling algorithm is able to assign a fair share of the bandwidth, or a fair time share, to each user (video stream) or an aggregate of users [8]. The fair scheduler provides the total time share η for all video users (aggregate of their traffic) that share the streaming service. Within the aggregate service the time shares are distributed according the method presented in this paper. The aim here is to maximize the total quality of the delivered video under the time share constraint for the entire video service.

2.2. Overview of Existing Solutions

The 802.11 or 802.16 standards do not mandate a specific link adaptation scheme. The most common mechanism of selecting between the different transmission rates is to use SNR thresholds for the different transmission rates that meet a maximum error constraint, usually 10% PER for packet length of 1000 bytes [7]. The highest transmission rate that meets the maximum PER requirement is selected. To adapt the scalable video traffic to rate changes, different schemes may be used, as explained below.

2.2.1. Conventional Layer Drop

The conventional and simple solution for adapting the bit-rate of the scalable video to the available throughput is to drop the higher layers of video, until the remaining traffic fits in the available throughput for the stream. We call this method "conventional layer drop" (CLD), in this paper. The CLD method can be formulated as follows:

$$\max_{C^u, \hat{L}} \quad \hat{L} \quad \text{s.t.} \quad \sum_{l=0}^{\hat{L}} \tau_l^u(C_l^u) \leq \eta^u, \quad \text{and } p_l(C_l^u) \leq 10\% \tag{2}$$

where $\hat{L} \in \{0, 1, ...L\}$ is the highest admissible video layer, L is the maximum number of available video layers, p_l is the packet error probability associated with the selected transmission rate C_u for user u, and η^u is the temporal share of user u.

2.2.2. Intelligent Link Adaptation

A more intelligent method to is to replace the conventional link adaptation, and layer drop schemes, with a combined link adaptation and layer drop scheme that assigns different PHY rates to each layer and drops the enhancement layers that do not fit in the available throughput for the stream. This method is called Intelligent Link Adaptation (ILA) and has been studied in detail in [9]. ILA is based on per-stream traffic control, and aims at improving the video quality of users individually, and on a long term average basis. We formulate the ILA scheme as shown below:

$$\min_{\hat{L}, C^u} \bar{D}^u(\hat{L}, C^u), \text{ s.t. } \sum_{l=0}^{\hat{L}} \tau_l^u(C_l^u) \leq \eta^u, \tag{3}$$

where $\bar{D}^u(\hat{L}, C^u)$ is the time-averaged video distortion model given as a function of the maximum number of admissible video layers $\hat{L}$ and the PHY transmission rate C^u.

The solution to this problem consists of a combinatorial search over all achievable PHY rate points (and corresponding PER points) to choose the set that minimizes the video distortion function $\bar{D}^u$. Since ILA considers video streams individually, it can be used at any source that transmits the video, i.e., the base station or the subscriber stations.

3. PROPOSED RESOURCE ALLOCATION SCHEME

In this section, we present a new link-adaptation scheme for real-time resource allocation of multiple MGS scalable video streams. The objective of our optimization framework is to maximize the total quality of multiple video streams that share the same wireless channel, while maintaining the total load on the network constant.

3.1. Description of the Proposed Resource Allocation Scheme

The proposed link adaptation and traffic control modules shown in Fig. 2 work cooperatively through an optimization framework that determines the best configuration for each module.

We consider a wireless system where U scalable video (MGS) users/clients are served over a single wireless channel with a streaming service constraint η, where $\eta \leq 1$. For simplicity of illustration and without loss of generality, we assume that each video stream u is composed of a base-layer and $L^u = 2$ MGS enhancement layers. The scalable video streams are characterized in terms of their rate-distortion parameters: $\{\tilde{d}_0^u, \tilde{d}_1^u, \tilde{d}_2^u\}$ and $\{\tilde{r}_0^u, \tilde{r}_1^u, \tilde{r}_2^u\}$ given in [10]. The rate and distortion parameters are calculated for fixed values of base and enhancement layer QPs. In a multirate wireless physical layer considered here, different PHY rates are achieved by changing the modulation and coding schemes, resulting in different

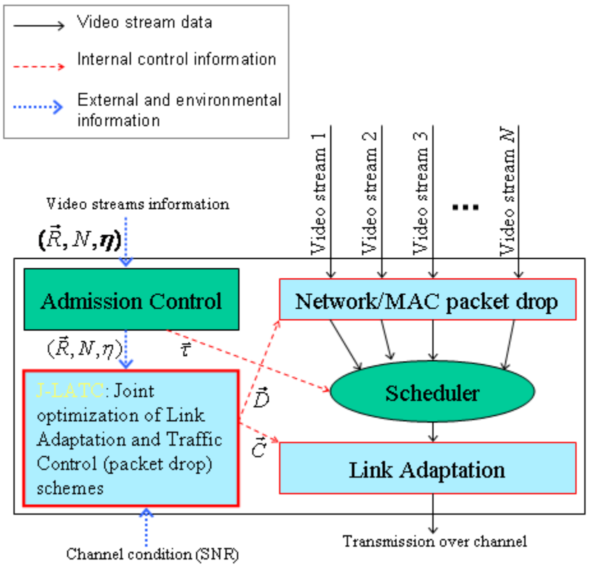


Fig. 2. The Joint operation of the Link-Adaptation and Traffic-Control modules in our proposed framework. The algorithm combines the resources $(\vec{R}, N, \vec{\tau})$ assigned to all users allowing dynamic allocation of these resources on a short term basis. This results in more efficient use of the limited capacity η and higher overall received video quality $\vec{D}$ of all transmitted streams that share the same wireless channel.

packet loss ratios under a given SNR γ. We denote such loss ratio as $p_l = f(C_l, \gamma)$, for each video layer assigned a PHY rate C_l.

Let t and G be the GOP index and GOP size, respectively. We define $\tilde{D}_t^u$ to be the predicted average PSNR for GOP t of video stream u, such that

$$\begin{aligned} \tilde{D}_t(P) = \; & p_0 d_{EC} + (1-p_0)\tilde{d}_0 \\ & +(1-p_1)(1-p_0)(\tilde{d}_1 - \tilde{d}_0) \\ & +(1-p_2)(1-p_1)(1-p_0)(\tilde{d}_2 - \tilde{d}_1) \end{aligned} \quad (4)$$

where d_{EC} is the distortion due to the error concealment mismatch, and $P = f(C, \gamma) = [p_0 p_1 p_2]^T$ is the packet error rate (PER) vector. Note that we dropped the superscript u from the expression above for clarity of illustration.

The predicted temporal time share of a GOP t of stream u, denoted as $\tilde{\tau}_t^u$, can be expressed as follows:

$$\tilde{\tau}_t(C) = \frac{\tilde{r}_0}{C_0} + \frac{\tilde{r}_1}{C_1} + \frac{\tilde{r}_2}{C_2}. \quad (5)$$

We propose to employ a packet dropping/stopping stage in the proposed scheme that blocks the transmission of some packets of each layer, effectively reducing the bit-rate of the layer.

Let x_l be the percentage of blocked packets of layer l, resulting in an effective video layer bit-rate $\tilde{R}_l = \tilde{r}_l(1 - x_l)$. Therefore, we can rewrite the video stream's predicted PSNR and corresponding time share as shown below:

$$\begin{aligned} \tilde{D}_t(X, C) &= p_0 d_{EC} + (1-p_0)\tilde{d}_0 \\ &\quad +(1-x_1)(1-p_1)(1-p_0)(\tilde{d}_1 - \tilde{d}_0) \\ &\quad +(1-x_2)\textstyle\prod_{l=0}^{2}(1-p_l)(\tilde{d}_2 - \tilde{d}_1) \\ \tilde{\tau}_t(X, C) &= \tfrac{\tilde{r}_0}{C_0} + (1-x_1)\tfrac{\tilde{r}_1}{C_1} + (1-x_2)\tfrac{\tilde{r}_2}{C_2} \end{aligned} \quad (6)$$

where l is the video layer index, and C_l is the PHY transmission rate of layer l. Notice that we do not assign a drop rate for the base layer to avoid the costly quality degradation associated with error concealment mismatch and to satisfy quality of service (QoS) guarantees.

The new multi-user resource allocation problem can now be formulated as the following constrained optimization problem with variables $\mathbf{X}$ and $\mathbf{C}$:

$$\begin{aligned} \max_{\mathbf{X},\mathbf{C}} \quad & \textstyle\sum_{u=1}^{U} \tilde{D}_t^u(X^u, C^u) \\ \text{subject to} \quad & \textstyle\sum_{u=1}^{U} \tilde{\tau}_t^u(X^u, C^u) \le \eta_t, \\ & C_0^u \le C_1^u \le C_2^u, \\ & 0 \le x_1^u \le x_2^u \le 1 \text{ for all } u, \end{aligned} \quad (7)$$

where $\mathbf{X} = [X^1 X^2 ... X^U]$, $X^u = [x_1^u x_2^u]^T$, $\mathbf{C} = [C^1 C^2 ... C^U]$, and $C^u = [C_0^u C_1^u C_2^u]^T$ defined in (6), $u \in \{1, 2, ... U\}$ is the user index.

The constrained optimization problem defined in (7) is a mixed integer non-linear programming problem whose solution is non-trivial. The variables $X^u \in [0, 1]$ are continuous, while $C^u \in \mathcal{C}$ are discrete and $\mathcal{C} = \{\mathcal{C}_0, \mathcal{C}_1, ... \mathcal{C}_M\}$ is the set of feasible PHY transmission rates associated with the current channel SNR, and M is the cardinality of $\mathcal{C}$.

3.2. Solution of the Global Optimization Problem

Mixed integer programming problems are typically NP-hard. Therefore, we develop an algorithm in this section to solve the above mentioned problem (defined in (7)) by first solving the continuously-relaxed problem illustrated below, then projecting the solution of the continuous relaxation on the set of achievable PHY rate points and solving for the layer drop rates X^u that satisfy the temporal share constraint η.

3.2.1. Continuous relaxation of the optimization problem

The continuous relaxation of the discrete constrained optimization problem of equation (7) can be performed by replacing the discrete variable C^u with a continuous valued variable $W^u = [w_0^u w_1^u w_2^u]^T \in \mathcal{W}^3$, where $\mathcal{W} = [\mathcal{C}_0, ... \mathcal{C}_M]$, and finding the continuous approximation of the function $P(C^u, \gamma^u)$, where γ^u is the channel SNR of user u.

We re-write the continuously relaxed constraint and objective functions as follows:

$$\begin{aligned} \tilde{D}_t(W) &= \rho(w_0)d_{EC} + (1-\rho(w_0))\tilde{d}_0 \\ &\quad +(1-\rho(w_1))(1-\rho(w_0))(\tilde{d}_1 - \tilde{d}_0) \\ &\quad +\textstyle\prod_{l=0}^{2}(1-\rho(w_l))(\tilde{d}_2 - \tilde{d}_1) \\ \text{and} & \\ \tilde{\tau}_t(W) &= \tfrac{\tilde{r}_0}{w_0} + \tfrac{\tilde{r}_1}{w_1} + \tfrac{\tilde{r}_2}{w_2}, \end{aligned} \quad (8)$$

where $\rho(W^u, \gamma^u)$ is the continuous approximation of the PER function $P(C^u, \gamma^u)$.

3.2.2. Normal approximation of the PER curves

The PER vs PHY transmission rate relationship is given by a discrete set of achievable points that are a direct consequence of the channel SNR and the employed modulation and coding scheme. We have found that this relationship can be modeled using the continuous complementary CDF of the normal distribution $N(np_c, np_c(1-p_c))$ shown below:

$$\rho(n, C, p_c) = \frac{1}{2}\left[1 - \mathrm{erf}\left(\frac{n - C - \mu}{\sqrt{2\sigma^2}}\right)\right], \qquad (9)$$

where C is the PHY transmission rate, $\mu = np_c$ and $\sigma^2 = np_c(1-p_c)$, $\mathrm{erf}(.)$ is the Gauss error function, and n and p_c are model parameters calculated offline.

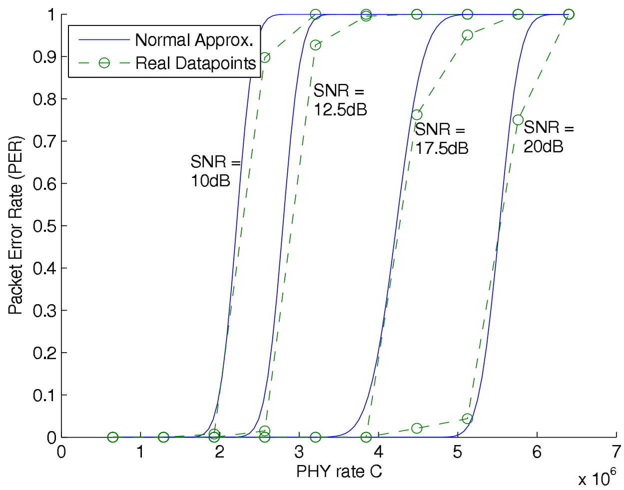


Fig. 3. Example of the achievable packet error rate (PER) curves and their continuous approximation as a function of the PHY transmission rates for different SNRs.

Fig. 3 shows the achievable PER vs PHY rate curves and their continuous approximation using the gaussian complimentary CDF for different channel SNRs. The packet error rate values are calculated for an average packet length of 1000 bytes. It can be seen from the figure that the function ρ of (9) is non-convex over the full range of W. Fig. 4 illustrates the non-convex shape of ρ over the full range of W, which renders the constrained optimization problem non-convex. Since ρ is either 0 or 1 for most of the range of W, and a PER rate greater than 50% is simply useless, we have narrowed down the feasible range of W to the convex interval where $0 < \rho \leq 0.5$. This interval corresponds to the following bounds for W:

$$n - \mu - \mathrm{erf}^{-1}(0.99)\sqrt{2\sigma^2} \leq W \leq n - \mu, \qquad (10)$$

where μ and σ^2 are the mean and variance of the approximate normal distribution function shown in equation (9). The new feasible region is now convex and corresponds to the highlighted area in Fig. 4.

3.2.3. Joint Link-Adaptation and Traffic-Control (JLATC) Algorithm

For simplicity of presentation, we describe the algorithm for a three layer scenario. The continuously-relaxed constrained optimization

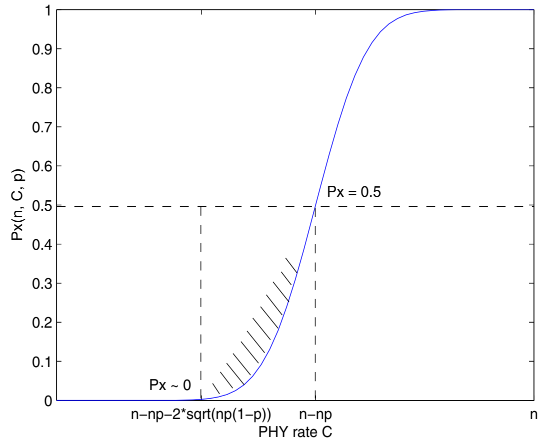


Fig. 4. Plot of the function $\rho(.)$ showing the non-convex shape of the function over the full range of W and the convex region over the reduced feasible interval.

problem can now be written as shown below:

$$\begin{array}{ll} \max\limits_{\mathbf{W}} & \sum_{u=1}^{U} \tilde{D}_t^u(W^u) \\ \text{subject to} & \sum_{u=1}^{U} \tilde{\tau}_t^u(W^u) \leq \eta_t, \\ & n - \mu - 2\sqrt{2\sigma^2} \leq w_l^u \leq n - \mu, \\ & \text{and } w_0^u \leq w_1^u \leq w_2^u, \\ & \text{for all } u \in \{1, 2...U\}, l \in \{0, 1, 2\}, \end{array} \qquad (11)$$

where $\mathbf{W} = [W^1 W^2 ... W^U]$, $W^u = [w_0^u w_1^u w_2^u]^T$ is the continuous valued PHY rate defined in (8).

The solution to Eq. (11) is very straightforward, since the problem is convex, and results in the continuous valued PHY rate allocation matrix $\mathbf{W}^*$. The optimal rates $\mathbf{W}^*$, however, are not realizable since the transmitter can only use the predefined set of discrete PHY rates $\mathcal{C}$. Moreover, each optimal rate point w_l^{u*} falls between two achievable PHY rate points in $\mathcal{C}$. Therefore, for each optimal rate vector $W^{u*} = [w_0^{u*} w_1^{u*} w_2^{u*}]^T$ of user u, we propose the following approach:

1: Find the rate points C_l' and C_l'', for all $0 \leq l \leq 2$, such that $\{C_l' \leq w_l^{u*} \leq C_l''$, and $C_l', C_l'' \in \mathcal{C}\}$ are the discrete achievable PHY rate points adjacent to w_l^{u*}.

2: Form the set of vectors

$$\hat{C} = \begin{bmatrix} \hat{C}_0 \\ \hat{C}_1 \\ \hat{C}_2 \end{bmatrix},$$

where $\hat{C}_0 = C_0'$, $\hat{C}_1 \in \{C_1', C_1''\}$, and $\hat{C}_2 \in \{C_2', C_2''\}$.

3: For every vector $\hat{C}$, find the layer drop rates $\hat{X}^u$ that solve the following equation:

$$\begin{array}{ll} \max\limits_{\mathbf{X}} & \sum_{u=1}^{U} \tilde{D}_t^u(\hat{C}, \hat{X}^u) \\ \text{subject to} & \sum_{u=1}^{U} \tilde{\tau}_t^u(\hat{C}, \hat{X}^u) \leq \eta_t, \\ \text{and} & 0 \leq x_1^u \leq x_2^u \leq 1 \text{ for all } u. \end{array} \qquad (12)$$

4: Choose the set of mapped PHY rate points C^u and layer drop rates X^u that results in the maximum value for the objective function in (12) as shown below:

$$\{C^u, X^u\} = \arg \max_{\{\hat{C}, \hat{X}\}} \tilde{D}_t^u(\hat{C}, \hat{X}).$$

Fig. 5 illustrates the mapping process from the optimal rate vector W^* to the achievable PHY rate points. Note that w_0^* is mapped to the lower rate point C_0' to avoid a possible increase in PER for the base layer, while w_1^* and w_2^* can each be mapped to two possible rate points C_1', C_1'' and C_2', C_2'', respectively.

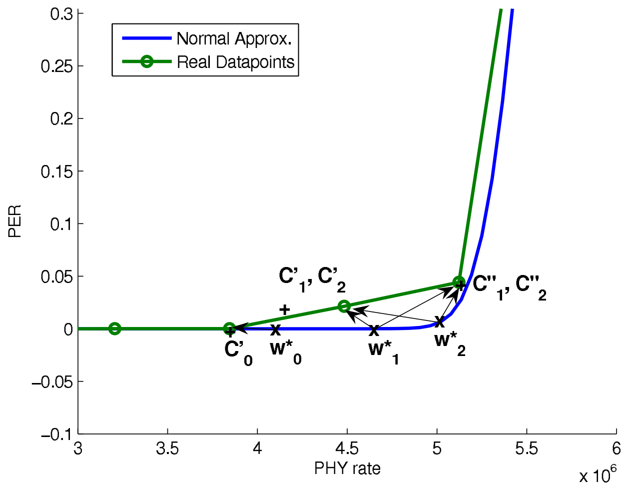


Fig. 5. Example of the mapping process involved in discretizing the continuous valued optimal rate points w_l^* to the achievable discrete PHY rates C_l' or C_l'', where $l \in \{0, 1, 2\}$.

This algorithm, in effect, narrows down the combinatorial search range limiting it to the achievable PHY rate points that are adjacent to the optimal solution given by $\mathbf{W}^*$.

4. PERFORMANCE EVALUATION

In this section, we compare the performance of our proposed streaming approach to existing streaming schemes. For our comparisons, we used the JSVM-9-8 reference software [11] to encode 7 reference video sequences in CIF resolution: Foreman, Football, Bus, Mobile, Soccer, Crew, and City. Each sequence is composed of 150 frames encoded in SVC, with an H.264/AVC compatible base layer, and two MGS enhancement layers. The coded video streams are composed of I and P frames only, with an IDR period of 32 frames, a frame rate of 30 fps, and minimum QoS guarantee corresponding to the base-layer quantization parameter value of $q_0 = 38$. The first and second MGS enhancement layers have QP values of 32 and 26, respectively.

The channel BER performance curves were obtained using an elaborate MATLAB model developed at UBC for the 802.11a/n PHY, based on the work in [12] and [13]. Using bit error rate (BER) curves of all valid combinations of modulation and coding, a look up table is constructed. This look up table is used to generate one-to-one mapping between the PHY rate and PER. For simplicity of simulations and experiments we have only included the performance curves for the Space Time Block Coding (STBC) modes of a 2X2 802.11n MIMO system. This does not have any effect on the generality of the optimization problem, and the results are easily extendable. BER curves for all STBC MCS indices for a 2x2 MIMO system can be seen in Table 1. The values of MCS are 0 to 7, with corresponding bitrates of: {6.5, 13, 19.5, 26, 39, 52, 58.5, 64} Mbps.

To demonstrate the advantages of our proposed Joint Link Adaptation and Traffic Control (JLATC) algorithm, we compare its performance with that of the ILA and CLD schemes. Resource allocation using each of the three schemes is performed for every group of eight pictures. Therefore, the ILA model parameters are calculated for every GOP of size $G = 8$ and stored at the transmitter. A major drawback for the ILA scheme is that the model parameters of future GOPs cannot be predicted from the parameters of the current GOP. As a result, the ILA scheme suffers in real-time applications and can only use the initial model estimates for the entire streaming session. Our JLATC, on the other hand, requires only the model parameters of the first GOP which it uses consequently to predict and update the model parameter of future GOPs using the process described in [10].

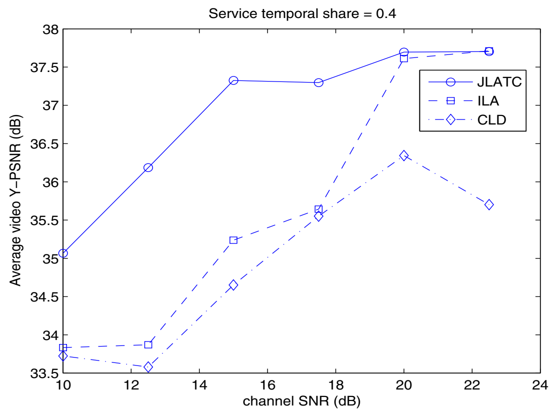
Table 1. Valid MCS Indices for 2x2 802.11n WLAN

MCS	Bitrate (Mbps)	Code Rate	SM streams	Modulation
0	6.5	1/2	1	BPSK
1	13	1/2	1	QPSK
2	19.5	3/4	1	QPSK
3	26	1/2	1	16-QAM
4	39	3/4	1	16-QAM
5	52	2/3	1	64-QAM
6	58.5	3/4	1	64-QAM
7	65	5/6	1	64-QAM

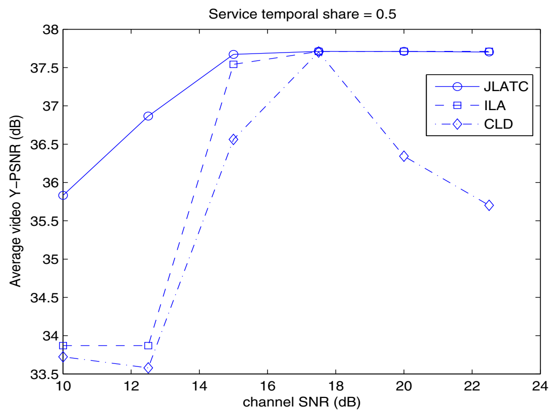
For our performance evaluations we use the video luminance peak signal-to-noise ratio (Y-PSNR) as the picture quality metric, and compare the received video PSNR from each resource allocation scheme for different channel SNR values and different bandwidth budgets η for the streaming service. Fig. 6 illustrates the results of the comparison in terms of the average Y-PSNR for all seven streams. The figure shows that for a temporal share $\eta = 0.4$ which corresponds to tight bandwidth constraints, the proposed JLATC scheme significantly outperforms its closest contender, the ILA scheme, by an average of 1.2dB for different channel SNR values. The performance gain peaks at 2.3dB in average Y-PSNR in the case where the channel SNR = 12.5dB. In the case where the channel is not congested the plots show that both the JLATC and ILA schemes approach the maximum achievable video PSNR that is given by the video stream encoding.

5. CONCLUSION

In this paper, we show that jointly optimizing the link-adaptation and traffic control of a multi-user wireless video streaming system considerably improves the received video quality for all video users and enhances the channel bandwidth utilization. Multi-rate networks such as IEEE 802.11 or 802.16 use link adaptation mechanisms in the physical layer to adjust the modulation and coding schemes that control the reliability of transmission for varying channel conditions. We propose a new resource allocation scheme that takes advantage of the robust and efficient delivery provided by scalable coded video streams to jointly optimize the link-adaptation scheme in the physical layer (PHY) with a new traffic control module in the network or MAC layer. The traffic control module operates by dropping the necessary percentage of packets from enhancement layers that cannot be fully transmitted, in order to fully utilize the available transmission bandwidth. Performance evaluations comparing our proposed scheme with existing solutions show that the proposed approach results in significant gains in terms of average video PSNR that can reach 3dB in some cases for different channel SNRs and different bandwidth budgets.



(a)



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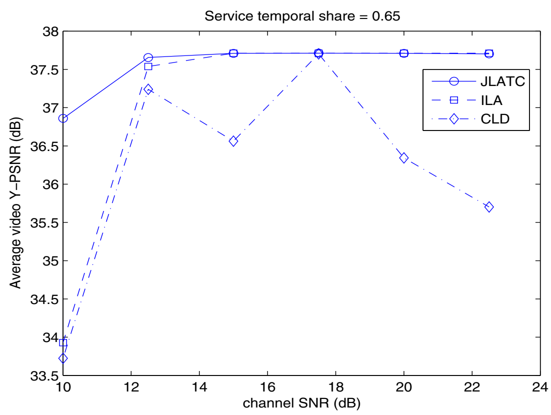

(c)

Fig. 6. Comparison in average Y-PSNR performance between the three resource allocation schemes: JLATC (proposed), ILA, and CLD. The performance of each scheme is plotted versus different channel SNRs and η.

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