Quality-Driven Joint Rate and Power Adaptation for Scalable Video Transmissions over MIMO Systems

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Abstract—We propose a joint rate and power adaptation scheme to maximize the decoding quality for scalable video coding (SVC)-based video transmissions over multi-input multi-output (MIMO) systems. The rate adaptation in our proposed scheme includes selecting the best modulation and coding schemes (MCSs), set of spatial channels, number of SVC layers (source coding rates) and their corresponding application layer forward error correction (APP-FEC) coding rates. The power adaptation involves the proper allocation of the power to each antenna in the MIMO system. SVC-based video transmissions require unequal error protection (UEP) for different SVC layers due to the inter-layer dependency. In most of the previous work, the bit stream of each particular SVC layer is allocated to one spatial channel and the UEP is achieved by transmitting the more important SVC layers through the spatial channels with higher channel gains. However, in our proposed scheme, the bit stream of each particular SVC layer is distributed to multiple spatial channels so that additional diversity gain can be exploited by applying APP-FEC. The UEP can also be achieved by allocating different APP-FEC coding rate on each video layer. Moreover, transmit power allocation is also effectively and jointly determined to improve the system performance. The effectiveness and favorable performance of our proposed scheme are shown by simulations with H.264 SVC traces of high definition (HD) video clips over MIMO systems.

Index Terms—Rate adaptation, power allocation, scalable video coding (SVC), multi-input multi-output (MIMO).

I. INTRODUCTION

As predicted in [1], 72% of all consumer mobile traffic will be mobile video traffic in 2019, up from 55% in 2014. Furthermore, mobile data traffic will exponentially increase between 2014 and 2019, representing a 57 percent of compound annual growth rate (CAGR), which is about three times faster than fixed IP traffic. The development of modern video delivery technologies have been boosted by the rapidly increasing demand of wireless multimedia applications [2]–[4]. Nevertheless, video streaming applications are bandwidth consuming and delay sensitive. Moreover, high packet loss rate, large delay and jitter, caused by the bandwidth-limited and error-prone nature of wireless channels [5], result in tremendous quality degradation of real-time video streaming services [6].

Many technologies have been developed to compensate for the effects caused by varying wireless channel quality. In the application (APP) layer, scalable video coding (SVC) [7], [8] is employed so that videos can be encoded with several spatial, temporal and quality scalabilities (layers), including one base layer and several enhancement layers, where valid bit streams can still be formed even when parts of the encoded bit streams (higher enhancement layers) are removed. With more decoded enhancement layers, the received video quality is improved. But the video layers are dependent such that the base layer and lower enhancement layers are required to be successfully decoded in order to decode higher enhancement layers. Thus, SVC can be used to accommodate varying terminal capabilities or network conditions as well as satisfying the various needs or preferences of end users. Another widely used APP layer technology for video streaming is application layer forward error correction (APP-FEC). With the APP-FEC, data packets are transmitted along with additional well-designed redundant packets. By receiving subsets of data and redundant packets, the receiver can reconstruct all of original data packets even when some packets are lost [9]. Therefore, APP-FEC can provide certain correction capability without retransmissions. This is suitable for delay-sensitive real-time video streaming applications [9], [10]. In the physical (PHY) layer, multi-input multi-output (MIMO) technology is one of the effective solutions to support high quality video streaming services [11]. By taking advantage of spatial diversity and/or spatial multiplexing, MIMO can significantly improve transmission reliability and/or spectral efficiency accordingly [12], [13]. When beamforming and power allocation techniques are applied, MIMO systems can also provide unequal error protection (UEP) on bit streams transmitted through different spatial channels [14]. Since SVC video layers have different decoding priorities due to their inter-layer dependency, MIMO systems are suitable for transmitting SVC-based videos with UEP on each video layer [15].

To efficiently utilize the varying wireless channel, it is crucial to adaptively configure the system parameters with cross-layer design so that the characteristics of technologies on
different open system interconnection (OSI) layers are jointly optimized. Various quality of service (QoS) measures, such as packet loss rate, delay and jitter etc., can be used as the criteria of network optimization for the general purpose designs of wireless transmission systems [16]–[18]. For video streaming services, the ultimate goal is to improve the decoding quality at the user end. In the recent video transmission research, transmission and video coding parameters are adjusted based on well-designed objective video quality measures, which have high correlation with users’ subjective perceptual satisfaction.

Many studies have been conducted in rate and power allocation for video streaming applications. In [19], an opportunistic layered multicast system is proposed for scalable video multicast, where APP-FEC rates and modulation and coding schemes (MCS) are jointly optimized for better video receiving qualities. A quality-driven resource allocation scheme for real-time video transmissions is proposed in [20], where the source coding rate and transmission data rate are jointly considered. The authors in [21] proposed a scheme for wireless video chat applications, where the system transmission parameters are adjusted based on a power-rate-distortion model.

Moreover, many studies have been conducted in transmitting scalable videos over MIMO systems. In most of the previous work, different UEP schemes are developed based on the dependency structure of SVC video layers [22]. In [15], authors proposed an adaptive channel selection (ACS) scheme where the UEP is achieved by transmitting higher priority bit streams (i.e., base layer and lower enhancement layers) through spatial channels with higher channel qualities. The advantage of this scheme is that it is simple, effective, and only requires partial channel information. UEP can also be achieved by power allocation [14], [23]–[25]. With full channel knowledge, the transmit power is adjusted based on empirical design [23] or optimized for SVC video decoding quality [14], [24]. With a well-designed transmit power allocation, the SVC video decoding quality at the user end is further improved compared with ACS [15]. In [25], an unequal power allocation scheme is developed for SVC video transmissions over massive-MIMO system, where multiple receivers are considered. In [26], an optimal power allocation scheme is proposed for transmitting multiple SVC-based video streams to multiple end users through MU-MIMO. A resource allocation scheme is proposed in [27], where power, modulation and bit-level FEC coding are adjusted according to video distortions. In the above work, each particular SVC video layer is transmitted through a single spatial channel and the number of video layers is restricted by the number of available spatial channels. This limits the flexibility of the system. Furthermore, the FEC applied in the above can only exploit the diversity gain in time domain since the bit stream of each SVC video layer is not interleaved to multiple spatial channels.

In our previous work, we proposed a novel MIMO transmission scheme for SVC-based video streaming in such a way that each bit stream of a particular SVC video layer can be spread over multiple spatial channels [28]. By applying FEC diversity in both the time and spatial domains can be exploited. The UEP of each video layer is achieved by different FEC coding rates, which is optimized based on video decoding quality. Moreover, the number of transmitted video layers and the spatial channels are jointly selected to better utilize the wireless resources. We demonstrate that when the spatial diversity gain can be exploited, the system performance with equal transmit power allocation can even outperform the ACS scheme with near-optimal power allocation proposed in [14], [24].

In this paper, we further extend our previous work in [28] in the following aspects: First, the adaptive modulation and coding (AMC) scheme is considered so that the system is more flexible in different channel conditions. Second, since the bit stream of each video layer is spread over multiple spatial channels, the power allocation schemes proposed in [14], [24] are no longer valid. In this work, we propose a novel power allocation scheme, which is specifically suitable in our proposed transmission scheme. Third, we apply APP-FEC to exploit the time-space diversity instead of using PHY-FEC as in [28]. By using APP-FEC, the proposed system can be more compatible with current wireless communication standards. Fourth, high-definition (HD) videos, which have different quality performance requirements than those of lower resolution videos, are used in the simulations.

This paper is organized as follows. System overviews, including SVC-based video coding, APP-FEC and MIMO systems, are introduced in Section II. In Section III, problem formulations, including SVC video layer selection, power allocation, adaptive APP-FEC rate control, AMC and spatial channel selection, are described. Problem solving strategies and detailed algorithms are proposed in Section IV. Simulation results and concluding remarks are given in Section V and VI respectively.

Notations: Upper (lower) boldface letters are used for matrices (column vectors). $E[\cdot]$ denotes the expectation. $\text{diag}(\mathbf{h})$ is a diagonal matrix with the elements of $\mathbf{h}$ sitting on the diagonal. $\mathbf{1}_N$ is $N \times 1$ unit vector. $\mathbf{I}_N$ denotes the $N \times N$ identity matrix. $(\cdot)^{T}$ denotes the transpose. $(\cdot)^{H}$ means the Hermitian. $\lceil \cdot \rceil$ represents the ceil. $\lfloor \cdot \rfloor$ is the floor. The curled inequality symbol (e.g., $\succeq$) represents the component-wise inequality.

II. SYSTEM OVERVIEW

A. SVC-Based Videos

As illustrated in Fig. 1, SVC can encode a video sequence into up to $L_{\text{max}}$ layers, including one base layer and $L_{\text{max}}-1$ enhancement layers with certain dependencies [7], [8], [22]. The base layer is the most important layer because it is mandatory to decode the whole video sequence. All the enhancement layers rely on the base layer. And a less important (higher-layered) enhancement layer relies on more important (lower-layered) enhancement layers. The more successfully decoded enhancement layers, the better the reconstructed video qualities. Due to the inter-layer dependency characteristic of SVC-based video, in wireless video transmission, the base layer and more important enhancement layers require stronger protection compared to the less important layers. Moreover, SVC can support all the temporal (frame rates), spatial (picture resolutions) and quality (image fidelity) scalabilities. In this
B. Utility and Video Decoding Quality Measure

The proposed scheme maximizes the overall video decoding quality at the receiver, which can be measured in utility values [19]. Much research has been conducted in objective video quality assessment (VQA) methods to quantify the video decoding quality. Among these VQA schemes, the Multi-Scale-Structural SIMilarity index (MS-SSIM) developed in [29], originally designed as an image quality assessment method, has been reported as a simple but effective VQA scheme, which has high correlation with subjectively perceived video quality [30]–[32]. In VQA applications, the MS-SSIM is applied frame-by-frame to the luminance component of the video and the overall MS-SSIM index can be calculated by averaging the frame-level quality score [32]. Therefore, we adopt the average MS-SSIM as the utility value of each encoded SVC video layer.

C. APP-FEC

APP-FEC can provide reliable end-to-end streaming applications with packet-level protection [10]. A source block consisting of $K$ packets is encoded into an FEC block with $N$ ($N \geq K$) packets so that $N - K$ redundancy packets are constructed and the encoding rate is $K/N$. For an ideal APP-FEC scheme, the decoder can reconstruct the original $K$ source packets from any $K$ packets with correction capability $t = N - (1 + \epsilon)K$, where $\epsilon$ is reception overhead efficiency, which makes the correction capability sub-optimal. However, the reception overhead efficiency of standardized Raptor code is close to ideal [10]. In this paper, we only consider the APP-FEC scheme with ideal correction capability.

D. MIMO System Model

The input-output relation of an $M_r \times M_t$ MIMO system can be expressed by the following linear equation:

$$y = Hx + n,$$

where $y$ is an $M_r \times 1$ receive complex symbol vector. $H$ is an $M_r \times M_t$ channel matrix in which all elements are i.i.d. zero mean circularly symmetric complex Gaussian (ZMCSCG) random variables with zero mean and unit variance, i.e., $CN(0, 1)$. $x$ is an $M_t \times 1$ transmit complex symbol vector with $E[xx^H] = \text{diag}(p) = \text{diag}(p_1, p_2, \ldots, p_{M_t})$. Here, $p$ is the $M_t \times 1$ i.i.d. complex additive white Gaussian noise (AWGN) noise vector with covariance matrix $N_0 I_{M_t}$. Therefore, the system signal-to-noise ratio (SNR) is $\rho = 1/N_0$.

With a singular value decomposition (SVD), the known MIMO channel matrix $H$ can be decomposed as:

$$H = UDV^H,$$

where $U$ and $V$ are unitary matrices. The diagonal matrix $D$ is:

$$D = \text{diag} \left[ \sqrt{\lambda_1}, \sqrt{\lambda_2}, \ldots, \sqrt{\lambda_R}, 0, \ldots, 0 \right],$$

where $R \leq \min(M_r, M_t)$ is the rank of channel matrix $H$. $\lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_R$ are the eigenvalues of $H^H H$. If accurate and full channel information is available at both transmitter and receiver sides, a precoder $V$ and a decoder $U^H$ can be appended on the transmitter and receiver side respectively so that the MIMO input-output relation can be reduced as:

$$\hat{y} = U^H HV + U^H n = Dx + \hat{n}.$$

Thus, the MIMO system can be decomposed into $R$ independent single-input single-output (SISO) channels. The SNR of the $i$th SISO channel is:

$$\text{SNR}_i = \rho \lambda_i p_r.$$
E. Modulation and Coding Schemes (MCSs)

In real world wireless services, different MCSs are used for varying wireless channel conditions. In this paper, we adopt six widely used MCS schemes and their bit error rate (BER) expressions can be approximated by [36]:

\[
P^{(\text{BER})}(\text{SNR} ; m) \approx a_m \exp (-b_m \times \text{SNR}) ,
\]

where \(a_m\) and \(b_m\) are coefficients corresponding to the MCS \(m\). The coefficients of all the six MCSs are listed in Table I.

<table>
<thead>
<tr>
<th>Type (m)</th>
<th>Modulation</th>
<th>Code Rate</th>
<th>(a_m)</th>
<th>(b_m)</th>
<th>Spectral Efficiency (c_m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BPSK</td>
<td>1/2</td>
<td>1.1369</td>
<td>7.5556</td>
<td>0.5 b/Hz</td>
</tr>
<tr>
<td>2</td>
<td>QPSK</td>
<td>1/2</td>
<td>0.3531</td>
<td>3.2543</td>
<td>1 b/Hz</td>
</tr>
<tr>
<td>3</td>
<td>QPSK</td>
<td>3/4</td>
<td>0.2197</td>
<td>1.5244</td>
<td>1.5 b/Hz</td>
</tr>
<tr>
<td>4</td>
<td>16 QAM</td>
<td>9/16</td>
<td>0.2081</td>
<td>0.6250</td>
<td>2.25 b/Hz</td>
</tr>
<tr>
<td>5</td>
<td>16 QAM</td>
<td>3/4</td>
<td>0.1936</td>
<td>0.3484</td>
<td>3 b/Hz</td>
</tr>
<tr>
<td>6</td>
<td>64 QAM</td>
<td>3/4</td>
<td>0.1887</td>
<td>0.0871</td>
<td>4.5 b/Hz</td>
</tr>
</tbody>
</table>

F. Proposed System Structure

The system structure of our proposed cross-layer joint rate and power allocation scheme is shown in Fig. 2. The source video clip is encoded into \(L_{\text{max}}\) SVC layers, including one base layer and \(L_{\text{max}} - 1\) enhancement layers. The source data rate of the \(l\)-th SVC layer is \(R_{l}^{(S)}\). A video layer selection module chooses a suitable number of video layers, i.e., \(L \leq L_{\text{max}}\) to be transmitted. Then, the bit streams of selected video layers are packetized with fixed packet length \(S\), which is chosen to be \(S = 4800\) bits in this paper. The source packets are then fed into the APP-FEC encoder every \(T_s\) second to form an FEC block. \(T_s\) is assumed to be 10 ms in this work. To fit the source data rate of video layer \(l\), the number of source packets per FEC block is approximately \(K_l = \lceil R_l^{(S)} T_s / S \rceil\). A channel selection module determines a set of spatial channels \(S \subseteq R\) to be used for transmission, where \(R = \{1, 2, ..., R\}\) denotes the set of indices of available spatial channels and \(|S| \leq R\). Moreover, as shown in Fig. 4, the channel selection module interleaves the packets of each video layer to the selected multiple spatial channels, instead of allocating the packets of more important video layers to the channels with higher channel gains as in the previous work (illustrated in Fig. 3). There are two advantages of the proposed channel selection method. First, the number of video layers is not restricted by the number of spatial channels because of interleaving. Second, by interleaving the packets of each video layer to several spatial channels, the diversity gain of both time and space domains can both be exploited with APP-FEC. In the proposed system, packet allocation is based on the throughput of each spatial channel, which is determined by the corresponding MCS used for transmission. For instance, if the throughput of a spatial channel \(r\) is \(R_r^{(F)}\), \(r \in S\), and in total \(N_l^{(l)}\) encoded packets of a video layer \(l\) needs to be transmitted, the number of packets of the video layer \(l\)
transmitted through the spatial channel $r$ is approximately

$$N_{r,l} \approx \frac{N^{(l)} R^{(T)}_r}{\sum_{k \in S} R^{(T)}_k}. \quad (7)$$

The exact number of packets can be calculated by the algorithm described in Section IV. The modulated symbols are transmitted through the wireless channel after power allocation and precoding. All the transmission parameters, including number of SVC layers (source coding rates), APP-FEC rate, the MCS of each spatial channel and its corresponding transmit power, are jointly optimized by the proposed joint rate and power adaptation scheme based on cross-layer information at the transmitter side and channel state information (CSI) from the receiver side. At the receiver, the channel estimation module estimates the channel and feeds back the CSI. In this work, we assume perfect and full channel knowledge at both transmitter and receiver sides. After MIMO decoding, detection, demodulation, PHY-FEC decoding and APP-FEC decoding, the received bit streams are saved in receiving buffers and fed into the SVC decoder. The bit stream of the video layer $l$ is dropped if a transmission error is detected or its dependent layers (i.e., from the base layer to the $(l-1)^{th}$ layer) are not correctly decoded.

III. PROBLEM FORMULATION

The video decoding quality at the receiver side can be optimized by maximizing the average utility of the system.

$$P_r^{(V)}(m,t,p) = \prod_{j=1}^{l} \left( P_j^{(BRC)}(m,t_j,p) \right)^b, \quad (9)$$

where $b$ denotes the number of APP-FEC blocks in each group of pictures (GoP) time period. $P_j^{(BRC)}(m,t_j,p)$ is the APP-FEC block correction rate of the $j^{th}$ SVC layer. If we define $X_{r,j}$ as a random variable of having erroneous packets in one APP-FEC block of the SVC layer $j$ transmitted through spatial channel $r$, it follows the Binomial distribution and its probability mass function (PMF) is:

$$f_{X_{r,j}}(x) = \binom{N_{r,j}}{x} \left( P_r^{(PLR)} \right)^x \left( 1 - P_r^{(PLR)} \right)^{N_{r,j} - x}, \quad (10)$$

where the PLR of the $r^{th}$ spatial channel is given by:

$$P_r^{(PLR)} = 1 - \left( 1 - P_r^{(BER)}(p_t,m_r) \right)^S = 1 - (1 - a_{m_r} \exp (- b_{m_r} \lambda_t p_t))^S. \quad (11)$$

Thus, the APP-FEC block correction rate in (9) can be represented as:

$$P_j^{(BRC)}(m,t_j,p) = \sum_{k=0}^{t_j} f_{Y_j}(k), \quad (12)$$

where $f_{Y_j}(y)$ is the PMF of random variable $Y_j$ and

$$Y_j = \sum_{r \in S} X_{r,j}, \quad (13)$$

Therefore, $f_{Y_j}(y)$ can be derived by calculating the convolution sums of $f_{X_{r,j}}(x)$. In (8), the first constraint means that the transmit power allocated on each spatial channel is non-negative. The second constraint means that the sum of power is limited by a unit power $1$. The third constraint means
that the error correction capability of each APP-FEC block is non-negative. The last constraint sets the total number of transmitted packets in each sampling period of an APP-FEC encoding block (i.e., $T_s$ seconds) equal to the total number of packets that the network can transmit in this time period.

\[ \sum_{l=1}^{L} t_l + K_l = \sum_{r=1}^{R} T_s R_{r}^{(T)} \left( m_r^{(C)} \right) \]

where $m_r^{(C)}$ is the $C^{th}$ possible combination of the MCS vector $m$. Each sub-problem provides one candidate solution set $\{ L, m_r^{(C)}, t_{L,C}, p_{L,C} \}$. Note that for each sub-problem, the parameters $L$ and $m_r^{(C)}$ are pre-determined. The solution of the original problem can be obtained by searching the candidate solution set with highest utility, i.e.,

\[ \{ L^*, m^*, t^*, p^* \} = \arg \max_{C} \max_{l=1}^{L} u_l P_l^{(N)} (t_l, p_l, m_l^{(C)}) \]

IV. PROPOSED ALGORITHMS

A. Sub-Problems

To reduce the complexity of the original optimization problem in (8), we define the maximum SVC layers to be $L$, with the MCS vector being $m$, and decompose the original problem into several sub-problems:

\[ \mathcal{Q}_{L,C} : \max_{t,p} P_L^{(N)} (t, p; m^{(C)}) \]

subject to

\[ p \geq 0, \quad \sum_{r=1}^{R} p_r = 1, \quad t \geq 0, \]

\[ \sum_{l=1}^{L} t_l + K_l = \sum_{r=1}^{R} T_s R_{r}^{(T)} \left( m_r^{(C)} \right) \]

where $m^{(C)}$ is the $C^{th}$ possible combination of the MCS vector $m$. Each sub-problem provides one candidate solution set $\{ L, m_r^{(C)}, t_{L,C}, p_{L,C} \}$. Note that for each sub-problem, the parameters $L$ and $m_r^{(C)}$ are pre-determined. The solution of the original problem can be obtained by searching the candidate solution set with highest utility, i.e.,

\[ \{ L^*, m^*, t^*, p^* \} = \arg \max_{C} \max_{l=1}^{L} u_l P_l^{(N)} (t_l, p_l, m_l^{(C)}) \]

where $C$ denotes the set containing all $L_{\text{max}} \times C$ candidate solutions. The problem solving strategies including the relationships between the original problem, the sub-problems, the candidate solution set and the final solution are illustrated in Fig. 5.

Fig. 5. Problem solving strategies: decomposing the original problem into several sub-problems.

B. Spatial Channel Weightings and Packet Mapping

To exploit the diversity gain of different spatial channels, the APP-FEC encoded packets of each SVC layer are mapped to multiple spatial channels. As indicated in (7), the number of packets of the $r^{th}$ SVC layer over the $r^{th}$ channel (i.e., $N_{r,l}$) is proportional to the normalized throughput of the $r^{th}$ channel. Let $N$ be an $R \times L$ packet mapping matrix with elements $N_{r,l}$. Let $w$ be an $R \times 1$ vector with each element

\[ w_r = \frac{R_{r}^{(T)}}{\sum_{k \in S} R_k^{(T)}} \]

representing the rate distribution target (weighting) of the $r^{th}$ spatial channel. The throughput of the $r^{th}$ channel is

\[ R_{r}^{(T)} = B c_{m_r}. \]

Table II shows the packet mapping algorithm to calculate $N$.

The proposed packet mapping algorithm iteratively allocates one packet to the spatial channel whose weighting $w_{r}^{(\text{temp})}$, calculated in line 4 of Table II, is the smallest comparing to its corresponding target weighting $w_r$. And the packet number distribution for each spatial channel $r$ approaches to the target weighting $w_r$ for each iteration.

Table II: Algorithm for packet mapping

<table>
<thead>
<tr>
<th>Inputs:</th>
<th>Weighting vector: $w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output:</td>
<td>Packet mapping matrix: $N$</td>
</tr>
<tr>
<td>1.</td>
<td>Initialization: $N_{r,l} := 0$ for all $r$ and $l$; $N_{1,1} := 1$;</td>
</tr>
<tr>
<td>2.</td>
<td>for $l = 1 \rightarrow L$</td>
</tr>
<tr>
<td>3.</td>
<td>while $N^{(l)} &gt; 0$</td>
</tr>
<tr>
<td>4.</td>
<td>$w_{r}^{(\text{temp})} := \sum_{l} N_{r,l} / \sum_{r} N_{r,l}$ for each $r \in S$;</td>
</tr>
<tr>
<td>5.</td>
<td>$r^{*} := \arg \max \left( w_r - w_{r}^{(\text{temp})} \right)$ for each $r \in S$;</td>
</tr>
<tr>
<td>6.</td>
<td>$N_{r,l} := N_{r,l}^{*} + 1$;</td>
</tr>
<tr>
<td>7.</td>
<td>$N^{(l)} := N^{(l)} - 1$;</td>
</tr>
<tr>
<td>8.</td>
<td>end while</td>
</tr>
<tr>
<td>9.</td>
<td>end for</td>
</tr>
<tr>
<td>10.</td>
<td>return $N$;</td>
</tr>
</tbody>
</table>
C. Power Allocation

As indicated in (14), the goal of power allocation is to maximize the successful decoding probability \( P_L^{(V)} (t, p; m^{(C)}) \), which is equivalent to maximizing the APP-FEC block correction rate \( P^{(BER)}_j (t_j, p; m) \) in (9). When \( N_{r,j} \) is large and \( P^{(PLR)}_r \) is small, the PMF of \( X_{r,j} \) can be approximated by the Poisson distribution with parameter \( \gamma_{X_{r,j}} = N_{r,j} \times P^{(PLR)}_r \). Therefore, \( Y_j \) in (13) also follows Poisson distribution with parameter [37]

\[
\gamma_{Y_j}(p) = \sum_{r \in S} N_{r,j} P^{(PLR)}_r(p_r) \approx N_j \sum_{r \in S} w_r P^{(PLR)}_r(p_r) . \tag{18}
\]

If the MCS vector \( m \) and the APP-FEC correction capability \( t \) are given, the APP-FEC block correction rate \( P^{(BER)}_j (p; m, t_j) \) is maximized when \( \gamma_{Y_j}(p) \) is minimized. Therefore the power allocation problem can be written as

\[
Q^{(PA)}_{L,C}: \quad \mathbf{p}^{*}_{L,C} = \arg \min_{\mathbf{p}} J \left( \mathbf{p}; m^{(C)} \right) \tag{19}
\]

subject to

\[
P_r \geq 0, \quad \sum_{r=1}^{R} p_r = 1 ,
\]

where

\[
J \left( \mathbf{p}; m^{(C)} \right) = \sum_{r \in S^{(C)}} w_r \left( m^{(C)}_r \right) P^{(PLR)}_r(p_r) \tag{20}
\]

is the weighted sum of packet loss rate of each spatial channel \( r \).

When \( P^{(BER)}_r \) is small, \( P^{(PLR)}_r \) in (11) can be approximated by

\[
P^{(PLR)}_r(p_r; m_r) \approx S \cdot a_m \exp \left( -b_m \rho \lambda_r p_r \right) , \tag{21}
\]

which is convex function with respect to \( p_r \). Therefore, the objective function in (20) can also be approximated as a convex function since the non-negative sum of convex functions is still convex [38]. The power allocation problem in (19) can thus be efficiently solved by (22) when the approximation is valid (see Appendix A for derivations).

\[
\left[ \mathbf{p}^{*}_{L,C} \right]_r = \begin{cases} 
\frac{\mu + \log \left( S w_r a_m b_m \rho \lambda_r \right)}{b_m \rho \lambda_r}, & r \in S \\
0, & r \notin S
\end{cases} \tag{22}
\]

where

\[
\mu = \frac{1 - \sum_{r \in S} \log \left( S w_r a_m b_m \rho \lambda_r \right)}{\sum_{r \in S} \left( 1/b_m \rho \lambda_r \right)} . \tag{23}
\]

However, when the approximation is not valid, i.e., \( P^{(BER)}_r \) is not small enough, more power than necessary is allocated on the channels with low channel gains, resulting in wasted power. Let \( J^{\text{appx}}(p) \) denotes the objective function in (19) with the approximation in (21), the power allocation solution is trustable if \( J \left( \mathbf{p}^{*}_{L,C}; m^{(C)} \right) - J^{\text{appx}} \left( \mathbf{p}^{*}_{L,C}; m^{(C)} \right) \) is less than a threshold \( Th \), which is empirically set as 0.001. Otherwise, the channel with smallest gain is removed from the selected channel set \( S \) and its corresponding power is set as 0. Then, \( \mathbf{p}^{*}_{L,C} \) is recalculated by (22) until the solution is trustable or only one channel is left in \( S \), i.e., \(|S| = 1 \). The algorithm for power allocation is described in Table III.

D. APP-FEC Rate Adaptation

Since the transmitted packets of each SVC layer are spread over multiple spatial channels, the channel conditions experienced by each SVC layer are similar. Therefore, the UEP cannot be achieved by channel selection as in [14]. Instead, under the overall allowed packet number constraint, determined by the system throughput, the UEP can be achieved by assigning different APP-FEC rates on each SVC layer. This results in the following APP-FEC rate adaptation problem:

\[
Q^{(FECA)}_{L,C}: \quad \mathbf{t}^{*}_{L,C} = \arg \max_{\mathbf{t}} P_L^{(V)} \left( \mathbf{t}; m^{(C)}, \mathbf{p}^{*}_{L,C} \right) \tag{24}
\]

subject to

\[
\mathbf{t} \geq 0, \quad \sum_{l=1}^{L} t_l + K = \sum_{r=1}^{R} T_r R^{(T)}_r (m^{(C)}_r) / |S| .
\]

Note that the APP-FEC rate adaptation is conducted after the optimal power allocation vector \( \mathbf{p}^{*}_{L,C} \) is obtained. Therefore, all the parameters \( L, m^{(C)} \), and \( \mathbf{p}^{*}_{L,C} \) are determined and the only variable left is \( \mathbf{t} \). In this paper, a simple steepest ascent algorithm, shown in Table IV, is proposed to find the optimal solution of the APP-FEC rate of each SVC layer. Note that the objective function of (24), \( P_L^{(V)}(\mathbf{t}) \) is non-decreasing with respect to the FEC correction capabilities \( \mathbf{t} \). Therefore, the steepest ascent algorithm can reach the global optimal solution.

The idea of the proposed APP-FEC rate adaptation algorithm iteratively adds one APP-FEC correction capability to the SVC layer with the highest gain in terms of video decoding probability. The iteration stops when no additional redundancy packets can be added due to the throughput limitation.

E. Overall Rate and Power Allocation Adaptation Algorithm

The overall proposed joint rate and power allocation adaptation algorithm, which combines all the above mentioned algorithms, is described in Table V.
TABLE IV
ALGORITHM FOR APP-FEC RATE ADAPTATION

<table>
<thead>
<tr>
<th>Inputs:</th>
<th>Number of APP-FEC blocks: ( b )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of source packets: ( K_l ) for each ( l = 1, 2, ..., L )</td>
</tr>
<tr>
<td></td>
<td>Channel MCS vector: ( \mathbf{m}^{(C)} )</td>
</tr>
<tr>
<td></td>
<td>System bandwidth: ( B )</td>
</tr>
<tr>
<td></td>
<td>APP-FEC block sampling time: ( T_s )</td>
</tr>
<tr>
<td></td>
<td>APP-FEC packet size: ( S )</td>
</tr>
<tr>
<td></td>
<td>Channel SNR gains: ( \rho_r ) for each ( r = 1, 2, ..., R )</td>
</tr>
<tr>
<td></td>
<td>Optimal power allocations: ( p_r^* ) for each ( r = 1, 2, ..., R )</td>
</tr>
<tr>
<td>Output:</td>
<td>APP-FEC correction capability vector: ( \mathbf{t}_{L,C}^* )</td>
</tr>
<tr>
<td>1.</td>
<td>Initialization: ( t := 0 )</td>
</tr>
<tr>
<td>2.</td>
<td>while ( 1 + \sum_{l=1}^{L} t_l + K_l \leq \sum_{r=1}^{R} \left( T_s R_l^{(s)} \left( m_r^{(C)} \right) \right) / S )</td>
</tr>
<tr>
<td>3.</td>
<td>for ( j = 1 \rightarrow L )</td>
</tr>
<tr>
<td>4.</td>
<td>Do packet mapping algorithm and obtain ( N )</td>
</tr>
<tr>
<td>5.</td>
<td>( t_{\text{temp}} := t )</td>
</tr>
<tr>
<td>6.</td>
<td>( t_j := t_{\text{temp}} + 1 )</td>
</tr>
<tr>
<td>7.</td>
<td>Calculate ( P_{l}^{(BCR)} ) by (12);</td>
</tr>
<tr>
<td>8.</td>
<td>( G_j(t_j) := P_{L}^{(V)} \left( t_{\text{temp}}; \mathbf{m}^{(C)}; \mathbf{p}_{L,C}^* \right) )</td>
</tr>
<tr>
<td></td>
<td>( -P_{L}^{(V)} \left( t; \mathbf{m}^{(C)}; \mathbf{p}_{L,C}^* \right) );</td>
</tr>
<tr>
<td>9.</td>
<td>end for</td>
</tr>
<tr>
<td>10.</td>
<td>( j^* := \arg \max G_j(t_j) )</td>
</tr>
<tr>
<td>11.</td>
<td>( t_{j^<em>} := t_{j^</em>} + 1 )</td>
</tr>
<tr>
<td>12.</td>
<td>end while</td>
</tr>
<tr>
<td>13.</td>
<td>return ( \mathbf{t}_{L,C}^* := t )</td>
</tr>
</tbody>
</table>

TABLE V
OVERALL ALGORITHM FOR RATE AND POWER ADAPTATION

<table>
<thead>
<tr>
<th>Inputs:</th>
<th>Number of APP-FEC blocks: ( b )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum SVC layer: ( L_{\text{max}} )</td>
</tr>
<tr>
<td></td>
<td>Source packet number: ( K_l ) for each ( l = 1, 2, ..., L_{\text{max}} )</td>
</tr>
<tr>
<td></td>
<td>Possible MCSs table</td>
</tr>
<tr>
<td></td>
<td>Utility vector: ( \mathbf{u} )</td>
</tr>
<tr>
<td></td>
<td>System bandwidth: ( B )</td>
</tr>
<tr>
<td></td>
<td>APP-FEC block sampling time: ( T_s )</td>
</tr>
<tr>
<td></td>
<td>APP-FEC packet size: ( S )</td>
</tr>
<tr>
<td></td>
<td>Channel gain: ( \rho_r ) for each ( r = 1, 2, ..., R )</td>
</tr>
<tr>
<td>Output:</td>
<td>Optimal solution set: ( { \mathbf{L}^<em>, \mathbf{m}^</em>, \mathbf{t}^<em>, \mathbf{p}^</em> } )</td>
</tr>
<tr>
<td>1.</td>
<td>Initialization: ( \text{utility}^{(\text{max})} := 0 )</td>
</tr>
<tr>
<td>2.</td>
<td>for each MCS combination ( C )</td>
</tr>
<tr>
<td>3.</td>
<td>Calculate weighting vector ( \mathbf{w} ) by (16);</td>
</tr>
<tr>
<td>4.</td>
<td>Do power allocation and obtain ( \mathbf{p}_{L,C}^* );</td>
</tr>
<tr>
<td>5.</td>
<td>for ( L = 1 \rightarrow L_{\text{max}} )</td>
</tr>
<tr>
<td>6.</td>
<td>Do APP-FEC rate adaptation and obtain ( \mathbf{t}_{L,C}^* )</td>
</tr>
<tr>
<td>7.</td>
<td>( \text{utility} := \sum_{l=1}^{L} w_l P_{l}^{(V)} \left( \mathbf{m}^{(C)}; \mathbf{t}<em>{L,C}^*; \mathbf{p}</em>{L,C}^* \right) );</td>
</tr>
<tr>
<td>8.</td>
<td>if ( \text{utility} &gt; \text{utility}^{(\text{max})} )</td>
</tr>
<tr>
<td>9.</td>
<td>( \text{utility}^{(\text{max})} := \text{utility}; )</td>
</tr>
<tr>
<td>10.</td>
<td>( { \mathbf{L}^<em>, \mathbf{m}^</em>, \mathbf{t}^<em>, \mathbf{p}^</em> } := { \mathbf{L}, \mathbf{m}^{(C)}; \mathbf{t}<em>{L,C}^*; \mathbf{p}</em>{L,C}^* } );</td>
</tr>
<tr>
<td>11.</td>
<td>end if</td>
</tr>
<tr>
<td>12.</td>
<td>end for</td>
</tr>
<tr>
<td>13.</td>
<td>end for</td>
</tr>
<tr>
<td>14.</td>
<td>return ( { \mathbf{L}^<em>, \mathbf{m}^</em>, \mathbf{t}^<em>, \mathbf{p}^</em> } );</td>
</tr>
</tbody>
</table>

TABLE VI
VIDEO CODING AND TRANSMISSION PARAMETERS

<table>
<thead>
<tr>
<th>Video</th>
<th>Layer 1</th>
<th>Layer 2</th>
<th>Layer 3</th>
<th>Layer 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cactus</td>
<td>2.487 Mbps</td>
<td>5.389 Mbps</td>
<td>16.79 Mbps</td>
<td>59.92 Mbps</td>
</tr>
<tr>
<td>Kimono</td>
<td>1.0327 Mbps</td>
<td>1.889 Mbps</td>
<td>5.844 Mbps</td>
<td>21.94 Mbps</td>
</tr>
</tbody>
</table>

TABLE VII
CUMULATIVE BIT RATE OF DIFFERENT VIDEO LAYERS

<table>
<thead>
<tr>
<th>Video</th>
<th>Layer 1</th>
<th>Layer 2</th>
<th>Layer 3</th>
<th>Layer 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cactus</td>
<td>889 Kbps</td>
<td>1889 Kbps</td>
<td>3633 Kbps</td>
<td>8407 Kbps</td>
</tr>
<tr>
<td>Kimono</td>
<td>389 Kbps</td>
<td>799 Kbps</td>
<td>1833 Kbps</td>
<td>3807 Kbps</td>
</tr>
</tbody>
</table>

V. SIMULATION RESULTS

The effectiveness and favorable performance of our proposed algorithm are evaluated by intensive simulations. Two high definition (HD) video clips “Cactus” and “Kimono” are encoded by the Joint Scalable Video Model (JSVM) version 9.19 [39]. The detailed video coding and transmission parameters are listed in Table VI. Both videos are encoded with medium-grain scalability (MGS). Both motion compensation and estimation are constrained at the current layer [14]. The cumulative source coding bit rates of the 4 SVC layers are listed in Table VII. The encoded network abstraction layer units (NALUs) are packetized into packets with 600 bytes. A 4 × 4 MIMO system is used for transmissions. The channel matrix changes randomly every channel coherence time. And the CSIs with full channel knowledge are fed back every channel coherence time. The sampling period \( T_s \) of APP-FEC block is 10 ms. At the receiver side, control messages such as video coding parameters and MCS information are assumed to be correctly received. Perfect error detection is assumed and erroneous packets are dropped. The undecodable NALU, which is caused by either packet loss of its own SVC layer packets or unsatisfied SVC layer dependencies, is discarded before SVC decoding.

In total 6 different schemes are simulated. Their corresponding techniques and abbreviations are listed in Table VIII. Note that the “FEC” scheme, which uses APP-FEC to exploit the diversity of different spatial channels, is similar to our previous work in [28]. The “Baseline” scheme in Table VIII refers to a similar system proposed in [15], where the bit stream of the \( l \)th SVC layer is transmitted through the spatial channel with the \( l \)th highest channel gain. In this case, to meet the bit rate requirement of each SVC layer, the MCS of transmitting the SVC layer 1 (base layer), 2, 3 and 4 are set as: QPSK.
1/2, QPSK 1/2, 16-QAM 9/16 and 64-QAM 3/4 respectively. Also, the same MCSs are applied for all the schemes without AMC for fair comparisons. The Baseline+PA scheme is similar to the work in [14], where the power allocation algorithm is applied on the Baseline system.

Figure 7 shows the received SVC layer index of each decoded video frame of “Cactus” when the system SNR is 10 dB. It is obvious that the proposed packet mapping and FEC rate adaptation scheme (i.e., “FEC” scheme) has more video frames with higher enhancement layers decoded. This is because the proposed scheme can better exploit the multi-channel diversity gain. If the AMC scheme is applied (i.e., “AMC+FEC” scheme), the performance of the proposed scheme can be further improved since the best MCSs are chosen according to different channel qualities. The best system performance is achieved when both AMC and power allocation are applied with FEC rate adaptation (i.e., “AMC+FEC+PA” scheme).

The cumulative distribution functions (CDF) of the power allocated on each spatial channel are plotted in Fig. 8. The “Baseline+PA” scheme allocates power based on the fact that each SVC video layer is transmitted through a single spatial channel. While both “AMC+FEC+PA” and “FEC+PA” schemes allocate power based on the algorithm in Table III, which minimizes the weighted sum of packet loss rate. Since the AMC scheme is applied (i.e., “AMC+FEC” scheme), the performance of the proposed scheme can be further improved since the best MCSs are chosen according to different channel qualities. The best system performance is achieved when both AMC and power allocation are applied with FEC rate adaptation (i.e., “AMC+FEC+PA” scheme).

The per-frame MS-SSIM and PSNR of decoded video “Cactus” at system SNR 10 dB are plotted in Fig. 9 and Fig.

---

### Table VIII

<table>
<thead>
<tr>
<th>Abbreviations</th>
<th>Techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMC+FEC+PA</td>
<td>Proposed algorithm in Table V</td>
</tr>
<tr>
<td>AMC+FEC</td>
<td>Proposed algorithm in Table V with equal power allocation on each channel.</td>
</tr>
<tr>
<td>FEC+PA</td>
<td>Proposed algorithm in Table V with fixed MCS on each channel.</td>
</tr>
<tr>
<td>FEC [28]</td>
<td>Proposed algorithm in Table V with fixed MCS and equal power allocation on each channel.</td>
</tr>
<tr>
<td>Baseline+PA [14]</td>
<td>Similar system as in [14]</td>
</tr>
</tbody>
</table>
decoding quality is the best with “AMC+FEC+PA” method. One can observe that the video efficiency of the “FEC” and “Baseline” schemes at system SNR 3 dB are limited and the system performance cannot be further improved even when channel quality becomes better. The decoded videos of “Cactus” of “AMC+FEC+PA”, “FEC” and “Baseline” schemes at system SNR 10 dB are available for reviews at [40]. One can observe that the video decoding quality is the best with “AMC+FEC+PA” method.

Figure 14 shows the average MS-SSIM index and the average PSNR at different average channel SNRs. Apparently, without AMC and power allocation, our proposed scheme (i.e., “FEC” scheme) still outperforms “Baseline” and “Baseline+PA” schemes. However, with fixed MCSs, the system throughput is limited and the system performance cannot be further improved even when channel quality becomes better. If the AMC scheme is applied (i.e., “AMC+FEC” scheme), decoded video quality becomes better when channel quality improves. Power allocation can provide additional decoding
Similar results can be demonstrated by the video clip “Kimono”. Figure 15 shows the SVC quality layer indices of the reconstructed video when system SNR is 12 dB. The CDFs of the power allocated on each spatial channel is shown in Fig. 16. The corresponding MS-SSIM and PSNR plots are shown in Fig. 17 and Fig. 18 respectively. Clearly, the proposed methods outperform the others. The average power and spectral efficiency of each spatial channel are plotted in Fig. 19 and Fig. 20 respectively. The average APP-FEC coding rates of each SVC layer are plotted in Fig. 21. The visual comparison of the decoded frame of “AMC+FEC+PA”, “FEC” and “Baseline” methods at system SNR 12 dB are available at [40]. Since AMC+FEC+PA can decoded more enhancement layers than the others, its video quality is the best. The average quality gain as shown in the “AMC+FEC+PA” scheme.

Fig. 14. Average MS-SSIM index and PSNR of reconstructed video “Cactus”.

Fig. 15. SVC layer indices of received frames. “Kimono”, SNR: 12 dB.

Fig. 16. CDF of power on each spatial channel. “Kimono”, SNR: 12 dB.

Fig. 17. Per-frame MS-SSIM indices of video. “Kimono”, SNR: 12 dB.

MS-SSIM indices and average PSNR at different system SNR are plotted in Fig. 22. Still, the proposed rate adaptation and power allocation scheme (i.e., “AMC+FEC+PA”) has the best performance among the other schemes.

VI. Conclusion

A quality-driven joint rate and power adaptation scheme for scalable video transmissions over MIMO systems is proposed. Unlike previous work, which achieve UEP by transmitting higher priority bit streams through spatial channel with higher
gains, we propose to interleave the bit stream of each SVC layer to multiple spatial channels and use APP-FEC to exploit both time and multi-channel diversity gain. In the proposed scheme, number of video layers (source coding rate), APP-FEC encoding rate for each video layer, transmit power, the best spatial channel and MCS choices are jointly optimized. The original optimization problem is decomposed into several sub-problems, which can be further decomposed into packet mapping, power allocation and APP-FEC rate adaptation problems. The encoded packets are interleaved based on the available throughputs of the selected spatial channels. Optimal power allocation is obtained by solving a convex optimization problem with a closed-form formula. UEPS on different video layers can be achieved by assigning different APP-FEC coding rates. Each sub-problem generates a candidate solution and the final optimal solution is obtained by searching the candidate solution with best estimated decoding quality (highest utility). Intensive simulations with two HD videos under different channel conditions demonstrate the effectiveness and favorable performance of our proposed system.

**Appendix A**

**Derivation of (22) and (23)**

Consider the optimization problem in (19) with objective function $J_{appx}(p)$, the corresponding Lagrangian is:

$$L(p, \xi, \nu) = S \sum_{r \in S} w_r a_m e^{-b_{tr} \rho_r} p_r - \sum_{r \in S} \xi_r p_r + \nu \left( \sum_{r \in S} 1 \right),$$

(25)

where $\xi$ and $\nu$ are Lagrange multipliers associated with the inequality constraints and equality multiplier constraint respectively. For each $r \in S$, the Karush-Kuhn-Tucker (KKT) conditions can be expressed as:
Therefore, (23) is obtained by reforming (31). Note that the notation \( p^* \) used in this Appendix denotes the optimal solution of (25), which has different meaning to the notation \( p^* \) used in (15) and the rest of this paper.

1) Primal feasible: \( p^* \geq 0; \quad 1^T \cdot p^* = 1 \).

2) Dual feasible: \( \xi^* \geq 0 \).

3) Complementary slackness: \( \xi^*_r \cdot p^*_r = 0 \).

4) Gradient of Lagrangian vanishes:

\[
\frac{\partial L(p, \xi, \nu)}{\partial p_r} = -Sw_r a_m, b_m, \rho_l r e^{-b_m, \rho_l r} \cdot \xi^*_r + \nu^* = 0.
\]  

Since the optimization problem in (19) with objective function \( J_{\text{app}}(p) \) is convex, any point satisfying the above KKT conditions is primal and dual optimal with zero duality gap [38]. The above KKT conditions imply:

\[
\nu^* \geq Sw_r a_m, b_m, \rho_l r e^{-b_m, \rho_l r} p^*_r, \quad (27)
\]

and

\[
(\nu^* - Sw_r a_m, b_m, \rho_l r e^{-b_m, \rho_l r} p^*_r) p^*_r = 0 \quad (28)
\]

If \( p^*_r = 0 \), the approximation \( J_{\text{app}}(p) \) is not valid and the \( r \)-th channel should be removed from \( S \). Thus, we only consider \( p^*_r > 0 \) in (28).

Therefore, \( \nu^* = Sw_r a_m, b_m, \rho_l r e^{-b_m, \rho_l r} p^*_r \).

Let \( \mu = \log (1/\nu^*) \),

\[
p^*_r = \frac{\mu + \log (Sw_r a_m, b_m, \rho_l r)}{b_m, \rho_l r}, \quad (30)
\]

which is equivalent to (22). Since \( 1^T \cdot p^* = 1 \),

\[
\mu \sum_{r \in S} \frac{1}{b_m, \rho_l r} + \sum_{r \in S} \frac{\log (Sw_r a_m, b_m, \rho_l r)}{b_m, \rho_l r} = 1. \quad (31)
\]

Therefore, (23) is obtained by reforming (31). Note that the notation \( p^* \) used in this Appendix denotes the optimal solution of (25), which has different meaning to the notation \( p^* \) used in (15) and the rest of this paper.


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Dr. Hwang received the 1995 IEEE Signal Processing Society’s Best Journal Paper Award. He is a founding member of Multimedia Signal Processing Technical Committee of IEEE Signal Processing Society and was the Society’s representative to IEEE Neural Network Council from 1996 to 2000. He is currently a member of Multimedia Technical Committee (MMTC) of IEEE Communication Society and also a member of Multimedia Signal Processing Technical Committee (MMSP TC) of IEEE Signal Processing Society. He served as associate editors for IEEE T-SP, T-NN and T-CSVT, T-IP and Signal Processing Magazine (SPM). He is currently on the editorial board of ETRI, IJDMB and JSIPS journals. He was the Program Co-Chair of ICASSP 1998 and ISCAS 2009.

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Professor Ritcey served as the General Chair of the 1995 International Conference on Communications in Seattle. He also served as Technical Program Chair of the 1992 and General Chair of the 1994 Asilomar Conference on Signals, Systems, and Computers and is currently a member of the Steering Committee.

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