A QoE-Based APP Layer Scheduling Scheme for Scalable Video Transmissions over Multi-RAT Systems

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Abstract—We propose an application (APP) layer scheduling scheme for scalable video transmissions over multiple radio access technologies (multi-RATs). More specifically, the proposed scheme adaptively adjusts the transmission parameters based on estimated network characteristics so that the decoding quality of experience (QoE) at user end is maximized. These parameters include number of transmitted video layers (source coding rate), the APP layer forward error correction (FEC) redundancy for each video layer (channel coding rate), and the transmission data rates in both cellular network and wireless local area network (WLAN). The network conditions are estimated by real-time protocol (RTP) and real-time control protocol (RTCP). Since the proposed scheme is an APP layer design, it can be easily implemented without changing the configurations of lower layers (e.g., transport or MAC layers). Simulations are conducted in network simulator 3 (NS-3), and demonstrate the effectiveness of our proposed scheme.

Keywords—APP-FEC; QoE; SVC; multi-RAT; APP scheduler

I. INTRODUCTION

The rapidly increasing communication and computing capabilities of mobile devices have boosted the demand of wireless video transmissions, which dominate the wireless resource consumptions in modern wireless communication systems. Therefore, it is necessary to efficiently use the limited wireless resources to maximize the quality of experience (QoE) at receiver sides [1].

Nowadays, the unprecedented increase in data traffic creates severe congestions in mobile/cellular networks, which ultimately degrades customers experience. As a result, mobile data offloading, which uses complementary network technologies for transmitting data originally targeting for mobile/cellular networks, is studied to reduce the cost and impact of carrying bandwidth consuming services on the mobile network [2]. It is anticipated that the next generation of base stations are capable of transmitting simultaneously on both licensed and unlicensed bands. Therefore efficient integration of multiple radio access technologies (multi-RAT) such as cellular and WiFi has recently attracted significant interest from industry, academia and standardization bodies [3].

However, the wireless channel capacity is time-varying due to user mobility, multipath and shadowing effects. Furthermore, the fading wireless channel also causes packet loss and delay in multimedia communications [4]. Many application (APP) layer techniques have been developed to deal with the effects caused by varying wireless channel qualities. One such technique is the scalable video coding (SVC), which can encode videos into bit streams with spatial, temporal and quality scalabilities. At receiver side, valid bit streams can still be formed when portions of the encoded bit streams are removed [5]. With the scalability nature, SVC based video can be used to satisfy the heterogeneous terminal capabilities or network conditions [6]. For delay sensitive video streaming applications, APP layer forward error correction (APP-FEC) can provide a more reliable packet transmissions over erasure networks without retransmission schemes [7], [8]. With APP-FEC scheme, additional redundant packets are transmitted along with data packets to the receiver side. By receiving enough data and redundant packets, the receiver can reconstruct all of original data packets even when some packets are lost [7].

A joint optimal rate allocation and scheduling scheme for media streaming over multipath network is proposed in [7], where the link characteristics including available bandwidth, average loss probability and propagation delay are assumed to be perfectly known. A distortion aware rate control and scalable stream adaptation scheme for scalable video streaming to multi-network clients is proposed in [9]. In this work, rate control is based on measurements of available bit rate and round-trip time. A real-time video streaming scheme over multiple wireless access networks is proposed in [10], where APP-FEC is not considered.

In this paper, we propose an APP layer scheduling scheme for real-time scalable video transmissions over multi-RAT
systems. More specifically, video server uses real-time protocol (RTP) and real-time control protocol (RTCP) to collect network quality statistics. The proposed APP layer scheduler then chooses appropriate transmission parameters including number of video layers (source coding rate), APP-FEC coding rate for each video layer and transmission data rate on each RAT. The objective of our proposed APP layer scheduling algorithm is to maximize QoE (utility) at user ends. Since the proposed scheme is an APP layer design, it can be easily implemented without changing the configurations of lower layers (e.g., transport or MAC layers).

This paper is organized as follows. System overview including SVC-based video coding, APP-FEC and proposed multi-RAT system are described in Section II. In Section III, proposed transmission data rate adaptation scheme based on RTP/RTCP is given. Our proposed joint video layer selection and APP-FEC rate adaptation scheme are provided in Section IV. Simulations and conclusion remarks are given in Section V and VI respectively.

Notation: Lower boldface letters are used for column vectors. \((.)^T\) denotes the transpose. \((.]\) is the floor. \(Pr (. )\) denotes the probability function.

II. SYSTEM OVERVIEW

A. SVC-Based Videos

The encoded SVC bit streams consist of one base layer and several enhancement layers [5]. Base layer is mandatory to decode the whole video sequence and lower enhancement layers are required in order to decode higher enhancement layers for better decoding qualities. All the quality (image fidelity), spatial (picture resolutions), and temporal (frame rates) scalabilities are supported by SVC. Without loss of generality, videos with quality scalability are used in this paper. But our proposed idea can also be applied to videos with temporal and/or spatial scalabilities.

At the receiver side, QoEs can be measured in utility values [11]. In this work, we adopt a simple perceptual quality model for SVC-based videos with quality scalabilities [12]:

\[
u_l = \begin{cases} e^{(1-q_l/q_{\min})}, & l = 1 \\ e^{(1-q_l/q_{\min})}, & l \geq 2 \end{cases},
\]

where \(u_l\) denotes the utility values for the \(l\)-th SVC video layer; \(q_l\) is the quantization stepsize of the \(l\)-th video layer; and \(q_{\min}\) is the minimum quantization stepsize corresponding to the video layer with the highest quality; Also note that \(c\) is a video dependent model parameter.

B. APP-FEC

Unlike link and physical layer FEC, APP-FEC operates at APP layer and can provide reliable end-to-end streaming applications with packet level protection [8]. A source block with \(K\) packets is encoded into an FEC block with \(N\) packets, which consists of \(N-K\) additional redundancy packets. Ideally, for this FEC block, the decoder can reconstruct the original \(K\) source packets from any \(K\) out of \(N\) received packets [8]. If the packet losses are independent and identically distributed \((i.i.d.)\), for an \((N,K)\) systematic APP-FEC code, the decoding correction probability is:

\[
P(t) = \sum_{i=0}^{t} \binom{N}{i} p^i (1-p)^{N-i},
\]

where \(p\) is the packet loss rate (PLR); \(t\) is the correction capability of the APP-FEC. For practical APP-FEC schemes, \(t = N - (1+\epsilon)K\), where \(\epsilon\) is reception overhead efficiency [8]. If \(K\) is large enough, the \(\epsilon\) is very small for the advanced APP-FEC scheme such as Raptor codes [8]. Therefore, we assume an ideal APP-FEC code is used in this paper, i.e., \(\epsilon = 0\) and \(t = N - K\).

C. Multi-RAT

The multi-RAT scenario is illustrated in Fig. 1. A remote server transmits an SVC-based video stream to an intended receiver, which can receive packets from both LTE and WiFi networks simultaneously. The remote server is connected to both WiFi access point (AP) and LTE packet data network gateway (PGW) with point-to-point links. Other user equipment (UE) nodes and station (STA) nodes are located near the intended receiver to compete for wireless resources. Therefore, the network conditions such as available bandwidth, PLR etc. are time varying for both LTE and WiFi networks.

D. Proposed System Structure

Figure 2 shows the proposed system structure for transmitting SVC-based videos to the intended receiver. A video sequence is encoded up to \(L_{\text{max}}\) layers, including one base layer and \(L_{\text{max}}-1\) enhancement layers. The SVC stream is defined as a sequence of network abstract layer units (NALUs). Each NALU has a header, which carries decoding information about the NALU. In this work, we use a 12-byte NALU header defined in [13]. A video layer selection module selects proper number of video layers to be transmitted. The selected SVC NALUs are packetized so that each packet contains NALUs from a single video quality layer and a single group of pictures (GoP). The packet size is the same for each packet and is set as 256 bytes in this paper. Large NALUs are fragmented to fit the packet size and the same NALU header is added.
to each fragment. The packet streams are then fed into the packet level APP-FEC module, which adds different amount of redundancy packets to each stream. All of APP-FEC encoded packets are added with FEC payload IDs as defined in [14]. A channel selection module distributes the APP-FEC encoded packets to WiFi and LTE networks based on their estimated transmission data rates. Two different RTP sessions with user datagram protocol (UDP) sockets are created for transmitting packets through WiFi and LTE networks respectively. Each RTP session is responsible for monitoring its corresponding network conditions and sends back RTCP reports to the server. Our proposed algorithm is implemented in the APP layer scheduler, which selects proper video layer, APP-FEC rate for each selected video layer and transmission data rate for each network. The proposed algorithm optimizes system utility (received video quality) based on the utility value of each network and the estimated channel conditions from RTCP reports. In this paper, we only use RTCP receiver reports (RR) for collecting network statistics. The RTCP feedback rate is set as 5% of transmission data rate of its corresponding network [15]. The proposed algorithm are executed every GoP period, which is about 267 ms for videos with GoP size 8 and frame rate 30 fps. At receiver side, the received packets from both WiFi and LTE networks are saved in corresponding receiving buffer. Every GoP period, the received packets are fed into different APP-FEC decoders based on the source block number (SBN) information carried in FEC payload ID. Packets of previous decoded GoPs are considered as late packets and are dropped. The whole FEC block is discarded if the number of packet losses is larger than its correction capability. The decoded packets are then fed into different decoding buffers based on the quality ID (QID) information carried in NALU header. The NALUs of video layer \( l \) is dropped if the required lower layers (e.g., from base layer to the \((l-1)\)-th layer) are not received. Finally, the video is reconstructed based on the successfully received NALUs. Note that the proposed scheme is an APP layer design, it can be easily implemented without changing the configurations of lower layers (e.g., transport or MAC layers).

### III. Transmission Data Rate Adaptation Scheme

Due to the limited wireless resources, the large amount of competing nodes cause severe congestion/collision problems in LTE/WiFi networks, which further increase the transmission delay and degrade the QoE of delay sensitive video streaming applications. Therefore, it is crucial to adaptively adjust the transmission data rates for both LTE and WiFi networks based on their network qualities. Please note that in this paper, the transmission data rates are determined in APP layer. If the transmission data rate is higher than the available data rate in the network, large delay and packet loss will occur on the delivered packets.

Our proposed transmission data rate adaptation scheme can be decomposed into two stages: intra-network stage and inter-network stage. In the intra-network stage, the transmission data rate is adaptively determined based on the corresponding estimated network quality. In the inter-network stage, the proposed scheme tries to compensate the decrease of data rate in one network by increasing the data rate in another network so that the total target data rate remains the same.

#### A. Intra-Network Stage

Suppose the target transmission data rate \( D^{(T)} \) is determined by the service provider, without loss of generality, the target transmission data rates for LTE and WiFi networks are arbitrarily assumed to be \( D_{LTE}^{(T)} = D_{WiFi}^{(T)} = D^{(T)}/2 \) for load balancing on both networks. When the video streaming connection is set up, the initial transmission data rates of LTE and WiFi networks equal to their corresponding targets, i.e., \( D_{LTE} = D_{LTE}^{(T)} \) and \( D_{WiFi} = D_{WiFi}^{(T)} \). When RTCP RR reports are received, the sender can estimate the number of received packets \( N^{(R)} \) and the number of packets under delivering \( N^{(D)} \) based on the “highest sequence number received” field reported from RTCP RR. Therefore, the available transmission data rates \( D^{(A)}_{LTE/WiFi} \) of LTE or WiFi networks can thus be estimated:

\[
D^{(A)}_{LTE/WiFi} = N^{(R)}_{LTE/WiFi} \times S/T_{GoP}, \quad (3)
\]

where \( S \) denotes the packet size in bits and \( T_{GoP} \) denotes the GoP period. Note that the network statistics are estimated...
every GoP period since the proposed APP layer scheduling scheme is performed once every GoP period.

Due to the transmission latency and relatively longer feedback period of RTCP reports, the number of received packets is normally less than the number of total transmitted packets even when network quality is good. Therefore, we define a threshold $T_h$ to indicate whether a large delay occurs in the network. In this paper, the threshold $T_h$ is defined as:

$$T_h = D_{LTE/WiFi} / (S \times FR),$$

(4)

where $D_{LTE/WiFi}$ denotes the transmission data rate of either LTE or WiFi network and $FR$ denotes the video frame rate. If $N^{(D)} > T_h$, i.e., the packets of previous GoP under delivering cannot be received within the time of displaying next video frame, the corresponding network is considered in “congestion state”. Otherwise, the corresponding network is considered in “non-congestion state”.

Therefore, the actual transmission data rates of LTE and WiFi networks in intra-network stage are determined as:

$$D_{LTE/WiFi} = \begin{cases} \max (D^{(A)}_{LTE/WiFi}, D^{(min)}_{LTE/WiFi}), & N^{(D)}_{LTE/WiFi} > T_h \\ \frac{D_{LTE/WiFi} + D^{(T)}_{LTE/WiFi}}{2}, & N^{(D)}_{LTE/WiFi} \leq T_h \end{cases},$$

(5)

where $D^{(min)}$ is the minimum data rate used to avoid zero transmission data rate so that the network statistics are still available from the RTCP feedbacks. That is, if the network is in “congestion state”, its corresponding transmission data rate is set as the estimated available data rate or the minimum data rate. Otherwise, the transmission data rate is increased by half of the difference of target data rate and previous data rate.

B. Inter-Network Stage

If the transmission data rate of one network is less than 95% of its target data rate, our proposed APP layer scheduling algorithm tries to maintain the total target data rate by increasing the data rate of the other network if it is in “non-congestion state” and its current data rate is close to its target data rate. Therefore, the transmission data rates of LTE and WiFi networks are determined as:

$$D_{LTE/WiFi} = \begin{cases} D^{(T)}_{LTE} - D^{(W)}_{WiFi}, & D_{LTE} > 0.95D^{(T)}_{LTE} \text{ and } N^{(D)}_{LTE} \leq T_h \\ D_{LTE}, & \text{otherwise} \end{cases},$$

(6)

$$D_{WiFi/WiFi} = \begin{cases} D^{(T)}_{LTE} - D^{(W)}_{WiFi}, & D_{WiFi} > 0.95D^{(T)}_{WiFi} \text{ and } N^{(D)}_{WiFi} \leq T_h \\ D_{WiFi}, & \text{otherwise} \end{cases}$$

IV. VIDEO LAYER AND APP-FEC RATE ADAPTATION

The network PLR can be estimated based on the “cumulative number of packet lost” reported by RTCP feedbacks. The PLR is calculated every GoP period. Once the transmission data rates of the two networks are determined, inspired by [16], the proposed APP layer scheduler chooses proper number of video layers and their corresponding APP-FEC rates so that the video decoding quality is maximized at the receiver side.

Therefore, the optimization problem can be formulated as:

$$\begin{equation}
Q : \max_{t, L, u} \sum_{l=1}^{L} u_l f_l (t), \quad (8)
\end{equation}$$

subject to $t_l \geq 0; \sum_{l=1}^{L} t_l + K_l = N_{WiFi} + N_{LTE}$

where $u_l$ is the utility value of the $l$-th video layer; $t = \{t_1, t_2, ..., t_L\}$ is the FEC redundancy of each video layer; $K_l$ is the number of message packets of the $l$-th video layer; $N_{WiFi}$ and $N_{LTE}$ are the total number of packets allowed for transmission according to the determined transmission data rates:

$$N_{LTE/WiFi} = \frac{T_{GoP} \times D_{LTE/WiFi}}{S},$$

(9)

$f_l(t)$ is the correction rate of the $l$-th video layer, and can be expressed as:

$$f_l(t) = \prod_{k \in P_l} (1 - P_k(t_k)), \quad (10)$$

where $P_k(t_k)$ is FEC block correction rate of the $k$-th video layer. If we define $X_k$ and $Y_k$ as random variables of erroneous symbols of the $k$-th video layer in LTE and WiFi networks respectively, they all follow Binomial distribution, i.e., $X_k \sim \text{Binomial}(N_{LTE,k}, \frac{D_{LTE,k} - D_{LTE,k}}{D_{LTE,k}})$ and $Y_k \sim \text{Binomial}(N_{WiFi,k}, \frac{D_{WiFi,k} - D_{WiFi,k}}{D_{WiFi,k}})$, where $N_{LTE,k}$ and $N_{WiFi,k}$ are the number of packets of the $k$-th video layer in LTE and WiFi network respectively; $P_{LTE}$ and $P_{WiFi}$ are PLRs in LTE and WiFi networks respectively.

The FEC block correction rate is thus represented as:

$$P_k(t_k) = \sum_{j=0}^{t_k} \Pr (X_k + Y_k = j),$$

(11)

where $\Pr (X_k + Y_k = j)$ is the probability mass function (PMF) of the sum of random variables $X_k$ and $Y_k$, which can be calculated by doing convolution sum of PMFs of $X_k$ and $Y_k$.

The optimization problem $Q$ can be decomposed into $L_{max}$ sub-problems if up to the $L$-th video layer are selected for transmission. The $L$-th sub-problem is therefore:

$$Q_L : \max_{t, L} \sum_{l=1}^{L} \log (P_l (t_l)), \quad (12)$$

subject to $t_l \geq 0; \sum_{l=1}^{L} t_l + K_l = N_{WiFi} + N_{LTE}$

and $L = 1, 2, ..., L_{max}$. Each sub-problem provides one candidate solution set $\{L, t^*_L\}$. The optimal solution of $Q$ is obtained from the candidate solution set with maximum system utility:

$$\{L^*, t^*\} = \arg \max_{\{L, t^*_L\}} \sum_{l=1}^{L} u_l f_l (t^*_l).$$

(13)

In this paper, a heuristic algorithm, shown in Table I, is used to search the optimal solution of the sub-problem $Q_L$. For each iteration, one more redundancy packet is added to the video layer with higher gain of FEC block correction rate. The iteration process stops until no additional redundancy packet can be added.
In this section, the effectiveness and favorable performance of our proposed APP layer scheduling scheme is evaluated. Video clip “City” with CIF resolution is encoded by the SVC reference software JSMV version 9.19. Both GoP size and intra period are set as $8$ so that the frame pattern is one I-frame followed by $7$ B-frames in one GoP. The frame rate is $30$fps. There are $297$ frames encoded, which contains $37$ GoPs with one additional I-frame. The video is encoded into four quality layers with medium-grain scalability (MGS), where motion estimation and compensation are constrained at current quality layers with medium-grain scalability (MGS), where motion estimation and compensation are constrained at current layer [12]. The basis quantization parameters are: $QP = [48, 42, 36, 30]$ for the four quality layers, with the corresponding uniform quantization stepsizes being: $q = 2(QP - 4)/6$ [12]. The video dependent parameter $c$ in Eq. (1) is set as $0.13$ [12]. The utility values and cumulated source coding rates of the four layers are listed in Table II. The missed video frames are concealed by simply copying the last received frame.

### TABLE I
ALGORITHM FOR SOLVING SUB-PROBLEM $Q_L$

1. $t := 0$
2. while $\left(1 + \sum_{t=1}^{N_{LTE} + N_{WiFi}} t_i \right)$
3. for each $j = 1, 2, \ldots, L$
4. $G_l(t_i) := \log (P_l (t_i + 1)) - \log (P_l (t_i))$
5. end for
6. $t^* := \arg \max G_l(t_i)$
7. $t_{t^*} := t_{t^*} + 1$
8. end while
9. return $t$

### V. SIMULATION RESULTS

In this section, the effectiveness and favorable performance of our proposed APP layer scheduling scheme is evaluated. Video clip “City” with CIF resolution is encoded by the SVC reference software JSMV version 9.19. Both GoP size and intra period are set as $8$ so that the frame pattern is one I-frame followed by $7$ B-frames in one GoP. The frame rate is $30$fps. There are $297$ frames encoded, which contains $37$ GoPs with one additional I-frame. The video is encoded into four quality layers with medium-grain scalability (MGS), where motion estimation and compensation are constrained at current layer [12]. The basis quantization parameters are: $QP = [48, 42, 36, 30]$ for the four quality layers, with the corresponding uniform quantization stepsizes being: $q = 2(QP - 4)/6$ [12]. The video dependent parameter $c$ in Eq. (1) is set as $0.13$ [12]. The utility values and cumulated source coding rates of the four layers are listed in Table II. The missed video frames are concealed by simply copying the last received frame.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Utility</th>
<th>Cumulative Source Coding Rate (Kbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.4025</td>
<td>211.1</td>
</tr>
<tr>
<td>2</td>
<td>0.2745</td>
<td>309.6</td>
</tr>
<tr>
<td>3</td>
<td>0.2010</td>
<td>626.8</td>
</tr>
<tr>
<td>4</td>
<td>0.1219</td>
<td>1223.9</td>
</tr>
</tbody>
</table>

We use the network simulator 3 (NS-3) version 19 as the simulation platform. Four fixed nodes, including a remote server, PGW, eNodeB and WiFi AP are located with inter-node distance set as $60$m. $20$ UEs are randomly allocated around the eNodeB within $200$m radius. $4$ WiFi STAs are allocated around the AP within $50$m radius. The intended receiver belongs to both UE and STA nodes. Random walk mobility model is used for all the UE and STA nodes. IEEE 802.11n standard with data rate $6.5$Mbps is used in WiFi network. Default LTE parameters in NS-3’s LTE module are used. SVC application between the remote server and the intended receiver starts at the $1$st second of the simulation. The total target transmission data rate is set as $1.6$ Mbps. All the UE and STA nodes, except the intended receiver, are installed with on-off application with constant bit rate as $1$Mbps. The on-off applications of UE nodes start at the $3$-rd second and stop at the $7$-th second. The on-off applications of STA nodes start at the $5$-th second and stop at the $9$-th second. Therefore, for the intended receiver, network congestion occurs in the LTE network from the $3$-rd second to the $7$-th second; and collision happens in the WiFi network from the $5$-th second to the $9$-th second. The PLR of the point-to-point link between the remote server and the PGW node is set as $0.05$. And that between the remote server and the AP is set as $0.1$.

Figure 3 shows the transmission data rates and the PLRs of the LTE and WiFi networks experienced by the intended receiver using the proposed APP layer scheduling scheme. The huge PLR peaks are caused by the burst data traffics when the on-off applications are turned on. The initial transmission data rates of the LTE and WiFi networks are both $800$ Kbps. When congestion only occurs in the LTE network (from GoP index $8$ to $16$), its transmission data rate decreases while that of the WiFi network increases so that the average transmission data rate remains. When congestions occur in both LTE and WiFi network (from GoP index $16$ to $23$), the average transmission data rate starts to decrease since both networks cannot reach their data rate targets. When the LTE network quality becomes good (from GoP index $23$ to $37$), its transmission data rate starts to recover (from GoP index $23$ to $25$), and becomes higher than its target data rate (from GoP index $26$ to $37$). As expected, the average data rate also recovers.

![Fig. 3. Transmission data rates and PLRs of LTE and WiFi networks experienced by the intended receiver using the proposed APP layer scheduling scheme.](image-url)
TDRA+EEP scheme uses equal FEC redundancy on each video layer instead of solving the optimization problem $Q$. Therefore, by comparing with TDRA+EEP scheme, the effectiveness of the APP-FEC rate adaptation part of the proposed scheme can be demonstrated.

The SVC quality layer indices of reconstructed frames are plotted in Fig. 4. The per-frame PSNR of the three schemes are shown in Fig. 5. When congestions occur in LTE network (from frame index 65 to 129), few frames are missed for the proposed and TDRA+EEP scheme. However, the proposed scheme can still receive more video frames with higher layers comparing to TDRA+EEP scheme. In this case, NS+UEP scheme has the best performance since it only uses WiFi network for transmission. When congestion/collision starts to occur in WiFi network (from frame index 130 to 185), the performance of NS+UEP scheme drops dramatically since some video frames are missed. In this case, our proposed scheme and TDRA+EEP scheme have acceptable decoding quality but our proposed scheme still outperforms TDRA+EEP scheme. When the congestions in LTE network diminishes (from frame index 186 to 297), the performance of the three schemes become better and our proposed scheme outperforms the other two.

![SVC quality layer indices of reconstructed video frames](image1)

![Per-frame PSNR](image2)

VI. Conclusion

In this paper, an APP layer scheduling scheme is proposed for SVC-based video transmissions over multi-RAT systems. Based on the RTCP feedback and the estimated network conditions, the proposed scheme adaptively determines the transmission data rates of LTE and WiFi networks, the SVC video layer to be transmitted and APP-FEC redundancy for each video layer so that the decoding quality is maximized at the receiver side. Simulations show the effectiveness of our proposed scheme.

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