Chapter 6

Cross-layer UEP using FEC and HQAM

6.1 Introduction

As discussed in the previous chapters that in embedded video bitstreams, different bits have their varying importance as well as have different sensitivity to channel errors. To optimize the communication resources, these bitstreams are non-uniformly protected against channel noise according to their importance which leads to unequal error protection (UEP).

The UEP can be provided at different layers of wireless or IP networks. The most common among them are (i) Application layer UEP using forward error correction (discussed in chapter 5) and (ii) Physical layer UEP using asymmetrical (or hierarchical) modulation (discussed in chapter 4). To implement UEP, wavelet coded video bitstream was partitioned into high priority (HP) and low priority (LP) substreams. In chapter 4, the use of physical layer UEP using Hierarchical QAM (HQAM) was investigated to provide relatively higher protection to HP and lesser protection to LP substreams. Although, the HQAM based UEP is bandwidth efficient, it protects the important information at the cost of other information. Chapter 5 investigates the application layer UEP for wavelet coded video bitstream using forward error correction (FEC) codes, where HP bits were protected with higher order channel codes than the LP bits.

From the results of chapter 4 and 5, it was observed that FEC based UEP is more efficient in protecting bits against the channel errors than the HQAM based UEP, but it is not bandwidth efficient. In this chapter, the objective is to develop a cross-layer UEP combining FEC-based UEP of application layer and HQAM-based UEP of physical layer, so that communication resources can be optimally utilized.
Although the decoupled layered protocol reduces network design complexity, independently optimized protocol paradigm is not well suited for wireless networks due to dynamically varying bandwidth and error rates, user mobility, high interferences, limited power and complexity [17]. Cross-layer design methodologies that rely on interaction among different protocol layers hold great promises for addressing these challenges of providing reliable wireless video communication [154, 155].

A number of investigations have been done in cross-layer design but they are mainly in the perspective of cross-layer networking architecture [159], video distortion driven routing [160], scheduling [161], link adaptation [162], energy efficiency [163], etc. To implement error control strategies, a number of researchers have used application layer FEC and Media Access Control (MAC) layer ARQ to provide cross-layer error protection for wireless LANs [168, 169, 170, 155]. However, for large networks such as cellular mobile, the delay introduced by MAC layer ARQ may not be suitable for delay sensitive video applications. Also, for applications such as multicast, there is no provision of feedback channel to support ARQ protocol. Therefore, for such scenarios, cross-layer error protection employing different combinations of application layer FEC and adaptive modulation is a viable alternative [39, 40, 41]. The investigations for cross-layer error control strategies using application layer FEC and modulation have been performed mostly for DCT coded video bitstream and limited studies have been done for wavelet coded videos. For example, in [39], a combination of turbo code and hierarchical QAM is used to provide UEP for two layer scalable H.264/AVC bitstream. Similarly, a combination of rate compatible punctured convolution code (RCPC) and non-uniform phase shift keying (PSK) modulation is suggested in [40] and [41] to achieve UEP in H.263+ layered video bitstreams.

Furthermore, to efficiently utilize the communication resources, optimization of the cross-layer parameters are required. However, the optimization of these cross-layer parameters on the fly for real time video applications is not possible due to computational complexity and large delay required in optimization. Therefore, off-line optimization of the cross-layer parameters is the viable solution for real time video based applications which is the main theme of this chapter.

In this chapter, optimized cross-layer design for providing UEP to wavelet coded embedded video is proposed. This design relies on interaction between the application layer FEC and the physical layer HQAM to achieve reliable and high quality end-to-end performance in wireless channels as depicted in Fig. 6.1. The function of cross-layer allocator is to allocate the channel resources for video data with different priorities. Specifically, the compressed video bitstream is partitioned into two priority substreams: high priority (HP) and low priority (LP).
An FEC based UEP is employed at application layer and HQAM based UEP is provided at physical layer. By controlling three parameters, \( r_{\text{avg}}, \gamma \) and \( \alpha \) (or \( r_{HP}, r_{LP} \) and \( \alpha \)), defined in previous chapters, cross-layer UEP can be achieved. Based on the noise condition of the channel, cross-layer allocator allocates and sends FEC coding rates \( (r_{HP}, r_{LP}) \) and HQAM modulation parameter \( (\alpha) \) to the application and physical layers, respectively. For video compression, WBTC based video coder is used, which provides significant benefits for wireless video transmission due to its inherent rate scalability and easy prioritisation of video packets for UEP purposes. However, the focus of this thesis is on cross-layer solution (using application and physical layers) for UEP of scalable video bitstreams under bandwidth and power constraints, and not on a particular video coding scheme.

This chapter firstly investigates the non-optimized cross-layer UEP combining application layer FEC and physical layer HQAM. Then based on the investigation, the optimized cross-layer UEP is proposed to deliver best quality of the reconstructed video. Finally, the simulation results and discussion are presented.

### 6.2 Non-optimized Cross-layer UEP

The objective behind cross-layer UEP of wavelet coded video bitstream is to facilitate the video transmission using portable devices under power and bandwidth constrained environments while achieving the best overall quality. Here,
the cross-layer UEP is obtained by combining the application layer FEC with
the physical layer adaptive HQAM. The block diagram of video communication
system using cross-layer UEP is shown in Fig. 6.2. The encoded video bitstream
is partitioned into two separate substreams, namely: HP and LP substreams,
according their importance and sensitivity to channel errors. These substreams
are firstly protected unequally by controlling FEC-based UEP parameters, \( \gamma \) and
\( r_{\text{avg}} \), defined in Eqns. (5.7) and (5.9) respectively. The FEC coded HP and LP
substreams are then multiplexed to form symbols to be mapped over asymmet­
rical constellations of HQAM. In HQAM, the HP and LP are further protected
unequally using modulation parameter, \( \alpha \), defined in Eqn. (3.1). These symbols
are then transmitted over AWGN channel. At the receiver, the reverse process
is performed to demodulate and recover the video bitstream. Therefore, in the
cross-layer UEP scheme, three parameters, namely, \( r_{\text{avg}}, \gamma \) and \( \alpha \) control the rel­
tive error protection of HP and LP substreams.

Before developing algorithm for optimization of these parameters, it is impor­
tant to study how these parameters affects the performance of cross-layer UEP.

**Performance Analysis**

In order to investigate the effect of different parameters on the performance of
cross-layer UEP, two separate cases are considered; Case I: Application layer
EEP (\( \gamma = 1 \), fixed \( r_{\text{avg}} \)) and physical layer UEP (varying \( \alpha \) of HQAM). Case II:
Application layer UEP (varying \( \gamma \) and \( r_{\text{avg}} \)) and physical layer UEP (varying \( \alpha \)
of HQAM).

The performance of cross-layer UEP is compared with two schemes, namely
application layer EEP and application layer UEP. That is, this is to investigate
that what happens if application layer EEP and UEP are modified by providing
further protection of HP and LP substreams using HQAM. These are analysed as follows.

Fig. 6.3 compares the quality of reconstructed Foreman sequence when the wavelet coded video (coded at 1000 kbps) is transmitted over AWGN channel employing fixed rate channel coding at application layer (fixed $r_{\text{avg}}$ and $\gamma = 1$) and hierarchical modulation, HQAM, with varying $\alpha$ at physical layer.

Fig. 6.3(a) and (b) shows the performance of cross-layer UEP (application layer UEP and physical layer UEP) at $r_{\text{avg}} = 0.76$, $\gamma = 1$, respectively and in both cases $\alpha = 1, 1.4$ and $1.8$ are considered. It can be observed that when physical layer UEP is applied over application layer EEP the quality of received video improves at lower CNR (up to CNR = 16 dB) but at higher CNR, cross-layer UEP perform worse than EEP scheme ($r_{\text{avg}} = 0.69, \gamma = 1, \alpha = 1$). While comparing Fig. 6.3(a) and (b), it can be observed that when $r_{\text{avg}}$ is reduced or EEP protection at application layer is increased the PSNR vs CNR curve shifts towards y-axis. That is, better quality at lower CNR (poor channel condition) is obtained. Furthermore, it can be observed that in comparison to $r_{\text{avg}} = 0.76, \gamma = 1$ and $\alpha = 1$, when $\alpha$ is increased there is a gain of up to 9 dB and 15.5 dB at $\alpha = 1.4$ and $\alpha = 1.8$ respectively, but at the same time PSNR decreases by almost the same amount at CNR = 18 dB. Therefore, at fixed $\alpha$, it is impossible to achieve PSNR improvement for each channel noise conditions.

Fig. 6.4 compares the performance of cross-layer UEP (UEP at application layer and UEP at physical layer) for fixed values of various application and physical layer parameters ($\gamma > 1$) under different noise conditions of AWGN channel for Foreman video sequence (coded at 1000 kbps). Following observations can be inferred from these figures:

(i) Fig. 6.4(a) compares cross-layer UEP ($r_{\text{avg}} = 0.76, \gamma = 1.52, 1 \leq \alpha \leq 1.8$) with application layer UEP ($r_{\text{avg}} = 0.76, \gamma = 1.52, \alpha = 1$). It can be observed that as $\alpha$ is increased, the quality of reconstructed video increases by approx. 8 dB at CNR = 14 dB. Whereas, it decreases by approx. 6 dB at CNR = 20 dB in comparison to application layer UEP ($\alpha = 1$).

(ii) Fig. 6.4(b) depicts similar comparison but at $r_{\text{avg}} = 0.69, \gamma = 1.59$. The similar trends (as discussed in (i)) is observed that the graphs are shifted towards y-axis.

From these results, it seems that cross-layer UEP performs better than application layer EEP and UEP only at lower CNR whereas at moderate to high CNRs, the application layer EEP or UEP gives better performance. That is single set of parameters may not be sufficient to provide error resiliency for each channel conditions and hence these parameters need to be adaptive. Furthermore, it
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Figure 6.3: The objective quality of reconstructed Foreman sequence coded at 1000 kbps against different noisy conditions for cross-layer UEP (combining application layer EEP and physical layer UEP) for (a) $r_{avg} = 0.76$ and (b) $r_{avg} = 0.69$.
Figure 6.4: Objective quality of Foreman video sequence coded at 1000 kbps against different noisy condition for cross-layer UEP (combining application and physical layers UEP) at (a) $r_{\text{avg}} = 0.76$ and (b) $r_{\text{avg}} = 0.69$
needs to be investigated that how these parameters \((r_{avg}, \gamma, \alpha)\) should be selected for each channel conditions so that best end-to-end video quality can be obtained. Thus, there is a need for optimization of the parameters which will be discussed in the next section.

### 6.3 Optimized cross-layer UEP

As discussed earlier, that by varying \(r_{avg}, \gamma\) and \(\alpha\) a cross-layer unequal error protection of video over erroneous channels can be achieved. It was observed that cross-layer UEP performs better at lower CNR than application layer UEP while its performance decreases at higher CNR. These observations were based on the heuristic values of parameters (that is non-optimized parameters) and that too are fixed for all noise conditions. In this section, an optimized cross-layer UEP is proposed for transmission of coded video bitstream over AWGN channel. The results are compared with optimized UEP based on individual layers.

Fig. 6.5 shows the block diagram of a video communication system with optimized cross-layer UEP. The system is almost similar to that shown in Fig. 6.2, except that the cross-layer parameter are firstly optimized for each noise conditions and then placed in a look-up table. The look-up table stores the optimized values of cross-layer parameters for wide range of CNR, obtained using off-line optimization algorithm. At the time of video communication, transmitter takes the parameter values from the look-up table for a given channel conditions.
6.3.1 Problem Formulation

The end-to-end quality of received video sequences measured in term of Peak Signal-to-Noise Ratio (PSNR) is the function of BER in HP and LP substreams, that is

$$\text{PSNR} = f(P^{HP}_e, P^{LP}_e)$$  \hspace{1cm} (6.1)

where $P^{HP}_e$ and $P^{LP}_e$ are the probability of error of channel decoded HP and LP substreams respectively, which are the function of average channel code rate, $r_{avg}$; $\gamma$ specifying relative protection of HP and LP substreams; and $\alpha$, modulation parameter of HQAM. That is

$$P^{HP}_e = f_1(r_{avg}, \gamma, P^{HP}_e)$$ \hspace{1cm} (6.2)

$$P^{LP}_e = f_2(r_{avg}, \gamma, P^{LP}_e)$$ \hspace{1cm} (6.3)

where $P^{HP}_e$ and $P^{LP}_e$ are the probability of errors of HQAM demodulated HP and LP substreams, respectively and these are the function of modulation parameter, $\alpha$, for a given channel as given below

$$P^{HP}_e = f_3(\alpha)$$ \hspace{1cm} (6.4)

$$P^{LP}_e = f_4(\alpha)$$ \hspace{1cm} (6.5)

The relationships among $P^{HP}_e$, $P^{LP}_e$, $\alpha$ and CNR for AWGN channel are the same as given in Eqns. (3.72) and (3.73). Combining Eqns. (6.2), (6.3), (6.4) and (6.5), Eqn. (6.1) can be rewritten as

$$\text{PSNR} = f(r_{avg}, \gamma, \alpha)$$ \hspace{1cm} (6.6)

That is, at fixed transmission rate and channel conditions, the end-to-end video quality is the function of $r_{avg}$, $\gamma$ and $\alpha$. Among these, $r_{avg}$ and $\gamma$ are the parameters of application layer channel coding and $\alpha$ is the parameter of physical layer HQAM.

Let $X$ be the cross-layer parameter vector defined as

$$X = \left\{ \begin{array}{c}
    r_{avg} \\
    \gamma \\
    \alpha
  \end{array} \right\}$$ \hspace{1cm} (6.7)

Then the PSNR of decoded video can be re-written in terms of parameter vector,
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\[ \text{PSNR} = f(X) \]  

(6.8)

In order to achieve the best end-to-end video quality for a given channel conditions (specified bandwidth and noise power), the parameter vector, \( X \), should be optimized to maximize the PSNR. Furthermore, as the channel condition (CNR) changes, the optimized vector, \( X \), needs to be adapted to deliver the best quality of service. In other words, the objective is to find the value of vector, \( X \), (for a given CNR and transmission rate) such that PSNR is maximum, that is

\[ \text{PSNR}_{\text{max}} = \max_{X} f(X) \]  

(6.9)

where the maximization is performed individually for each CNR.

Let, \( X_m \) be the cross-layer parameter vector which maximizes the PSNR such that at a given CNR and transmission rate

\[ X_m \triangleq X \left| f(X_m) \geq f(X) \quad \forall X \right. \]  

(6.10)

where \( X_m \) is the values of \( r_{\text{avg}}, \gamma \) and \( \alpha \) at which Eqn. (6.10) is satisfied, denoted as

\[ X_m = \left\{ \begin{array}{c} r_{m}^{\text{avg}} \\ \gamma_{m} \\ \alpha_{m} \end{array} \right\} \]  

(6.11)

Although, the value of PSNR at \( X_m \) is guaranteed to be the best, searching for \( X_m \) satisfying Eqn. (6.10) result in the large dynamic range of \( X_m \). This effect is because of varying video characteristics and channel conditions which results small fluctuations in the PSNR. In a similar approach to chapter 4, an optimal \( X \) can be obtained, while relaxing the constraint of the best PSNR, such that it reduces the dynamic range of optimal \( X \) for the ease of hardware requirement.

Therefore, the optimal value of \( X \), \( X_{\text{opt}} \), is not the one which gives the best PSNR, but the minimal \( X \) at which PSNR is with \( \pm 0.5 \) dB margin of the best PSNR. The optimum parameter vector, \( X_{\text{opt}} \), may be defined as follows

\[ X_{\text{opt}} = [r_{\text{avg}}^{\text{opt}}, \gamma_{\text{opt}}, \alpha_{\text{opt}}]^T = \min\{X\} \left| f(X) \geq f(X_m) - 0.5 \ \text{dB} \quad \forall X \right. \]  

(6.12)

In the next subsection, the algorithm to obtain the optimized values of cross-layer parameters to provide UEP to wavelet coded video bitstream at different
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channel condition will be discussed. Since real-time optimization for each condition of time varying channel is difficult, therefore an off-line approach with look-up table (LOT) is suggested.

6.3.2 Design of optimized look-up table (LUT)

Based on the discussions, similar to that in the previous chapters, an off-line full search optimization is used to find the optimal values of cross-layer parameters, \( X_{opt} \). For a wide range of video sequences and at each CNR, \( X_{opt} \), that results near maximal video quality according to Eqn. (6.12) are obtained. These values are then stored in a look-up table.

In order to develop an algorithm to find the optimum cross-layer parameters \( X_{opt} \), it is worthwhile to study the variations in PSNR of reconstructed video varies with cross-layer parameters \( (r_{avg}, \gamma \) and \( \alpha ) \).

Surface plots of Figs. 6.6(a)-(d) shows the variation in PSNR of Foreman sequence against \( r_{avg} \) and \( \alpha \) (while \( \gamma = 1 \)) for CNR = 10, 14, 18 and 21 dB respectively. Since effect of varying \( \gamma, r_{avg} \) and that of \( \alpha \) on video quality has already been studied in the previous chapter, here we are interested in studying joint effect of \( \alpha \) and \( r_{avg} \) on the video quality and \( \gamma = 1 \) is fixed for simplicity.

Following observations can be inferred from these figures.

i) From Fig. 6.6(a), it can be observed that initially at fixed \( r_{avg} \), as \( \alpha \) increases the PSNR increases and then almost saturates. Furthermore, as \( r_{avg} \) decreases (i.e. protection increases) saturation in PSNR occur at lower value of \( \alpha \). For example, at \( r_{avg} = 0.6 \), PSNR starts increasing from approx. 9.5 dB (at \( \alpha = 1 \)) and saturates to approx. 25.5 dB at \( \alpha = 10 \). However, when \( r_{avg} \) to 0.4 (\( r_{avg} = 0.4 \)), PSNR starts increasing from approx. 9.8 dB at \( \alpha = 1 \) and saturates to approx. 23 dB at \( \alpha = 4 \). That is, when \( r_{avg} \) decreases form 0.6 to 0.4, saturation point moves from (10, 25.5) to (4, 23). It may be noted here that decreasing \( r_{avg} \) not only decreases the value of \( \alpha \) at which PSNR saturates but also the value of PSNR at which it saturates. This is because of increase in parity bits at lower \( r_{avg} \).

ii) Again from Fig. 6.6(a), it can be observed that at fixed \( \alpha \), as \( r_{avg} \) decreases (protection increases) PSNR increases up to certain value and after that for decrease in \( r_{avg} \), decreases the PSNR. The value of \( r_{avg} \) at which maximum PSNR is obtained is called optimum \( r_{avg} \). Furthermore, as \( \alpha \) increases, the optimum \( r_{avg} \) also increases. For example, at \( \alpha = 2 \), the optimum value of \( r_{avg} \) is 0.22, whereas, at \( \alpha = 10 \), the optimum value of \( r_{avg} \) is 0.57.

iii) From Fig. 6.6(b) (surface plot at CNR = 14 dB), a similar observation can
Figure 6.6: PSNR vs $\alpha$ and $r_{avg}$ for different CNR at 1000 kbps for foreman sequence keeping $\gamma = 1$ (contd...)
Figure 6.6: PSNR vs $\alpha$ and $r_{\text{avg}}$ for different CNR at 1000 kbps for foreman sequence keeping $\gamma = 1$
be deduced. The only difference between this figure and Fig. 6.6(a) is that for the same $r_{avg}$, saturation of PSNR starts at lower values of $\alpha$ and for the fixed $\alpha$, optimum value of $r_{avg}$ is increased.

iv) Fig. 6.6(c) shows the PSNR variation with respect to $\alpha$ and $r_{avg}$ for AWGN channel with CNR = 18 dB. It has almost similar variation as in Fig. 6.6(b) except at lower values of $\alpha$ and $r_{avg}$. At high $r_{avg}$, the PSNR increases and saturates with the increase in $\alpha$, but when $r_{avg}$ is low, the PSNR increases up to maximum value (at lower value of $\alpha$), and then decreases and saturates as $\alpha$ increases.

v) Likewise, similar trends is also observed in Fig. 6.6(d) for CNR = 22 dB. The only difference in this figure to that of Fig. 6.6(c) is that for each value of $r_{avg}$, the PSNR increases up to maximum value (at lower $\alpha$), and then decreases and saturates as $\alpha$ increases.

The reasons of these variation in PSNR against $\alpha$ and $r_{avg}$ for specified CNR are as follows:

1) At fixed CNR, with $\gamma = 1$, the HP and LP substreams are equally protected with channel code rate, $r_{avg}$. Variation in $\alpha$ at fixed $r_{avg}$, results similar variation in PSNR as seen in Fig. 4.3 in chapter 4 (section 4.3.2). That is, increasing the value of $\alpha$ increases the protection of HP substream at the expense of LP substream. Therefore quality of the reconstructed video increases up to a certain value of $\alpha$. After that, the reduction in the BER of HP substream (due to increase in $\alpha$) is negligible, which is also clear from the Fig. 3.5 in subsection 3.4.2, and hence increase in PSNR is almost zero at higher values of $\alpha$.

2) As $r_{avg}$ decreases, the protection of HP and LP substreams become stronger. At lower $r_{avg}$, since BER of HP substream is already small, attempt to further reduce the BER of HP substream by increasing $\alpha$ will have negligible effect on the video quality. This causes early saturation of PSNR (at lower values of $\alpha$) as $r_{avg}$ decreases.

3) For fixed $\alpha$, at a certain value of $r_{avg}$, called critical $r_{avg}$, the BER rate of the substreams become zero. It mean further reduction in $r_{avg}$ will not improve the quality of the reconstructed video. However, due to the use of joint source-channel coding (JSCC) at fixed transmission rate, decreasing the $r_{avg}$ beyond the critical value, causes reduction in the source bit rate and therefore reducing the reconstructed video quality.
From these observations, it is clear that there exist trade off among the cross-layer parameters and therefore, there is a need to find the optimal value of these parameters so that the best video quality at each CNR is achieved.

Since the wireless channel is time varying as discussed earlier, it is almost impossible to calculate $X_{opt}$ for each channel noise condition on the fly basis (as and when channel condition changes), within the permissible time limit. Similar to previous chapter, in this chapter also, we propose the use of look-up table to store optimal value of cross-layer parameters for each possible channel noise conditions. The optimal cross-layer parameters, for each channel noise condition are calculated by averaging the corresponding value of parameters obtained for each of the test video sequences at given CNR. To obtained the optimal cross-layer parameters, an off-line full search scheme (with controlled step size) is used. The optimal parameters are searched from the range of parameters specified by minimum to maximum values of parameters listed in Eqn. (6.13) and (6.14) respectively.

$$X_{min} = \begin{cases} \gamma = 1 \\ \alpha = 1 \end{cases} \quad (6.13)$$

$$X_{max} = \begin{cases} r_{avg} = 1 \\ \gamma = \gamma_{max} \\ \alpha = \alpha_{max} \end{cases} \quad (6.14)$$

In order to design a practical system, the look-up table should be applicable for larger set of video sequences. To achieve this, a large set of test video sequences are considered and optimum parameters, $X_{opt}$, are obtained, each of them over wide range of CNR using the off-line optimization. These optimal parameters are then averaged over all video sequences and stored in the look-up table corresponding to each of the channel conditions. A look-up table should contain the optimal parameters atleast for a set of video sequences used in a particular application. To incorporate the time varying nature of channel, the actual $X_{opt}$ for each CNR are obtained by averaging the values corresponding to 20 independent channel conditions. The proposed optimization algorithm is summarized in Algorithm 6.1

The steps to design the look-up table are elaborated in Algorithm 6.1. The algorithm starts with initialization of the ranges (minimum and maximum values) and step size of the cross-layer parameters. Then, for each video sequence and for each CNR value of channel, corresponding to every possible combination of
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**Algorithm 6.1** Steps for obtaining optimized cross-layer parameters, $X_{opt}$, and design of Look-up table

1: **Initialize:** CNR$_{min}$, $\delta$CNR, CNR$_{max}$, $\delta r, r_{min}, \delta \gamma, \gamma_{max}, \delta \alpha, \alpha_{max}$  
   $\triangleright$ $\delta$CNR, $\delta r$, $\delta \gamma$ and $\delta \alpha$ are step sizes

2: **for** CNR = CNR$_{min}$: $\delta$CNR: CNR$_{max}$ **do**

3:   **for** $r_{avg} = r_{min} : \delta r : 1$ **do**

4:     **for** $\gamma = 1 : \delta \gamma : \gamma_{max}$ **do**

5:       **for** $\alpha = 1 : \delta \alpha : \alpha_{max}$ **do**

6:         Do 20 simulation to obtain PSNR using Eqn. (2.3)

7:         Calculate $PSNR_{avg} = \frac{1}{20}$ \[ PSNR \]

8:     **end for**

9: **end for**

10: **end for**

11: Find $X_m$ according to Eqn. (6.10)

12: Find $X_{opt}$ according to Eqn. (6.12)

13: **end for**

14: Repeat all the above steps for each of the chosen test sequences

15: Compute the average $X_{opt}, \bar{X}_{opt}$, for each CNR under consideration

16: Construct a look-up table for $\bar{X}_{opt}$ for each CNR

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cross-layer parameters, the quality of received video (in term of PSNR) using communication system described in Fig. 6.5 is calculated. Then the optimal set of parameters that gives maximum PSNR of the reconstructed video are searched. These steps are repeated for all test video sequences and averaged values of these parameters corresponding to each CNR is considered as optimized parameter. Finally, these values of optimum cross-layer parameters for each CNR are stored in a look-up table.

6.3.3 Adaptive Reassembly of Received Bits

Similar to adaptive bit reassembly of received bits proposed in chapter 4, we adopt a similar strategy in cross-layer UEP also. That is, at lower CNR, the LP bits are discarded (as they are likely to be received erroneously) and are not used in the reconstruction of video. However, at higher CNR, both HP and LP bits are used in the video reconstruction. Therefore, we propose an adaptive reassembly of received HP and LP bits in cross-layer UEP. The threshold of CNR to decide if LP substream should be discarded or consider in the reconstruction of video, not only depend on $\alpha_{opt}$ (of physical layer) but also on the channel coding rate $r_{avg}$. This threshold of CNR is expected to be lower in cross-layer UEP than only physical layer UEP due to additional protection of HP and LP substreams by the application layer FEC. That is, the FEC protected substreams will be able to withstand more noise as compared to only HQAM based UEP.
Table 6.1: Look-up table (LUT) of optimized $r_{avg}$, $\gamma$ and $\alpha$ at different CNR

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<th>$r_{avg}^{opt}$</th>
<th>$\gamma_{opt}$</th>
<th>$\alpha_{opt}$</th>
<th>CNR (dB)</th>
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<td>27</td>
<td>1.00</td>
<td>1</td>
<td>1.0</td>
</tr>
</tbody>
</table>

6.4 Simulation Results

6.4.1 Simulation Environment

In order to investigate the performance of proposed optimized cross-layer UEP (combining FEC and HQAM) over AWGN channel, the same set of video coding parameters as listed in Table 3.1 on page 64 and video sequences are considered. These sequences are Akiyo (100 frames), Flower garden (100 frames), Football (90), Foreman (100 frames), Hall Monitor (100 frames), Bus (100 frames) and Mobile (100 frames). The parameters used in RS coding are the same as summarized in Table 5.1. For each tested channel conditions (specified in terms of CNR) and protection strategy, 20 different runs of the experiments were conducted.

6.4.2 Design of Look-up Table

In this section, the optimized values of cross-layer parameters, $(X_{opt})$, for each CNR of AWGN channel under consideration using the Algorithm 6.1 are obtained. The algorithm first searches for $X_m$, the value of $X$ that gives the best PSNR at each CNR. Then, $X_{opt}$ is obtained according to Eqn. (6.12).

Figs. 6.7(a), (b) and (c) show the plots of optimum values of cross-layer parameters, $r_{avg}^{opt}$, $\gamma_{opt}$ and $\alpha_{opt}$ respectively, each against channel CNR for all the seven test sequences. Also, averaged value (averaged over all test sequences) of each parameter are shown in the figures correspondingly. It can be observed from Figs. 6.7(a) that below CNR = 15 dB, the $r_{avg}^{opt}$ and $\gamma_{opt}$ varies from sequence to sequence in a random fashion. The reason of these fluctuations is that at lower
Figure 6.7: Variations of cross-layer parameters, $r_{av}^{opt}$, $\gamma_{opt}$ and $\alpha_{opt}$ with CNR for seven test sequences (contd...)

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Figure 6.7: Variations of cross-layer parameters, $r_{\text{avg}}^\text{opt}$, $\gamma_{\text{opt}}$ and $\alpha_{\text{opt}}$ with CNR for seven test sequences.

Figure 6.8: Deviation of the PSNR obtained at actual optimized, and average optimized parameters, $r_{\text{avg}}^\text{opt}$, $\gamma_{\text{opt}}$ and $\alpha_{\text{opt}}$, for each test sequence.
CNR, the effect of noise is very severe and RS-code of any channel coding rate is unable to correct all the errors which leads to poor PSNR. At and above the CNR = 15 dB, the $r_{avg}^{opt}$ increases with increasing CNR, which can be interpreted that the small error protection is sufficient at low noise condition. Furthermore, it can be observed that above CNR = 15 dB, the $r_{avg}^{opt}$ comes out to be almost same for each sequences. From Figs. 6.7(b), it is clear that optimal $\gamma$ comes out to almost closed to unity. This means that there is no need to protect HP and LP substreams with channel codes of different coding rates. That is, in the proposed cross-layer UEP, at application layer, EEP is optimal. This is contrary to general belief that application layer UEP is better than application layer EEP.

The variation of $\alpha_{opt}$ with CNR in Figs. 6.7(c) follows almost similar trend to that shown in chapter 4. It can be observed that at very poor channel conditions, the value of $\alpha_{opt}$ comes out to be small, then increases with CNR up to certain CNR, and afterwards, it decreases at higher CNR. However, for CNR = 15 dB and above, the $\alpha_{opt}$ comes out to be unity for all test sequences.

The average $r_{avg}^{opt}$, $\gamma_{opt}$ and $\alpha_{opt}$ are calculated by averaging the parameters for all test sequences and are plotted in Fig. 6.7. In fact, these values are used in the look-up table given in Table 6.1.

In order to compare the effectiveness of the proposed cross-layer UEP, the difference of the PSNR of reconstructed video obtained using optimized cross-layer parameters given in look-up table (Table 6.1) with the maximum PSNR for all test sequences is shown in Fig. 6.8. The figure shows that there is negligible loss in the video quality if look-up table is used for selecting the cross-layer parameters for almost all CNRs except CNR = 14 dB, at which, the quality difference is up to approx. 1 dB (for Foreman sequence). This is the small price which is to be paid for simplifying the video communication system, using offline optimization and the use of look-up table. It is worthwhile to sacrifice 1 dB for a practical real-time video communication having low computational complexity.

Figs. 6.9(a)-(f) compare the performance of the proposed cross-layer optimized UEP (using application layer FEC and physical layer HQAM) scheme with: 1) QAM (physical layer EEP only), 2) optimized physical layer UEP using HQAM only and 3) optimized application layer UEP using FEC and physical layer EEP, for six CIF sequences namely: Foreman, Football, Akiyo, Flower Garden, Hall Monitor and Mobile, respectively.

It can be seen from the Fig. 6.9(a) that for Foreman sequence although optimized physical layer only UEP (using HQAM) and FEC-based application layer UEP provide an improvement in the quality of the reconstructed video by approx. 13 dB and 23 dB respectively over QAM for CNR in the range of 12-24 dB. That is, either of the single layered optimised UEPs are suitable
Figure 6.9: Comparison of optimized cross-layer UEP with optimal physical and application layer UEP at 1000 kbps. (contd...)
Figure 6.9: Comparison of optimized cross-layer UEP with optimal physical and application layer UEP at 1000 kbps. (contd...)
Figure 6.9: Comparison of optimized cross-layer UEP with optimal physical and application layer UEP at 1000 kbps.
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for medium to high CNRs only. But at low CNRs (CNR below 10 dB), their performance is closed to that of QAM. Whereas, the optimized cross-layer UEP (using combination of FEC and HQAM) outperforms either of the single layer optimized UEP scheme at lower CNRs. It gives improvement up to approx. 15.5 dB at lower CNR (6-15 dB) and at higher CNR its performance is exactly the same as that of optimized FEC-based application layer UEP.

Almost similar trends are observed for the other sequences and optimized cross-layer UEP gives significant improvement of the order of 8-18 dB for highly noisy channel (CNR with range of 6-15 dB). For example, the proposed cross-layer UEP gives approx. 13 dB improvement for Football sequence (Fig. 6.9(b)), approx. 18 dB for Akiyo sequence (Fig. 6.9(c)), approx. 8 dB for Flower Garden sequence (Fig. 6.9(d)), approx. 12 dB for Hall Monitor sequence (Fig. 6.9(e)) and approx. 8 dB for Mobile sequence (Fig. 6.9(f)).

From these results in the Figs. 6.9, it may be concluded that single layer optimized UEPs provide resilience against the channel errors for CNR in the range of 12-24 dB only. While at lower CNR, they have the performance as good as that of simple QAM scheme. In contrast to that, cross-layer UEP scheme gives significant improvement at the lower CNR (6-15 dB) and provides exactly the same performance as that of application layer UEP at higher CNRs.

6.4.3 Effect of Adaptive bitstream Re-assembly

So far the performance of optimized cross-layer UEP for reliable transmission of wavelet coded video over AWGN channel is investigated and compared with single layer optimized UEP schemes. Although at lower CNR, cross-layer UEP gives significant improvement over both FEC-based or HQAM based optimized UEP, however, due to large value of \( \alpha_{opt} (\alpha_{opt} > 1.5) \) at thee CNRs, LP substream is likely to be received erroneously. If these bits are used in the video reconstruction, the quality of reconstructed video is likely to be inferior. Therefore, it is advisable to discard LP bits at lower CNR.

Figs. 6.10(a)-(f) compare the quality of reconstructed video sequences for a) Considering HP and LP bits in the video reconstruction, and b) Discarding LP bits. It may be observed from these figure that at low CNR (less than 15 dB), discarding LP bits improves the overall video quality by approx. 3 dB whereas at higher CNR using LP bits in the video reconstruction results better video quality. One of the possible reason for this is that when channel condition is very poor, both HP and LP bits are likely to be corrupted. The channel coding improves the BER of both substreams at same level but using high value of \( \alpha_{opt} \) makes the HP substream more error robust than the LP substream. This increases
Figure 6.10: Performance of cross-layer UEP using Adaptive reassembly with considering and discarding LP substream at 1000 kbps (contd...)
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Figure 6.10: Performance of cross-layer UEP using Adaptive reassembly with considering and discarding LP substream at 1000 kbps (contd...)

(c) Akiyo Sequence

(d) Flower Garden Sequence
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Figure 6.10: Performance of cross-layer UEP using Adaptive reassembly with considering and discarding LP substream at 1000 kbps
the BER of LP substream and discarding them during the reconstruction of the video is the best choice. However, when channel is in good state (less noisy), and $\alpha_{opt} \rightarrow 1$ resulting the similar BER of HP and LP substreams and therefore, both substreams should be considered for video reconstruction.

Furthermore, if LP bits are always discarded irrespective of channel condition, a sharp drop in the PSNR at CNR = 15 dB may be observed in Figs. 6.10 for all sequences. This is due to the fact that at CNR = 14 dB, the optimal cross-layer parameters are $r_{avg}^{opt} = 0.79$, $\gamma_{opt} = 1$ and $\alpha_{opt} = 3.5$ (see Table 6.1). For these parameters, channel coding at application layer provides equal protection to HP and LP substreams (as $\gamma_{opt} = 1$) while HQAM provides more protection to HP substream at the cost of low protection to LP substream. Therefore, discarding LP substream improves the video quality. But, at CNR = 15 dB, the optimized cross-layer parameters are $r_{avg}^{opt} = 0.24$, $\gamma_{opt} = 1$ and $\alpha_{opt} = 1$ (see Table 6.1). In this case also, the channel coding protects HP and LP substreams equally, but now HQAM also provide equal protection to HP and LP substreams. Therefore, LP bits have the same error protection as that of HP bits, and discarding it reduces the video quality compare to that at CNR = 14 dB. Similar trend is observed for all CNR above 15 dB. Thus, for CNR = 15 dB and above, discarding LP bits results into inferior video quality. Therefore, LP substream should be considered or discarded for the reconstructed video adaptively. The threshold of CNR for adaptation is found to be 15 dB. The performance of adaptive bitstream reassembly of LP bits is shown in Figs. 6.10 with bold lines.

On the bases of these discussions, it may be concluded that below CNR = 15 dB LP bits should not be considered in the reconstruction of received video. Whereas, at and above CNR = 15 dB, considering the LP bits is best option to provide reliable video communication.

Finally, in Fig. 6.11 the subjective quality of optimized cross-layer UEP is compared with single layer optimized UEPs (physical and application layers) for first 5 frames of Foreman sequence at transmission rate of 1000 kbps over AWGN channel at CNR = 10 dB. It is observed from the figures that at this high noise channel (CNR = 10 dB), both of the single layer optimized UEP (physical and application layers UEP) shown in Fig. 6.11(b) and (c) respectively, gives very poor quality of the reconstructed video and almost as worst as quality shown by no UEP scheme (QAM without channel coding). Whereas, optimized cross-layer UEP (combining application and physical layers UEP) considering LP substreams, shown in Fig. 6.11(d), withstands this high noise and gives good quality of the reconstructed video. Moreover, in optimized cross-layer UEP if LP substream are discarded in the reconstruction of the video, further small improvement is also observed as shown in Fig. 6.11(e). Therefore, from these subjective quality
comparison, it is concluded that at very poor channel conditions, the single layer UEP scheme fails to deliver even base quality of the video. Whereas, optimized cross-layer UEP with discarding LP bits in the reassembly of the bitstream gives fairly good quality of the reconstructed video.
Figure 6.12: Non-test sequence performance for cross-layer optimized UEP using Adaptive reassembly with considering and discarding LP substream at 1000 kbps
6.4.4 Performance of Non-test sequences

So far, the performance of proposed optimized cross-layer UEP with and without adaptive reassembly of LP bits are investigated only for those sequences which were used in the design of look-up table. In this section, the performance of proposed system for sequences other than those used in the look-up table design (called non-test sequences) is studied. For this purpose, two CIF sequences namely Coastguard and Container sequences each of 100 frames are considered. These sequences are encoded at 1000 kbps and are transmitted over AWGN channel using cross-layer UEP parameters.

Fig. 6.12(a) and (b) show the performance of proposed cross-layer UEP system using parameter listed in Table 6.1 for Coastguard and Container sequences respectively. It can be observed from these figures that proposed system for non-test sequences has the similar performance as that of test sequences. For example, for Coastguard sequence (Fig. 6.12(a)) the proposed cross-layer UEP considering LP substream in the reconstruction of the video gives improvement up to approx. 10 dB and 12 dB over optimized physical layer UEP using HQAM and application layer UEP using FEC, respectively, for the CNR in the range of 6-15 dB. Whereas, at higher CNR its performance is exactly the same as that of optimized application layer UEP. Moreover, if LP bits are discarded in the reconstruction of the video, further 3 dB of again is observed for lower CNRs (6-14 dB). Similarly, for Container sequence (Fig. 6.12(b)) the propose cross-layer UEP shows improvement up to approx. 10-13 dB over either of the single layer optimized UEP in the same lower range of CNRs (6-15 dB). Whereas, at higher CNR its performance is also same as that of optimized application layer UEP. Furthermore, if LP bits are discarded in the reconstruction of the video, 3-5 dB of improvement is observed for the lower CNR range (6-14 dB).

Therefore, from above results and discussions it can be concluded that the look-up table (LUT) is generic and can be used for any sequence.

6.5 Summary

In this chapter, a reliable video communication system based on cross-layer optimized UEP for wavelet coded embedded video bitstream has been investigated. The bitstream partitioned into high and low priority substreams are firstly protected using FEC at application layer and then modulated using 16-HQAM at physical layer. An off-line optimization is used to determine values of cross-layer parameters for optimal protection of coded video at given channel conditions. Due to practical limitations involved in real-time optimization of cross-layer pa-
rameters, a look-up table based approach is suggested as a viable alternative. The look-up table is designed for wide range of CNR and by considering a large number of video sequences. The proposed system is suitable for devices requiring low computational complexity due to limited power and limited processing capabilities. The simulation results show that proposed system gives better performance compared to single layer optimized protection for wide range of channel noise conditions. Furthermore, discarding LP substream at lower CNRs (below CNR = 15 dB) results in an additional, approximately, 3 dB improvement in the quality of the reconstructed video. Therefore, it is suggested to use LP bits adaptively for better quality of video at large range of CNRs. Although, the performance of system has been verified for wavelet coded embedded video bitstream, it can be used for any scalable video bitstream.