Optimized cross-layer transmission for scalable video over DVB-H networks

Keyan Deng, Lei Yuan, Yi Wan, Jie Pan

School of Information Science & Engineering, Lanzhou University, Lanzhou 730000, China
College of Electrical Engineering, Northwest Minzu University, Lanzhou 730000, China

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ABSTRACT

We investigate five efficient combinations of expanding window fountain (EWF) coding and hierarchical QPSK (H-QPSK) modulation in a cross-layer fashion, i.e., EWF coding at the application layer and H-QPSK modulation at the physical layer. We evaluate the performance of five cross-layer transmission schemes for scalable video over Digital Video Broadcasting-Handheld (DVB-H) networks by performing cross-layer optimization based on a genetic algorithm to find the optimal parameters and the optimization results are provided. Based on the cross-layer optimization results, we propose an adaptive transmission scheme for scalable video by using optimal combinations of these schemes over DVB-H networks, i.e., we adaptively exploit these five cross-layer transmission schemes in specific SNR regions to accommodate varying DVB-H channel conditions and achieve the best overall transmission performance. The results show that the proposed adaptive transmission scheme provides much better overall performance over DVB-H networks, especially in low SNR regions, than any single scheme used by itself.

1. Introduction

As the demand for multimedia applications, which are bandwidth intensive, is growing rapidly over wireless networks, the efficient transmission of compressed multimedia bitstreams over lossy packet networks is required.

Scalable coding technologies, e.g., JPEG 2000 [1] and H.264 Scalable Video Coding (SVC) [2], organize multimedia bitstreams into a number of layers of different importance in which the first and most important layer is referred to as base layer (BL), followed by progressively less important layers called enhancement layers (ELs). Scalable coding enables the receiver to progressively improve the reconstructed multimedia quality with the amount of the data being correctly transmitted and decoded. Obviously, we can exploit this characteristic to achieve robust transmission of pre-encoded images and videos over lossy packet networks.

However, owing to temporal and spatial dependencies in the compressed bitstream, packet losses in scalable coded sequence transmission will lead to different levels of quality degradation of the reconstructed source message. On the other hand, for a scalable coded sequence where the data importance decreases along the sequence, an early packet loss is propagated by the decoder to all future reconstructed packets, resulting in error propagation in both space and time [3]. Therefore, the efficient transmission of scalable coded sequence over lossy packet networks is still a challenge. Under such a scenario, scalable coded sequence is usually protected against channel errors by using forward error correction (FEC) schemes that can improve the successful data transmission probability and eliminate the costly retransmissions.

In recent years, fountain codes [4], such as LT codes [5] and Raptor codes [6], have been proposed as a more flexible and efficient FEC solution for information transmission over lossy packet networks. However, these codes are equal error protection (EEP) codes and have poor performance in scalable coded sequence owing to unequal importance of data in the scalable bitstream, where more important data require more protection and need to be reconstructed prior to less important data. In other words, scalable coded sequence calls for error correcting codes with unequal error protection (UEP) and unequal recovery time (URT) capabilities. Furthermore, it has been shown that an FEC scheme that provides UEP can achieve considerable quality improvement [7] and a better overall system performance [8] compared to the EEP. As such, UEP has been successfully utilized for the protection of scalable image and video [8]. Recently, fountain codes designed with the UEP property have emerged, e.g., expanding window fountain (EWF) codes. EWF codes [9], which are a novel approach to provide UEP and URT properties, can protect the different layers in an scalable coded sequence according to their importance at the application layer (AL).

In general, error resiliency schemes are performed by independently optimizing the resources accessible at individual network layers.
Specifically, many multimedia communication systems exploit AL-FEC to protect against channel errors. However, in order to efficiently utilize scarce radio resources and achieve overall quality of service (QoS) satisfaction, all available resources in a wireless communication system should be optimally utilized together. Naturally, the cross-layer approach is introduced to optimize the resources and achieve further improvement of QoS. Clearly, it is necessary to pursue a cross-layer design and optimization for scalable video transmission over wireless channels.

Cross-layer schemes for robust scalable video wireless communication have been extensively investigated [10–15]. An adaptive cross-layer protection strategy is achieved by means of Reed–Solomon (RS) codes used as the AL-FEC for robust and efficient scalable video transmission over 802.11 WLANs in [10]. Owing to the advantages in terms of complexity, performance, and flexibility over RS codes, fountain codes have been exploited as an AL-FEC solution. Moreover, as fountain codes can adapt to any erasure channel with unknown or varying characteristics, fountain codes are especially suitable for packet-level coding at the AL. Fountain codes-based cross-layer schemes for H.264 video transmission over wireless channels are investigated in [11] and [12]. Authors in [11] propose to use four combinations of cross-layer FEC coding schemes: EEP/UEP LT codes and rate-compatible punctured convolutional (RCPC) codes are utilized at the AL and the physical layer (PL), respectively, to improve the peak signal-to-noise ratio (PSNR) for a given channel bandwidth and signal-to-noise ratio (SNR). In [12], four cross-layer FEC schemes, where the systematic Raptor codes and the RCPC codes are utilized at the AL and the PL, respectively, are proposed to minimize the video distortion and maximize the video PSNR.

In this paper, inspired by [11] and [12], we propose five efficient combinations of EWF coding and hierarchical QPSK (H-QPSK) modulation in a cross-layer fashion, i.e., EWF coding at the AL and H-QPSK modulation at the PL. We first evaluate our proposed five cross-layer transmission schemes for H.264 SVC bitstreams over Digital Video Broadcasting-Handheld (DVB-H) networks by carrying out cross-layer optimization to find the optimal parameters that should be adjusted adaptively according to the DVB-H channel condition. The results indicate that these five cross-layer transmission schemes can exert their respective advantages to the utmost to achieve their best performances in specific SNR regions. Subsequently, we propose an adaptive transmission scheme for scalable video by using optimal combinations of these schemes over DVB-H networks, i.e., we adaptively exploit these five cross-layer transmission schemes in specific SNR regions to accommodate the varying DVB-H channel conditions and achieve the best overall transmission performance.

The main contributions of this paper include the following:

1. We propose five cross-layer transmission schemes using EWF codes at the AL and H-QPSK modulation at the PL to provide UEP for scalable video over DVB-H networks.
2. We carry out cross-layer optimization based on a genetic algorithm (GA) for the proposed transmission schemes to find the optimal parameters that should be adjusted adaptively according to the DVB-H channel condition.
3. We propose an adaptive transmission scheme for scalable video over DVB-H networks, based on the five cross-layer transmission schemes and cross-layer optimization.

The rest of paper is organized as follows. Section 2 provides background material about random linear coding, EWF codes, H-QPSK modulation, and DVB-H. Section 3 describes the design of EWF codes at the AL and H-QPSK modulation at the PL. Section 4 presents the cross-layer transmission schemes over DVB-H networks, and presents the packetization scheme in the DVB-H system. Section 4 presents the cross-layer optimization schemes of five cross-layer transmission schemes. The optimization results of the proposed five cross-layer transmission schemes and the adaptive transmission scheme for test scalable video are presented in Section 5. Finally, Section 6 concludes the paper.

2. Background

2.1. Random linear coding (RLC)

Random linear coding (RLC) [16–19] is a class of rateless codes and performs as a near-optimal FEC solution over erasure channels. RLC can produce encoded packets over a source message \( x = \{x_1, x_2, \ldots, x_k\} \) by random linear combinations of message packets with coefficients randomly selected from a finite field \( GF(2^m) \). For example, the \( i \)th encoded packet \( c_i \) can be represented as \( c_i = \sum_{j=1}^{k} a_{ij} \cdot x_j \), where \( a_{ij} \) is a randomly selected element of \( GF(2^m) \). Fountain coding, e.g., LT coding and EWF coding, is a special case of RLC, where \( a_{ij} \in \{0, 1\} \) for the \( i \)th encoded packet \( c_i \).

New RLC encoded packets can be generated by performing RLC encoding in a rateless fashion at the transmitter until the receiver collects enough RLC encoded packets to decode the source message using the Gaussian elimination (GE) [20] decoding.

Due to the rateless characteristic of RLC, expanding window random linear coding (EW RLC) [17,19,21] is used as an AL-FEC solution for UEP of the sliced-partitioned H.264/AVC video in the DVB-H standard [18]. In present study, EWF coding is used as a low-complexity EW RLC scheme at the AL to provide UEP for scalable video over DVB-H networks.

2.2. Expanding window fountain (EWF) codes

EWF codes are a novel class of UEP fountain codes based on the idea of “windowing” the information symbols to be transmitted. We consider the transmission of data, e.g., scalable video streaming, partitioned into consecutive source blocks of \( k \) symbols. Each source block is divided into \( r \) importance classes of size \( s_1, s_2, \ldots, s_r \) symbols, respectively, such that \( s_1 + s_2 + \cdots + s_r = k \), as shown in Fig. 1. The importance of classes decreases with chronological ordering of the symbols, i.e., the \( r \)th class is more important than the \( j \)th class, if \( i < j \). We compactly describe the division into importance classes using the generating polynomial 

\[
\Pi(x) = \sum_{i=1}^{r} \Pi_i x^i
\]

where \( \Pi_i = \frac{1}{i!} \).

Based on such a division, \( r \) expanding windows, where each window is contained in the next window, can be defined over each source block. Note that input symbols from the \( r \)th class of importance belong to the \( r \)th and all the subsequent windows. Namely, the \( r \)th window consists of the first \( k_1 = \sum_{j=1}^{s_r} s_j \) input symbols, where \( k_1 < k_2 < \cdots < k_r = k \) and \( s_1 = k_1 - k_{r-1} \). Therefore, the most important symbol class of size \( k_1 = s_1 \) is contained in all windows and the \( r \)th window consists of all the \( k \) symbols of the source block.

A new EWF encoded symbol is generated by performing standard LT encoding only on the input symbols from the selected window, where a window can be randomly chosen with respect to the window selection probability distribution \( \Gamma(x) = \sum_{i=1}^{r} \Gamma_i x^i \), where \( \Gamma_i \) is the probability of selecting the \( i \)th window. For the \( j \)th expanding window, the degree distribution is \( \Omega_j(x) = \sum_{i=1}^j \Omega_i x^i \). This procedure is repeated at the EWF encoder for each EWF encoded symbol. Therefore, the most important symbol class of size \( s_1 \) is protected by all other windows, whereas the least important symbol class of size \( s_r \) is only protected by the \( r \)th window. This feature is quite appropriate for UEP. In addition, when \( r = 1 \), i.e., there exists only a single window and all input symbols are of equal importance, an EWF code becomes a standard LT code for EEP.

For the sake of simplicity, an EWF code can be represented as \( \mathcal{F}_E(P, \Gamma, \Omega(1), \ldots, \Omega(r)) \). Therefore, when \( r = 2 \), i.e., the simple case of EWF code with two importance classes, an EWF code is \( \mathcal{F}_E(P, x + P_1 x^2 + P_2 x^3, \Omega(1), \Omega(2)) \), where \( P_1 + P_2 = 1 \) and \( \Gamma_1 + \Gamma_2 = 1 \).

For a given EWF code \( \mathcal{F}_E(P, \Gamma, \Omega(1), \ldots, \Omega(r)) \), the asymptotic erasure probability \( \eta_{ij} \) (as \( k \to \infty \)) that the source symbol of class \( j \) is not
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