An Unequal Protection FEC Scheme for Video over Optical Access Networks

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Abstract

In this paper, we propose an unequal protection physical coding sub-layer (PCS) forward error correction (FEC) scheme for efficient and high-quality transmission of video data over optical access networks. Through identifying and resolving the unequal importance of different video frames and passing this importance information from MAC-layer to PCS, FEC scheme of PCS can be adaptive to application-layer data. Meanwhile, we jointly consider the different channel situations of optical network unit (ONU) and improve the efficiency of FEC redundancy by channel adaptation. We develop a theoretical algorithm and a hardware method to achieve efficient FEC assignment for the proposed unequal protection scheme. The theoretical FEC assignment algorithm is to obtain the optimal FEC redundancy allocation vector that results in the optimum performance index, namely frame error rate, based on the identified differential importance and channel situations. The hardware method aims at providing a realistic technical path with negligible hardware cost increment compared with the traditional FEC scheme. From the simulation results, the proposed Channel and Application-layer data Adaptation Unequal Protection (CAAUP) FEC scheme along with the FEC ratio assignment algorithm and the hardware method illustrates the ability of efficient and high-quality transmission of video data against the random errors in the channel of optical access networks.

Keywords: Channel adaptation, unequal protection, forward error correction, video frame dependency, passive optical networks

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1. Introduction

With the users' rapidly increased demand of multimedia service, compressed video or streaming media has become prominent on networks, efficient and high-quality transmission of video data over networks is becoming increasingly important [1-2]. As well known, access networks are the "last mile" between users and core networks as **Fig. 1** shows. Therefore, it is the critical part to improve quality of service (QoS) and provide the user with a pleasant viewing experience of video. The passive optical networks (PON) have become the mainstream technology of access networks and achieved large-scale deployment around the whole world [3-5]. Therefore, how to achieve robust and high-quality transmission of video over PON is now an important issue. For video data, corruption is mainly derived from congestion-related loss and random bit errors. The former can be concealed or combated by source-side coding algorithm, packet-oriented loss resilience and transport-level protection schemes which have been well researched in previous works. In this paper, we divert attention to the latter. We aim to achieve efficient and high-quality transmission of video data over optical access networks e.g. PON by improving PCS FEC scheme.

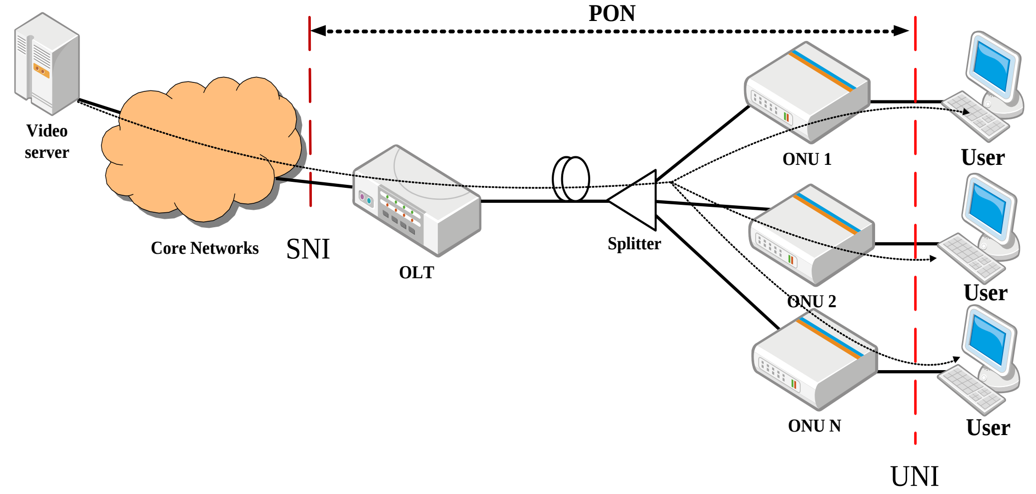

Fig. 1. Video transmission over PON system

Generally, a PON network is connected in tree topology which consists of one optical line terminal (OLT), a 1: N passive coupler (or splitter/combiner), and multiple ONUs as **Fig. 1** shows. In the downstream direction, a PON is a point-to-multipoint architecture, where data transmitted by the OLT pass through the splitter and broadcast to ONUs. Each ONU extracts the data based on its own logic link identification (LLID). In the upstream direction, a PON is a multipoint-to-point network, where multiple ONUs transmit data to the OLT by sharing a common transmission channel between the passive coupler and OLT. OLT is the central controller which controls the ONU's access to the upstream channel by a poll-and-report protocol. In high-speed PON architecture, FEC in PCS layer is mandatory to protect the upstream/downstream data and Reed-Solomon (RS) codes are generally chosen for the error control due to its good feasibility and capacity of correcting errors. Taking 10G EPON as an example, RS (255,223) encoder generates 32 parity symbols based on 223 line-encoded (e.g. 64B/66B) information symbols by a parity calculation process. The generated parity symbols are added after the corresponding information symbols and transmitted together with them.

The currently-used FEC scheme encodes information symbols by the fixed RS code. We can see that the static and equal PCS FEC scheme does not sufficiently consider the different channel situations of ONU and unequal importance of video frames. Although this scheme provides an electrical coding gain of 7.2dB which relaxes un-decoded bit error ratio (BER) to 1.1×10^{-3}, it introduces large quantities of redundancy that reduce the information link rate from 10.3 Gbit/s to 9.0 Gbit/s thus decreasing the system capacity by 10% approximately.

In this paper, we focus on unequal protection for robust and high-quality transmission of video data. To apply channel-adaptation and unequal protection to PCS FEC efficiently, we exploit the channel characteristic in PON and explore unequal importance embedded in video stream. First, compared with wireless access networks, channel condition in PON is relatively stable and time-invariant. Nevertheless ONU may experience different channel situations due to their distances to OLT or other factors. Fixed-code FEC scheme does not consider this difference. In this sense, FEC code can be chosen according to channel situation of ONU. Second, the unequal importance of data can be found in the video stream. Most of the current video coding algorithms, such as H.261/263/264 and MPEG-1/2/4, are based on a hybrid structure of motion compensated prediction and transform coding of the residue prediction error. After compressed coding, strong spatial-temporal dependency among video frames is generated. In a group of pictures (GOP), the earlier an error happens, the more frames will be corrupted. Bit errors in I-frames that cannot be corrected by FEC will result in a wrong frame and influence all of the dependent frames, but an error in P-frame or B-frame does not bring about such serious affection. In this sense, bits corresponding to I-frame in the bitstream are more important than the others. If bits corresponding to the I-frames are protected better, I-frame error will be lower, and it is possible to improve the quality of received video under certain redundancy significantly. PCS FEC scheme can be adaptive to different bits corresponding to frame types.

Through exploring the channel situations of ONU and unequal importance of bitstream, we offer a Channel and Application-layer data Adaptation Unequal Protection (CAAUP) FEC scheme for efficient and high-quality transmission of video data over optical access networks. In the FEC scheme, channel-adaptation and application-aware unequal protection is jointly considered for optimization of system capacity and video data transmission quality. We first present the architecture of CAAUP, and then formulate the system model as a problem of finding the redundancy assigning strategy to optimize the proposed performance metric subject to constraints of a certain redundancy ratio and the priority gotten from unequal importance in application data. We then propose an effective and feasible assignment method for hardware implementation.

The assignment algorithm for CAAUP is designed to obtain the optimal allocation of FEC redundancy in terms of the proposed performance metric. A video frame consists of multiple packets. Quality of delivered video depends on the “frame error rate” at which transmitted frames are not correctly received i.e. one or more (≥1) packets are lost in a frame. Increment of BER corresponding to an individual frame type results in a considerable increment of its “frame error rate”. We use frame error rate as the performance metric. Based on “frame error rate” metric, a theoretical algorithm is provided in this paper. However, unlike the application-level or packet-level FEC scheme, PCS FEC must be implemented and operated on hardware. The theoretical algorithm is computationally formidable when it is used in a hardware environment because too much multiplication and iteration are contained in the algorithm. Therefore, we develop a hardware method with low requirement for hardware implementation.

The remainder is organized as follows. In Section 2, we describe previous related works.

The CAAUP framework and system model analysis are given in Section 3. The theoretical FEC assigning algorithm and hardware method for CAAUP is presented in Section 4. Simulation results and analysis are presented in Section 5. Conclusions are drawn in Section 6.

2. Related Works

In recent years, much prior work has focused on the transmission of video over the whole networks. Many source and channel-based methods are proposed. The source-based techniques try to improve the quality of received video by error resilience coding [6-7], scalable coding [8-9], multiple description coding [10-11] etc. The channel-based methods incorporate transport-level error-control techniques e.g. FEC or ARQ into video transporting systems [12-17]. FEC schemes are the focus of this paper.

Although the proposed unequal-protection FEC techniques are effective for robust video transmission over internet or wireless networks, few protection schemes have been proposed for video transmission over optical access networks. Video data may suffer from two problems in networks: (1) network congestion; and (2) bit errors in transmission channel. Most of previous studies on video quality consider network congestion for internet or error control for wireless networks or joint of the two [18]. Next, we will analyze the feature and uniqueness of PON from the congestion and bit errors perspective, whereby, we demonstrate the key problem this paper addresses.

Network congestion is caused by the local buffer overflow due to limited buffer or "overbooking" on certain network links. Benefitting from the reduced memory price, the buffers used in OLT/ONUs have been significantly increased, thereby buffer overflow in PON sharply decreased. Moreover, Sajjad Zare et al. gave an effective downstream link scheduling to reduce packet loss for video over PON [19]. This scheme can reduce packet loss rate by almost 55% and 10% respectively under traffic load 0.9. Therefore, network congestion is not a primary challenge PON faces in video transmission.

On channel bit errors, most of proposed schemes deal with packet loss due to channel errors based on packet-level unequal protection, and the schemes adaptively adjust RS encoding to generate variable numbers of redundancy packets according to actual wireless channel status [20-23]. In wireless networks, bit errors have "long burst" characteristic derived from channel fading, even though bit interleaving can reduce error burst to some extent [24].From the schemes, we can see that packet-level unequal protection schemes are efficient in combating burst errors [25]. Without FEC, a lost packet in wireless network may indicate multiple bit errors that concentrate in a packet length. In packet-level protection scheme of wireless networks, one transmitted redundancy packet can recover a lost packet, namely, one redundancy packet can eliminate the influence of multiple bit errors. Nevertheless, in PON, bit errors are random-noise-like [26]. Under the same BER and the same number of redundancy packets, the performance of packet-level protection may degrade or need more redundancy to achieve the same protection level. Utilization of redundancy packets in optical networks is lower than wireless networks.

Therefore, proposed unequal protection schemes for wireless networks are not applicable in PON. By contrast, PCS FEC is more effective for PON. Considering bandwidth challenge of data transmission, especially, video transmission over PON, FEC scheme should make full use of each parity bit and this is the key problem we have to address in this paper. In order to solve this problem, we concentrate our efforts on optimization of PCS FEC and introduce channel adaptation and unequal protection into it. Our aim is improving the bandwidth utilization and video quality by jointly considering channel situations and unequal importance information embedded in video data.

3. CAAUP FEC Scheme

3.1 The Scheme Framework

In the paper, RS codes are used for FEC. For RS (N, K), K bytes are protected by the generated parity bytes. The error-correcting capacity of RS (N, K) is determined by the number of parity symbols i.e. (N-K), and up to (N-K)/2 erroneous symbols per N-symbol block can be corrected. The FEC ratio is defined as (N-K)/K. The used RS codes in the paper are on Galois GF (8). N always equals 255.

As mentioned above, in a PON system, the upstream/downstream data transmission is protected by FEC. In downstream, OLT transmits video data to different ONUs. In our scheme, the PCS of OLT encodes the original data bound for each ONU by individual optimum RS code and transmits encoded-data through PMA sub-layer and PMD sub-layer. The optimum RS code is determined according to video data's importance degree and the channel status between OLT and the destination ONU. The determination process of optimum RS code in ONUs is the same but relatively simple because the data transmission of each ONU only has one destination (OLT). In our scheme, the FEC redundancy bytes attached after each transmitted information symbol block is variable and optimized. The aim is to achieve the optimum FEC redundancy assignment, whereby, under a given overall FEC ratio, the system performance and the quality of video data is improved.

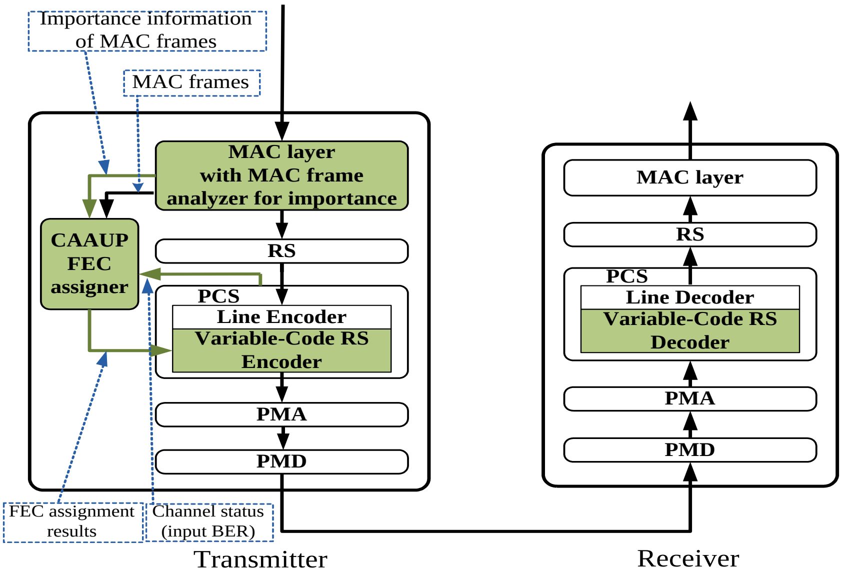

Fig. 2. Framework of CAAUP scheme

The proposed CAAUP scheme is shown in **Fig. 2**. In the framework of the scheme, we first identify the importance of the video data that appear as MAC frames. The importance is identified from the identification character that can be obtained through resolving the MAC frames. Considering PCS function is always implemented on hardware such as field programmable gate array (FPGA) or Application Specific Integrated Circuit (ASIC), frame resolution can be completed by "line-speed" byte matching that is a typical hardware process without slowing down the data-forwarding rate. This process only introduces slight hardware resources. Therefore, we can easily find the priority indication from video frames that are payload of MAC frames. Secondly, the parity level for each frame is determined by a CAAUP FEC assigning algorithm based on importance information and channel situation of the ONU that the frame is bound for. This algorithm is the key part of the paper and will be analyzed in detail. Here, channel situation in the form of BER can be taken from an existing channel monitoring function in PCS e.g. the error monitor specified in IEEE 802.3ae [27]. In [27], a method of channel monitoring, namely, bit interleaved parity N (BIP-N) using even (or odd) parity that reports BER periodically is also released. Thirdly, the parity bytes are generated by the variable-code RS encoder according to the indication of "FEC assignment results" as **Fig. 2** shows. Finally, the generated variable FEC parity is attached after information bytes forming the code block to be transmitted.

3.2 System Model of CAAUP FEC Assignment

Based on the importance information from the importance analyzer and the channel situation of ONU, the CAAUP FEC assigning algorithm is to achieve optimal redundancy allocation of FEC parity that minimizes the frame error rate subject to a certain redundancy and the differential protection levels. We divide the original information bytes transmitted during a given time T to J vectors according to the destinations (ONU) that they are bound for. Byte numbers of these J vectors can be denoted as a complex vector $\vec{A}=[\vec{A_1},\vec{A_2},...,\vec{A_j},...,\vec{A_J}]$. Let $\vec{R_1}$ to $\vec{R_J}$ denote FEC parity vectors assigned to $\vec{A_1}$ to $\vec{A_J}$ respectively, then the FEC redundancy assignment complex vector for $\vec{A}$ is $\vec{R}$. For $\vec{A_j}$, each element of it i.e. $A_{i,j}$ stands for the number of bytes in an information subset with importance level i. Similarly, $R_{i,j}$ is the number of FEC parity bytes for $A_{i,j}$. The optimal FEC redundancy assignment complex vector can be achieved by minimizing the proposed performance metric $P_e(\vec{R})$ which will be explained next. The problem of finding the optimal FEC redundancy assignment vector $\vec{R}$ can be presented as:

$$minimize(P_e(\vec{R})) \tag{1}$$

subject to

$$\sum_{i,j} R_{i,j} / \sum_{i,j} A_{i,j} = r_{FEC} \tag{2}$$

where r_{FEC} denotes the overall FEC redundancy ratio for the whole system. r_{FEC} is designed to be configurable in our scheme. FEC ratio for each ONU i.e. r_j should be decided by actual channel situation of individual ONU.

Redundancy assignment for information subsets with different importance levels within an ONU becomes the essential problem. Therefore, the problem formulation can be further simplified as:

$$minimize(P_e(\vec{R_j})),\ j=1,2,...,J \tag{3}$$

subject to: for $j=1,2,...,J$

$$BER_{i,j}^{bout} \le BER_{i+1,j}^{bout},\ i=1,2,...I-1 \tag{4}$$

$$r_{i,j} \ge r_{i+1,j},\ i=1,2,...,I-1 \tag{5}$$

$$\sum_{i} R_{i,j} / \sum_{i} A_{i,j} = r_j \tag{6}$$

where $BER_{i,j}^{bout}$ is BER after FEC for information subset with importance level i. We can also take BER as the probability of bit error. $r_{i,j}$ denotes the FEC ratio for this information subset.

The above constraints (4) and (5) are for the “decreasing importance” among each ONU. The constraint (6) means the already-decided FEC ratio for each ONU based on channel adaptation.

Random noise-like error model is widely used to model optical channel. The channel statistics of an optical channel is often described by BER. With this model, we can get the relationship between BER and redundancy ratio for the used RS codes.

$$BER_{i,j}^{bout} = 1-(1-BER_{i,j}^{Bout})^{1/8} \tag{7}$$

$$BER_{i,j}^{bin} = 1-(1-BER_{i,j}^{Bin})^{1/8} \tag{8}$$

$$BER_{i,j}^{Bout} = \sum_{t=(N-K_{i,j})/2+1}^{N} [\frac{t}{N} \bullet \frac{N!}{(N-t)!t!} \bullet BER_{i,j}^{Bin} \bullet (1-BER_{i,j}^{Bin})^{N-t}] \tag{9}$$

$$r_{i,j} = (N-K_{i,j})/K_{i,j} \tag{10}$$

where N is 255. $BER_{i,j}^{bin}$ or $BER_{i,j}^{Bin}$ denotes the bit error probability or byte error probability before FEC respectively. In the same way, $BER_{i,j}^{bout}$ or $BER_{i,j}^{Bout}$ is the bit error probability or byte error probability after FEC respectively.

Next, BER is further converted to PLR (packet loss rate) depending on the random error model,

$$PLR_{i,j} = 1-(1-BER_{i,j}^{bout})^{N_b} \tag{11}$$

where N_b is the average number of bits in a packet. Here $PLR_{i,j}$ can be considered as PLR for different byte subsets corresponding to individual video frames (I, P and B-frames). We express PLR of different video frames as PLR_I, PLR_P and PLR_B respectively. Next, we will analyze how the different PLR influences video quality.

Based on the above formulas, we can see the connection between PLR and the redundancy ratio. Our goal is to get the relationship between redundancy ratio and P_e. Next, we provide the performance index P_e mentioned above. P_e is the frame error rate. When calculating the frame error rate P_e, if one or more (≥1) packet is lost in a frame (or the effects of at least one packet loss from a reference frame are seen for P/B frames), then the frame is incorrect i.e. frame error happens. The frame error rate P_e is a sum of conditional probabilities:

$$P_e = \sum_i P(frm_i)P(error \mid frm_i) \tag{12}$$

where i goes over the frame types (I, P and B), and *error* is the event of an incorrect frame due to packet loss. frm_i is the event of the frame being type i.

Here, we know that that if at least one packet within a frame is lost, the frame will be regarded as “error frame”. In this case, we can determine P_e of I-frames from a Bernoulli random process. Now, we can express the conditional probabilities $P(error \mid frm_i)$ for each frame type.

$$P(error \mid I) = 1-(1-PLR_I)^{N_I} \tag{13}$$

where N_I is the average number of packets in an I-frame, and PLR_I is PLR for I-frames.

The conditional probabilities for P and B frames are based on the dependencies in a video GOP that is shown in **Fig. 3**. The correct decoding of a P-frame depends on all preceding I and P frames in a GOP, and the correct decoding of a B-frame depends on the correct decoding of the surrounding reference frames. We can get the probabilities as:

$$P(error \mid P) = \frac{1}{S_P}\sum_{k=1}^{S_P}[1-(1-PLR_P)^{N_I}(1-PLR_P)^{kN_P}] \tag{14}$$

$$P(error \mid B) \le \frac{1}{S_P}\sum_{k=1}^{S_p}[1-(1-PLR_I)^{N_I}(1-PLR_P)^{(k+1)N_P}(1-PLR_B)^{N_B}] \tag{15}$$

where N_P or N_B is the average number of packets in a P-frame or a B-frame respectively, S_P is the number of P-frames in a GOP. **Table 1** summarized the definition of system parameters.

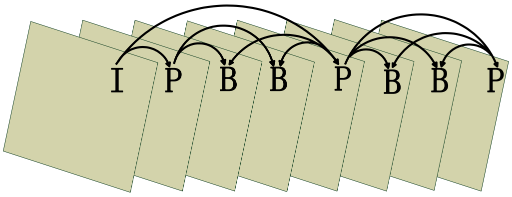

Fig. 3. Frame dependency in a GOP

From the above, we can finally get the relationship between the redundancy ratio $\overrightarrow{R_j}$ and the frame error index $P_e(\overrightarrow{R_j})$. Because higher protection priority is assigned to I-frame in our scheme, more FEC parity is generated for I-frames. Thus, the bits from I-frames can get higher-level protection and the error probability of these bits is lower than the other bits. PLR_I is also relatively lower consequently. Under the same redundancy, the qualitative result is that the condition of $PLR_I < PLR_P \le PLR_B$ can result in a better performance compared with the condition of $PLR_I = PLR_P = PLR_B$. We will give the quantitative simulation results and analysis to prove this result.

Table 1. Notation of the system model

Symbols	**Definition**
$A_{i,j}$	Byte number of the information subset with importance level *i* bound for ONU*j*
$\overrightarrow{A_j}$	Byte number vector of the information subsets bound for ONU*j*
$\overrightarrow{A}$	Byte number complex vector of the information subsets for J ONUs in the system
$R_{i,j}$	Number of FEC parity bytes for $A_{i,j}$
$\overrightarrow{R_j}$	Number vector of FEC parity bytes for $\overrightarrow{A_j}$
$\overrightarrow{R}$	Complex vector of FEC parity bytes for $\overrightarrow{A}$
r_j	FEC redundancy ratio for ONU*j*
r_{FEC}	Overall FEC redundancy ratio for the whole system[1]
$BER_{i,j}^{bout}$	BER after FEC for information subset with importance level *i* bound for ONU*j*
$BER_{i,j}^{Bout}$	Byte error rate after FEC for information subset with importance level *i* bound for ONU*j*
$BER_{i,j}^{bin}$	BER before FEC for information subset with importance level *i* bound for ONU*j*
$BER_{i,j}^{Bin}$	Byte error rate before FEC for information subset with importance level *i* bound for ONU*j*
N_b	Average number of bits in a packet
$PLR_{i,j}$	Packet loss rate for different byte subsets corresponding to individual video frames
P_e	Frame error rate
PLR_T	*PLR* of different video frames, T∈{I,P,B}
N_T	Average number of packets in a video frame, T∈{I,P,B}
S_P	Number of P-frames in a GOP

4. FEC Assignment Algorithm and Hardware Method for CAAUP

In this section, we give an effective FEC redundancy assignment algorithm for CAAUP. The theoretical FEC redundancy assignment algorithm is to achieve optimal allocation of FEC parity based on the proposed frame error index P_e. In order to make CAAUP appropriate for hardware, we also propose an assignment method for hardware implementation.

4.1 Theoretical Algorithm of FEC Assignment

```
Algorithm for CAAUP
Input:
      $r_{ini}$ : Initial overall FEC redundancy ratio
      $\overrightarrow{A}$ : Complex vector of information subsets
      $BER_j^{bin}$ : BER of ONUj before FEC
      $J$ : Number of ONUs
      $I$ : Number of information subsets in each ONU
      $\delta$ : Gradient value of FEC redundancy ratio for ONU
      $r^{up}$ : Upper limitation of FEC redundancy ratio for ONU
Output:
      $\overrightarrow{R}^{opt}$ :Optimal overall FEC redundancy assignment vector
  Initialization $\overrightarrow{R}^{opt} \leftarrow r_{ini} \times \overrightarrow{A};$
  BEGIN
    For $j=1;\ j \le J;\ j++\ do$
     /*Stage1: Solution to channel adaptation*/
        $Caculate\ r_j\ based\ on\ formulas(7\text{-}10);$
        $r^{temp} \leftarrow r_j; \overrightarrow{R_j}^{opt} \leftarrow r_j \times \overrightarrow{A_j}; R_j^{total} \leftarrow \sum_i R_{i,j}^{opt};$
        $Caculate\ P_e(\overrightarrow{R_j}^{opt})\ based\ on\ formulas(7\text{-}15);$
     /*Stage2: Solution to unequal protection i.e. application adaptation*/
        For $i=1;\ i \le I;\ i++\ do$
          For $r = r^{temp};\ r \le r^{up};\ r = r + \delta\ do$
            $R_{i,j}^{temp} \leftarrow r \times A_{i,j};$
            For $k = i+1; k \le I; k++\ do$
                $R_{k,j}^{temp} \leftarrow ((R_j^{total} - \sum_{i<k} R_{i,j}^{temp}) \times \frac{A_{k,j}}{\sum_{i \ge k,j} A_{i,j}});$
            End For;
            $Caculate\ P_e(\overrightarrow{R_j}^{temp})\ based\ on\ formulas(11\text{-}15);$
            If $P_e(\overrightarrow{R_j}^{temp}) < P_e(\overrightarrow{R_j}^{opt})$
                $P_e(\overrightarrow{R_j}^{opt}) \leftarrow P_e(\overrightarrow{R_j}^{temp}); \overrightarrow{R_j}^{opt} \leftarrow \overrightarrow{R_j}^{temp};$
            Else
                $r^{temp} \leftarrow \frac{R_{k,j}^{temp}}{A_{k,j}}; break;$
            End if;
          End For;
        End For;
    End For;
  End;
```

Fig. 4. The theoretical algorithm for CAAUP

In this part, a theoretical algorithm is developed. We divide the overall optimization problem into the following two sub-problems: (1) FEC parity decision for ONU based on channel situations; (2) FEC parity allocation among data byte subsets with different importance within one ONU.

Taking 10G EPON as an example, the static FEC scheme uses RS (255,223) to protect the information bitstream. However, when input BER i.e. BER at the PMD service interface of PON is lower than 5.4×10^{-4}, RS (255,231) can provide the desired output BER and RS (255,223) is not necessary anymore. In stage 1, OLT decides the appropriate protection level for each ONU according to its channel situation. “Reference code” is the result of Stage 1. This “reference code” is a just-effective code that meets the requirement for video transmission. In PON system, the “reference code” guarantees a PCS BER of 1.0×10^{-12}. That is to say, Stage 1 endows the scheme with the ability of channel adaptation.

In Stage 2, we let each information subset have the same starting FEC ratio r_j obtained from Stage 1. Then, for $A_{i,j}$, we change r by adding a gradient value of δ (the upper limitation of r is r^{up}) from r_j, and repeat the minimization of $P_e(\overrightarrow{R_j})$ with respect to the changed FEC rate. Meanwhile, the overall amount of parity for each ONU should be invariant. The ratio r is iteratively increased from r^{temp} to r^{up}. The iteration process is stopped when the $P_e(\overrightarrow{R_j})$ stops decreasing with the changing r. Finally, the optimal vector $\overrightarrow{R_j}^{opt}$ for ONU$_j$ is obtained. After $\overrightarrow{R_j}^{opt}$ for all ONUs have been obtained, the overall solution $\overrightarrow{R}^{opt}$ giving the minimum $P_e(\overrightarrow{R})$ is determined as the optimal FEC assignment.

In the above algorithm shown by **Fig. 4**, r_{ini} denotes the initial FEC ratio. In OLT of PON system, both stages of the algorithm should be operated, however in ONU, only Stage 2 needs to be operated because ONU can be informed of the “reference code” by OLT. The design can reduce the implementation complexity effectively. It can be seen that the implementation complexity of this algorithm depends on the gradient value δ and the number of information subsets I. If I is larger and δ is smaller, the time of iteration increases sharply.

4.2 Assignment Method for Hardware

If the above theoretical FEC assignment algorithm is applied in hardware e.g. FPGA or ASIC, enormous multiplication, addition and iteration will result in unacceptable hardware complexity. Therefore, it is necessary to develop a FEC assignment method with much lower computation complexity for hardware implementation. A fast FEC assignment method is proposed based on the fundamental principle that bits with higher priority should be given more parity to prevent the bit error in optical channel. To reach a much simpler way of FEC parity allocation, Stage 2 that aims to assign parity among different video information subsets is the key part to be developed. In the following, we describe how FEC parity ratios are assigned in step (1)-(4), considering the condition in practice.

Step (1) Decision of “reference code” for each ONU. If the assignment method is operated in OLT, this step must be contained, yet if in ONU, this step is not necessary because ONUs are informed the “reference code” by OLT. The decision process is easy. It is not described again here. After the decision is finished, OLT records the results of which ONUs are informed by informing schemes e.g. modified MPCP protocol.

Step (2) Decision of available protection levels. Once the “reference code” is decided, the lowest protection level can be determined. The highest protection level is configured by the users. We use a gradient of δ (i.e. 8 bytes) to generate the available protection levels. In this step, counters for video-data subsets are started at the same time. The counters record numbers of bytes in different video-data subsets (i.e. Bytes from different video frames) during a given time T which can also be configured by users. Based on the counters, ratios of individual frames are calculated periodically so as to provide a foundation for Step (4).

Step (3) Assignment of FEC ratios to information subsets with differential importance. This step is the essence of this assignment method. We consider the relationship between the number of FEC ratios and the levels of importance that is gotten from the preceding importance identifier. The basic FEC ratio (reference code) is assigned to the lowest importance level. Then the other available FEC ratios are assigned to the importance levels one-to-one correspondingly. If the number of FEC ratios is not enough, FEC ratios are assigned from high level to low level to guarantee the most important bits are protected strongly.

Step (4) Adjustment of FEC assignment according to video-data byte counters. This step is triggered per period of T. Because the ratios of different video frames are not fixed, but time varying, FEC assignment should be adjusted according to the network situation. Adjustment process is independent of the above steps and has a higher operation priority. Adjustment strategy is that the most important subset with a ratio less than 5% improves its protection level by one in this step.

In summary, we try to protect the most important information as strongly as possible. When channel situation is better, the "reference code" has lower redundancy, and the amount of available RS codes is much larger. The basic principle is distributing the FEC parity to different information subsets uniformly. From these steps, we can see that slight computation increment is introduced by this hardware method compared with traditional FEC scheme.

5. Simulation Results

The simulation is based on downstream video data in a 10G EPON system set in the MATLAB as shown in **Fig. 5**. The PON system consists of an OLT and 32 ONUs in a tree topology. Let R_u be the rate of the downlink/uplink between the OLT and ONUs and R_d be the rate of the link between "Average video quality analyzer" and ONUs. They are assumed to be 10.3 Gbit/s and 1 Gbit/s respectively. The distances from ONUs to the OLT are assumed to be between 5 km and 20 km uniformly, and OLT has a 20MB buffer. We use three classic video sequences for simulation. The sequences are shown in **Table 2**.

Table 2. Video sequences for simulation

Sequence name	Coastguard(CIF)	Stefan(CIF)	Foreman(QCIF)
K	64 packets	64 packets	32 packets
Frame rate	30 fps	30 fps	10 fps
CODEC	MPEG-4	MPEG-4	MPEG-4
GOP Length	15 frames	15 frames	15 frames

"Video traffic generator" in **Fig. 5** generates the video sequences and frames them into MAC protocol data units (i.e. MAC frames). When "Video traffic generator" connected to the OLT transmits data, the type of video frame in each MAC frame is identified. The sizes of MAC frames range between 64 bytes and 1518 bytes. The channel situations can be modeled and simulated by the random-error process with a range of BER. The "Average video quality analyzer" connects to 32 ONUs and "Video traffic generator" and is responsible for the statistics of average frame error rate P_e and PSNR. We use modified Euclidean (ME) implemented in MATLAB as the basic algorithm of the RS decoders. The following simulation results are obtained by averaging received video data of 32 ONUs. Through simulation, we demonstrated that the CAAUP scheme can be well adaptive to the channel situations indicated by average SNR of ONUs, and this scheme performs much better than the traditional static FEC scheme under the same FEC redundancy rate, i.e. the scheme can achieve the same performance with less FEC redundancy. The simulation scenario is summarized in **Table 3.**

The performance is compared among the following four FEC schemes.

(1) EP-RS: equal protection FEC scheme using RS codes.
(2) EP-RSCC: equal protection FEC scheme using concatenated RS codes which can provide coding gain increment compared with RS codes.
(3) CAAUP-HW: CAAUP scheme with the allocation method for hardware using RS codes on GF (8).
(4) CAAUP-TR: CAAUP scheme with the theoretical algorithm using RS codes on GF (8).

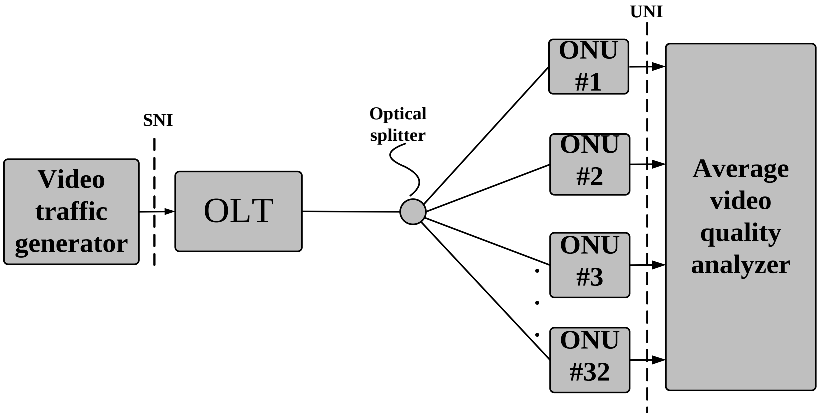

Fig. 5. The test system for CAAUP

Table 3. Simulation scenario

System simulation parameters	Value/value range
Number of ONUs in the system	32
OLT-ONU distance (uniform)	5-20 km
MAC frame length (uniform)	64-1518 bytes
Buffer size of OLT	20 MB
Downlink/uplink rate	10.3 Gbit/s
Access link rate	1 Gbit/s

Fig. 6 shows the average frame error rate P_e changing with average SNR of three video sequences under the same FEC percentage of 14.3%. For a distinct plotting of figures, we use average SNR instead of BER to indicate the channel situations. For average SNR=8.77dB, CAAUP-TR, CAAUP-HW and EP-RSCC can keep frame error rate under 33% (except EP-RSCC of Stefan), but EP-RS cannot maintain the same level. The lower limit of correction capability of RS (255,223) is about 9.7dB (SNR) (corresponding to a BER_{in} of 1.1×10^{-3}). When SNR is less than 9.7dB, the BER after FEC cannot meet the requirement of PCS service interface; thus, the packet loss will increase. For CAAUP-HW and CAAUP-TR, I-frames can be recovered by the additional protection even when SNR is lower than the threshold. The EP-RSCC can nearly maintain an acceptable frame error rate because it provides a higher coding gain. However, this gain is obtained at a high cost of hardware complexity introduced by interleavers and deinterleavers between outer/inner encoders or decoders. By contrast, our

scheme can be adaptive to channel situations with a lower implementation cost.

Fig. 7 illustrates average frame error rate of three video sequences as a function of FEC redundancy ratios under the same average SNR of 8.80 dB. We use RS (255, 247) to RS (255, 215) to provide the incremental FEC ratios for EP-RS and use a group of concatenated RS codes to provide the incremental FEC ratios for EP-RSCC. We can see that CAAUP-TR and CAAUP-HW outperform the EP-RS and EP-RSCC at most FEC ratios. It can be inferred that the quality of transmission of video data can be improved by CAAUP scheme. We can also see that, CAAUP-TR and CAAUP-HW can achieve graceful increment of frame error rate when the available FEC redundancy decreases. In other words, to achieve a certain video quality under a given channel situation, CAAUP can save FEC parity or system capacity compared with the traditional schemes.

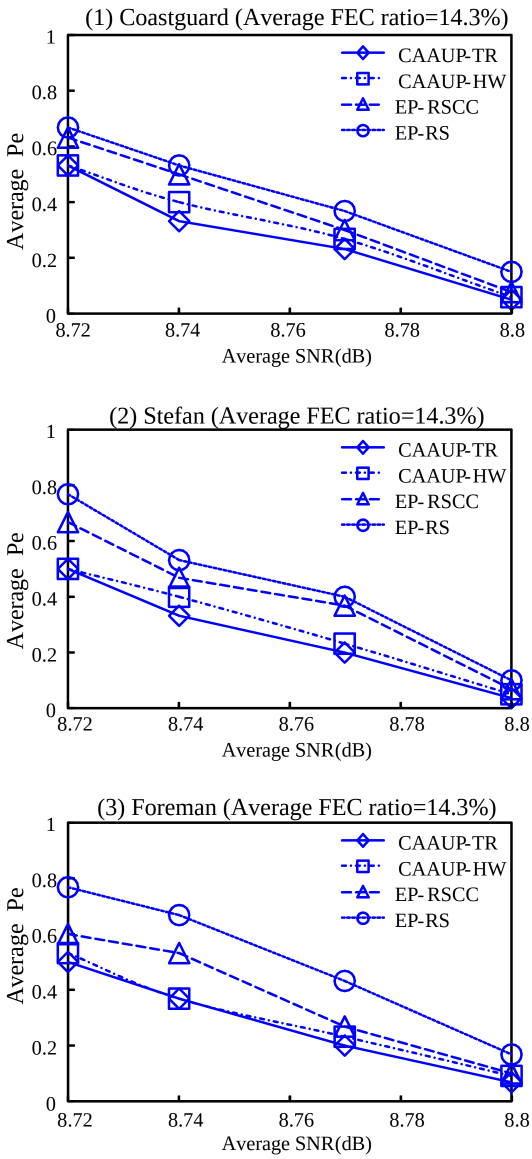

Fig. 6. P_e versus average SNR for sequences (i) Coastguard, (ii)Stefan, (iii)Foreman

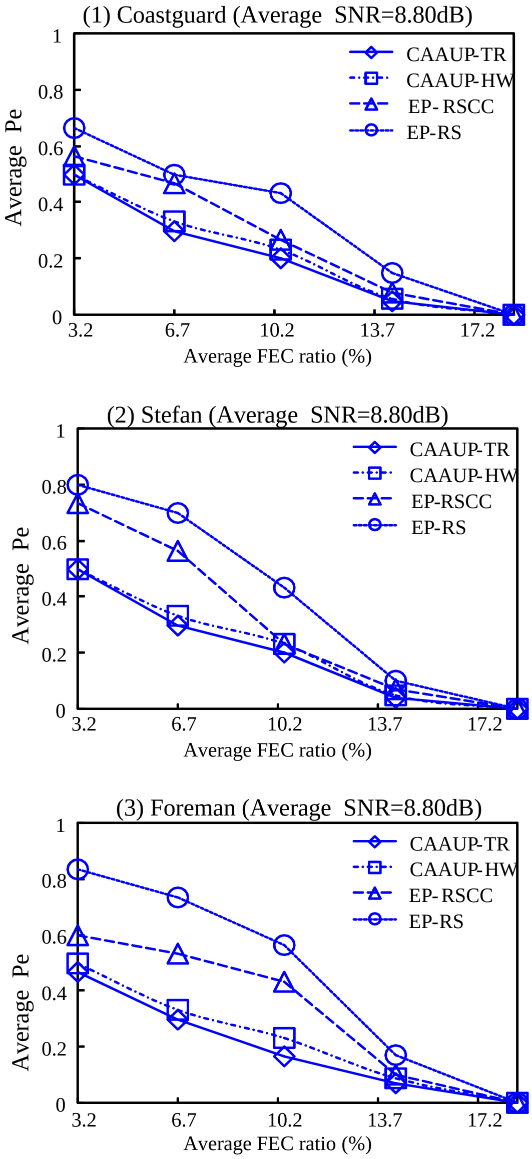

Fig. 7. P_e versus average FEC ratio for sequences (i) Coastguard, (ii)Stefan, (iii)Foreman

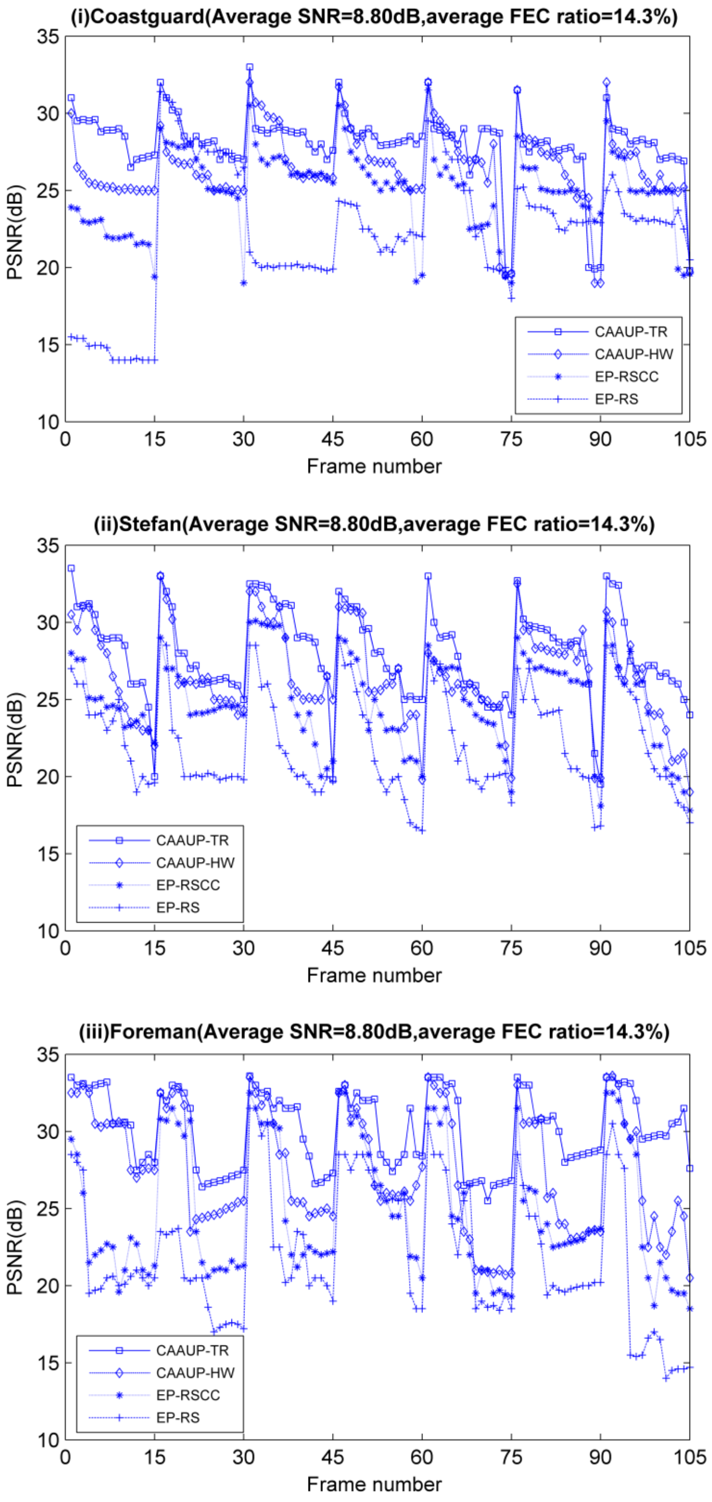

Fig. 8. Frame-by-frame PSNR for different protection schemes

Fig. 8 shows the frame-by-frame Y PSNR (PSNR for the luminance component) test of CAAUP-TR, CAAUP-HW, EP-RSCC, and EP-RS for *105* frames of each sequence. From the figure, we can see that the front frame in a GOP is protected better by our CAAUP scheme compared with the other two schemes. Therefore, CAAUP can effectively prevent the error propagation among video frames. In addition to this, the overall PSNR of CAAUP-TR and CAAUP-HW is also higher than the traditional protection methods.

In summary, for all situations, CAAUP-TR can achieve the best performance. CAAUP-HW obtains slightly lower performance. On the bad channel situations, CAAUP can still maintain an acceptable video frame error rate. So this scheme can be used in the long-reach PON system when the currently-used FEC scheme cannot meet the requirement of optical power budget without consideration of dispersion. At the mediate SNR situations (channel situations), thanks to the unequal protection and channel adaptation, CAAUP can prove the same quality of video data with less FEC redundancy. In addition to the performance improvement, considering the implementation, CAAUP-HW can be implemented in current or future PON systems with low increment of hardware complexity.

6. Conclusion

A Channel and Application-layer data Adaptation Unequal Protection (CAAUP) FEC scheme has been proposed for efficient and high-quality transmission of video data over the optical access networks i.e. PON by considering different channel situations of ONU and the unequal importance embedded in video data. A theoretical algorithm and an allocation method based on hardware have been developed. The theoretical algorithm is to achieve optimal assignment of FEC redundancy based on the performance index P_e which can accurately quantify propagation effect of bit errors on quality of the received video. The FEC parity allocation method based on hardware is designed to apply the efficient FEC assignment algorithm in practice so that it can be realistic in high-speed PON systems. From the simulation results and analysis, we can see that CAAUP scheme can achieve high-quality transmission of video data against bit errors in optical channel and be efficiently adaptive to varying channel situation.

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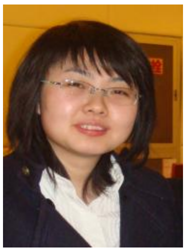

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