Layer-Aware Forward Error Correction for Mobile Broadcast of Layered Media

Cornelius Hellge, David Gómez-Barquero, Thomas Schierl, *Member, IEEE*, and Thomas Wiegand, *Fellow, IEEE*

***Abstract*—The bitstream structure of layered media formats such as scalable video coding (SVC) or multiview video coding (MVC) opens up new opportunities for their distribution in Mobile TV services. Features like graceful degradation or the support of the 3-D experience in a backwards-compatible way are enabled. The reason is that parts of the media stream are more important than others with each part itself providing a useful media representation. Typically, the decoding of some parts of the bitstream is only possible, if the corresponding more important parts are correctly received. Hence, unequal error protection (UEP) can be applied protecting important parts of the bitstream more strongly than others. Mobile broadcast systems typically apply forward error correction (FEC) on upper layers to cope with transmission errors, which the physical layer FEC cannot correct. Today's FEC solutions are optimized to transmit single layer video. The exploitation of the dependencies in layered media codecs for UEP using FEC is the subject of this paper. The presented scheme, which is called layer-aware FEC (LA-FEC), incorporates the dependencies of the layered video codec into the FEC code construction. A combinatorial analysis is derived to show the potential theoretical gain in terms of FEC decoding probability and video quality. Furthermore, the implementation of LA-FEC as an extension of the Raptor FEC and the related signaling are described. The performance of layer-aware Raptor code with SVC is shown by experimental results in a DVB-H environment showing significant improvements achieved by LA-FEC.**

***Index Terms*—LA-FEC, layered media, mobile TV, MVC, SVC, UEP.**

I. Introduction

LAYERED media formats, such as scalable video coding (SVC) [1] or multiview video coding (MVC) [2], open up new opportunities for distributing Mobile TV services. Such services can benefit from features like graceful degradation behavior or introducing new services, e.g., providing additional higher resolution or 3-D enhancements, in a backwards-compatible way. Layered media codecs are considered as a candidate technology in ongoing standardization on mobile broadcast services like, e.g., SVC in DVB-NGH [3] or already adopted in ATSC-M [4]. Due to inter-layer prediction, parts of the media stream are more important than others. The loss of a certain quality layer affects all layers that depend on it. Therefore, an efficient transmission of layered media requires a differentiation in robustness for the different layers of quality.

Forward error correction (FEC) is typically used in mobile broadcast systems to increase service robustness. FEC mechanisms can be categorized into those working at the physical layer or at any upper layer above it, such as the link or application layers [5]. On physical layer, typically LDPC [6] or Turbo codes [7] are applied. On upper layers, today's state-of-the-art FEC solutions of mobile broadcast standards are Raptor code [8] or RaptorQ [9]. All these FEC algorithms are optimized for transmitting single layer video. The traditional FEC approach to achieve a more efficient delivery for multi-layer media is to apply unequal error protection (UEP) to the media stream, where more important layers get stronger FEC protection. This approach can already be implemented using the existing upper layer FEC schemes within DVB (DVB-H [10] or DVB-SH [11]) or 3GPP (MBMS [12]) by applying different code rates to the different video layers. On the physical layer, UEP can be implemented by applying hierarchical modulation [13] or different modulation and coding for the different video layers [14]. However, when UEP is done in such a way that both streams are independent, the referencing video layer (enhancement layer) is unusable if the referenced video layer (base layer) is lost.

With traditional UEP, the FEC parity data are generated separately for each layer. Several protection schemes have been proposed, which benefit in performance by considering the layered characteristic by integrating the UEP behavior within the FEC algorithm [15]–[23]. The Layer-Aware FEC (LA-FEC) [27]–[30] follows a similar approach. But instead of changing the basic FEC algorithm, it extends existing FEC algorithms towards improved decoding capabilities in case of dependent video layers. The basic FEC algorithm is not modified, thereby preserving the optimized correction performance and easing backwards compatible introduction into existing systems. The LA-FEC scheme can be applied to the physical layer or upper layer FEC. In this paper, we focus on upper layer FECs.

The rest of the paper is organized as follows. In Section II, we discuss related work and the differences to this work. Section III gives a brief overview on layered video codecs and using FEC in mobile broadcast environments. In Section IV, the LA-FEC principle is explained, a combinatorial analysis is provided, and a discussion on implementation issues is given related to the integration into Raptor codes. The section further contains a discussion of the transport and signaling extensions required for the

Manuscript received October 31, 2010; revised March 04, 2011; accepted March 08, 2011. Date of publication March 22, 2011; date of current version May 18, 2011. The associate editor coordinating the review of this manuscript and approving it for publication was Dr. Yap-Peng Tan.

C. Hellge and T. Schierl are with the Multimedia Communications Group, Image Processing Department, Fraunhofer HHI, 10587 Berlin, Germany, and also with the Image Communication Laboratory, Berlin Institute of Technology, 10623 Berlin, Germany (e-mail: cornelius.hellge@hhi.fraunhofer.de; thomas.schierl@hhi.fraunhofer.de).

D. Gómez-Barquero is with the Universidad Politécnica de Valencia, Valencia, 46022 Valencia, Spain, and also with the Multimedia Communications Group, Image Processing Department, Fraunhofer HHI, 10587 Berlin, Germany (e-mail: dagobar@iteam.upv.es).

T. Wiegand is with the Image Processing Department, Fraunhofer HHI, 10587 Berlin, Germany, and also with the Image Communication Laboratory, Berlin Institute of Technology, 10623 Berlin, Germany (e-mail: twiegand@ieee.org).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TMM.2011.2129499

LA-FEC. In Section V, exemplary simulation results are presented for an upper layer FEC integration with a layer-aware Raptor code in a DVB-H scenario.

II. Related Work

Already in 1967, Masnick and Wolf proposed linear codes with UEP behavior [15] for the unequal protection of binary coded integer values. In 1972, the idea of two overlapping generator matrices was applied to cyclic codes by Kilgus and Gore [16] as well as to linear codes over Galois fields by Boyarinov and Katsman [17] in 1982. In 2006, Rahnvard *et al.* proposed a UEP-LDPC code [18], where parity symbols are generated across symbols of different importance classes. The selection of symbols depends on a probability distribution following its importance of the class. In [19], the same authors applied a similar scheme to LT-codes. Also in 2006, Bouabdallah and Lacan proposed to apply UEP erasure codes across temporal media coding dependencies within a single layer video stream [20]. In 2007, Bogino *et al.* [21] introduced a sliding window approach, which is based on a fixed size window following the chronological order of the data. This approach virtually increases the source block length which increases the FEC correction capability. In the same year, Sejdinovic *et al.* proposed the expanding window fountain (EWF) code [22], [23]. EWF codes generate multiple windows over the source symbols, where windows expand according to the importance of the data. Encoding symbols are generated from a certain window, selected by a probability distribution. All these approaches introduce the UEP behavior within the FEC algorithm, which can be referred to as inner UEP FEC. In contrast to the mentioned inner UEP FEC approaches, the LA-FEC approach can be seen as an outer UEP FEC, leaving the basic FEC algorithm untouched; i.e., the base layer processing is not changed at all. This eases the backwards compatible integration into existing systems, and preserves the high performance of state-of-the-art FECs like Raptor [8] or RaptorQ [9].

III. Technical Background

A. Layered Media Codecs

Rate distortion efficient video codecs use prediction for exploiting statistical dependencies in the video signal, which introduces dependencies that typically also exist between packets. One important dependency structure is introduced by motion compensation, where a reference picture (e.g., from the past) is used to predict another picture [43]. Another set of dependency structures is introduced in layered video coding allowing for efficient scalability of the media data, such as SVC [1] or MVC [2], where in the simplest case, a base layer is referenced by one enhancement layer (or enhancement view).

An enhancement layer can be further referenced by other enhancement layers potentially introducing multiple dependent layers. A loss of a picture in the base layer affects all pictures in the enhancement layer that reference the base layer, i.e., typically they cannot be decoded. Using layered media streams, each layer has a different level of importance in the decoding process of an access unit, representing a certain time instance of the video. If an access unit of a base layer gets lost, all referencing frames of the enhancement layers are affected as well.

Scalable Video Coding (SVC): The SVC extension of H.264/AVC allows for extracting different video representations from a single bitstream, where the different substreams are referred to as layers [1]. The base layer of SVC provides the lowest level of quality and is an H.264/AVC compliant bitstream to ensure backwards-compatibility with existing receivers. Each additional enhancement layer improves the video quality in a certain dimension. SVC allows up to three different scalability dimensions within one bitstream: temporal, spatial, and quality scalability. SVC utilizes different temporal and inter-layer prediction methods for gaining coding efficiency while introducing dependencies between quality layers of the SVC video stream. Fig. 1 shows an exemplary coding structure, with the base layer and one enhancement layer at the same time enhancing temporal and the spatial resolution of the base layer. The arrows in the figure denote the coding dependencies between the different access units. In case of a lost access unit, all referencing frames are affected, too; e.g., if the I frame of the base layer gets lost, all other frames are affected.

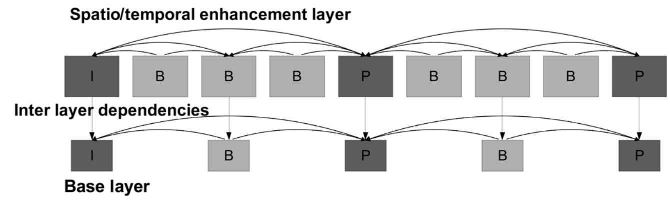

Fig. 1. Dependencies within an SVC bitstream using hierarchical prediction and inter-layer prediction.

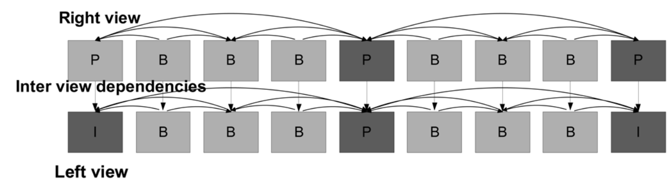

Fig. 2. Dependencies within two views of a MVC stream, where the right view is encoded dependent on the base view.

A differentiation in robustness is in general beneficial for the transmission of the SVC format, where the base layer gets a stronger protection than the enhancement layers.

Multiview Video Coding (MVC): MVC is an amendment of the H.264/AVC standard that enables efficient encoding of sequences captured simultaneously from multiple cameras using a single video stream [2]. For MVC, the single-view concepts of H.264/AVC are extended in a way that a picture uses temporal reference pictures as well as inter-view reference pictures for predictive coding. Fig. 2 illustrates an exemplary inter-view prediction structure using MVC. Due to the inter-view prediction in MVC, a differentiation in robustness is in general beneficial, like in SVC, where the base view gets a stronger protection than the enhancement view.

B. Forward Error Correction (FEC)

In mobile broadcast systems, the transmission is typically designed to serve the worst-case user. Retransmissions of lost packets are generally not feasible due to a missing return channel in broadcast systems. Therefore, error correction is achieved using FEC mechanisms transmitting redundant data in form of additional repair data. This repair data allows the receivers for reconstructing the original data even if some data are not correctly received due to transmission errors. The error correction is "forward" in the sense that no feedback (return channel) from the receiver to the transmitter is required. FEC

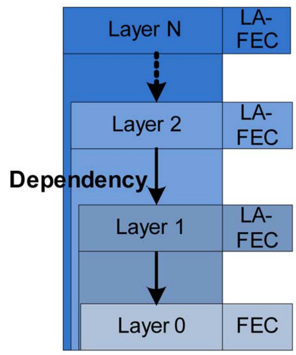

Fig. 3. Generation of FEC data by LA-FEC across layers following dependency within the media stream.

mechanisms can be categorized into those integrated at physical layer of a communication system and FEC mechanisms integrated at any layer above the physical layer, such as the link or application layers [24].

Physical layer FEC codes work at the bit level and are traditionally implemented as part of the radio interface of a wireless communication systems. Examples of physical layer FEC codes that are adopted in standards for mobile broadcasting are: convolutional codes in DVB-H [31], turbo-codes in DVB-SH [44] or 3GPP [46], and low-density-parity-check (LDPC) codes in DVB-T2 [45] or the future DVB-NGH system [3]. In contrast to physical layer FEC that corrects bit errors, upper layer FEC (UL-FEC) recovers packet losses and are categorized as block codes that work with fixed-size blocks (packets) of bits or symbols of a predetermined size performing erasure decoding. In UL-FEC, packets are considered either correct or lost. Examples of upper layer FEC codes in mobile broadcasting standards are Reed-Solomon in DVB-H [31] and Raptor codes in DVB-SH [44] and 3GPP [12].

IV. Layer-Aware Forward Error Correction (LA-FEC)

A. General Description

The basic idea of the layer-aware FEC (LA-FEC) approach is to extend the encoding process of the FEC algorithm across dependent video layers. The FEC processing of the base layer remains untouched, thereby still allowing the base layer to be decoded independently and preserving the correction capabilities of the original FEC algorithm. Due to the introduced connection from less important media layers within the FEC algorithm, the more important media layers are protected by additional repair data. This increases the error correction capabilities of the more important layers without adding additional repair data. The scheme in Fig. 3 illustrates the cross layer FEC generation. While the base layer ("Layer 0") FEC generation process is not changed, the FEC data of "Layer 1" are generated across source symbols of "Layer 1" and "Layer 0", FEC data of "Layer 2" are generated across "Layer 2", "Layer 1", and "Layer 0" and so on up to the FEC data of "Layer N", which are generated across the source symbols of "Layer N" and all dependent media layers. As a generic FEC approach, LA-FEC can be integrated at any OSI layer (physical, link, or application layer), and to FEC codes like LDPC, Raptor, or RaptorQ, by simply extending the encoding process of the media enhancement layers over all dependent media layers.

To illustrate the principle of the LA-FEC approach, we apply a simple FEC algorithm which generates parity bits by XOR combinations of source symbols (one bit per symbol). Fig. 4 compares the encoding process, and Fig. 5 the decoding process of standard FEC (ST-FEC) on the left side and LA-FEC on the right side of each figure. LA-FEC modifications are marked in green. In the given example, which is based on an erasure channel (erroneous packets are treated as lost packets), there are two media quality layers, where "Layer 1" depends on "Layer 0" within the media stream. Each layer consists of three source bits and two parity bits.

With respect to the exemplary encoding process presented in Fig. 4, the parity bits are computed by a simple XORing process of the source bits. Using ST-FEC, the XORing process is applied independently for each media layer, whereas using LA-FEC, the XORing process is extended across media layers following existing media coding dependencies. Hence, the parity bits of "Layer 1" are generated over the source bits of both layers, "Layer 0" and "Layer 1". The "Layer 1" parity bits can further be used jointly with the parity bits of "Layer 0" for error correction of both media layers. After FEC encoding, the source and parity bits of each media layer are combined to codewords. The codewords are in the example transmitted over an error prone channel.

In the decoding example in Fig. 5, the codeword of "Layer 0" is affected by three transmission errors labeled by "?". "Layer 1" is received error free. In case using ST-FEC, there are not enough parity bits within "Layer 0" for successful FEC decoding. The source bits can therefore not be recovered. Although "Layer 1" codeword is correctly received, it cannot be used due to the missing media coding dependencies on "Layer 0". In contrast to that, if using the LA-FEC, the parity bits of "Layer 1" can be used jointly with the parity bits of "Layer 0" for also correcting "Layer 0". Since "Layer 1" is correctly received, there are overall four parity bits available for correction of the three source bits of "Layer 0". In the given example, both media layers can only be corrected with LA-FEC. It should be noted that, if using the LA-FEC, the enhancement layer cannot be corrected independently of the base layer. Therefore, the improvement in base layer protection comes at the expense of a reduced protection of the enhancement layer. Nevertheless, in cases where the base layer is lost, the enhancement layer data cannot be used in the media decoding process anyway due to missing media dependencies within the media stream. Therefore, LA-FEC does not perform worse than the ST-FEC in terms of media quality.

B. Combinatorial Analysis of LA-FEC

In this section, the LA-FEC approach is analyzed towards its influence on the decoding probability of each media layer. The performance of LA-FEC in comparison to ST-FEC is shown by a combinatorial analysis based on an erasure channel model.

The conducted analysis is based on an example, illustrated in Fig. 6, with two video layers, "Layer 0" and "Layer 1". Due to media coding dependencies, "Layer 1" directly depends on "Layer 0". Each layer consists of a certain amount of source symbols k_1, k_2 and a number of parity symbols p_1, p_2. All symbols of the two media layers $n = n_0 + n_1$ are sent over a binary erasure channel. Transmission errors result in loss of a symbol. An ideal FEC code is assumed, where any k source symbols can be corrected as soon as $r \geq k$ symbols have been received. The average decoding probability for each layer is calculated for each number of r and all possible distributions of the lost symbols (loss constellations). In Fig. 7–9, r is referred to as ratio of received packets, which means the percentage of received

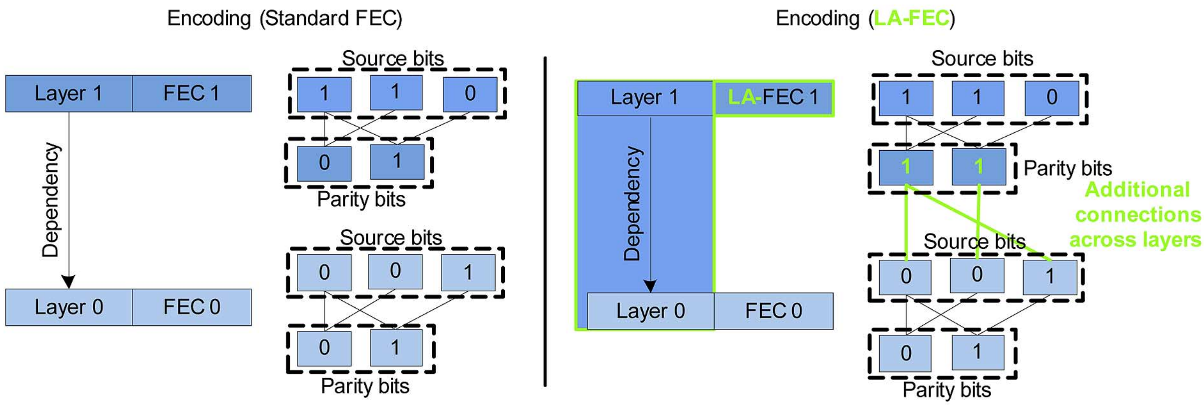

Fig. 4. Encoding for (left) ST-FEC and (right) LA-FEC. LA-FEC extends generation of parity bits across "Layer 0" symbols.

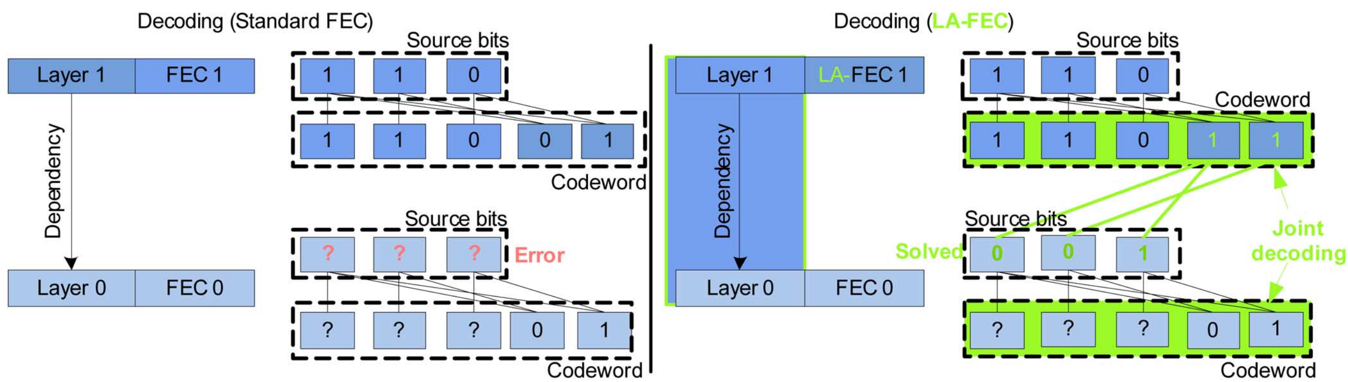

Fig. 5. Decoding of (left) ST-FEC and (right) LA-FEC. Using LA-FEC, the parity bits of both layers can be used for a combined decoding.

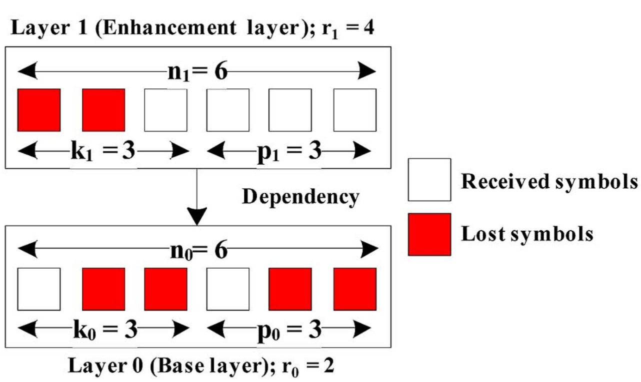

Fig. 6. Toy example with two layers and $n = n_0 + n_1 = 12$ transmitted and $r = r_0 + r_1 = 6$ received symbols. The figure shows one exemplary distribution of lost symbols for $r_0 = 2$ and $r_1 = 4$.

packets of the sent packets n, and can be calculated by $\frac{r}{n}$. Fig. 6 depicts the example with $k_0, k_1 = 3$, $p_0, p_1 = 3$, $n = 12$, and one exemplary loss constellation for $r_0 = 2$, $r_1 = 4$, and $r = 6$.

The number of all possible loss constellations $|\Omega|$ for a number of received symbols r can then be calculated by the binominal coefficient of the received packets r choose n sent packets as shown in (1):

$$|\Omega|(r) = \binom{n}{r} = \frac{n!}{r!(n-r)!}. \tag{1}$$

The decoding probability of each media layer $L : 0|1$ depends on the number of decodable loss constellations $|\Omega_{0|1}|$. For ST-FEC, the number of decodable combinations can be calculated by comparing the number of received symbols $r_{0|1}$ and source symbols $k_{0|1}$. Thus, for ST-FEC, media layer is decodable if condition (2) is true:

$$r_{0|1} \geq k_{0|1}. \tag{2}$$

The number of all constellations $|\Omega_{0|1}|$ fulfilling condition (2) for a given received number of symbols r can be derived by equation (3):

$$|\Omega_{0|1}|(r|r \geq k_{0|1}) = \sum_{x=\max(k_{0|1}, r-n_{1|0})}^{\min(r, n_{0|1})} \binom{n_{0|1}}{x}\binom{n_{0|1}}{r-x}. \tag{3}$$

For ST-FEC, the decoding probability $P(\Omega_{0|1})$ of each media layer can further be derived by (4):

$$P(\Omega_{0|1})(r) = \frac{|\Omega_{0|1}|(r|r \geq k_{0|1})}{|\Omega|(r)}. \tag{4}$$

However, the media coding dependencies between media layers are not taken into account in (4). Taking such media coding dependencies into account, the decoding probability of the media layers is also affected by the decoding probability of the media layer on which it depends. Thereby, the decoding probability of the enhancement layer $L = 1$ depends on the number of loss constellations fulfilling condition (5):

$$(r_1 \geq k_1) \cap (r_0 \geq k_0). \tag{5}$$

According to this formula, the number of constellations giving a successfully decodable enhancement layer $|\Omega_{1de0}|$ can be derived by (6). Note that for being able to decode both layers, condition $r \geq k_0 + k_1$ must be true:

$$|\Omega_{1de0}|(r|r \geq k_0+k_1) = \sum_{x=\max(r-n_1,k_0)}^{\min(r-k_1,n_0)} \binom{n_0}{x}\binom{n_1}{r-x} \tag{6}$$

and the probability $P(\Omega_{1de0})$ is calculated by (7):

$$P(\Omega_{1de0})(r) = \frac{|\Omega_{1\mathrm{de}0}|(r|r \geq k_0 + k_1)}{|\Omega|(r)}. \tag{7}$$

In the case of LA-FEC, the additional FEC connections between dependent media layers influences the decoding probability of all media layers. The decoding probability for the base layer is increased by the probability that the enhancement layer receives more symbols than required for decoding of the enhancement layer symbols. Therefore, with LA-FEC, the condition for a successfully decodable base layer in (2) changes to the condition in (8):

$$(r_0 \geq k_0) \cup (r_0 + r_1 \geq k_0 + k_1) \tag{8}$$

and thereby the number of decodable constellations is increased, where the additional constellations $\Delta|\Omega_{0-LA}|$ can be calculated by (9). Note that there is only gain if both layers can be decoded, i.e., the condition $r \geq k_0 + k_1$ is true:

$$\Delta|\Omega_{0-LA}|(r|r \geq k_0+k_1) = \sum_{\mathrm{x}=\max(r-n_1,0)}^{k_0-1} \binom{n_l}{x}\binom{n_{l+1}}{r-x} \tag{9}$$

and the decoding probability $P(\Omega_{0-LA})$ can be calculated by (10):

$$P(\Omega_{0-LA})(r) = \frac{|\Omega_0|(r|r \geq k_0) + \Delta|\Omega_{0-LA}|(r|r \geq k_0 + k_1)}{|\Omega|(r)}. \tag{10}$$

On the other side, using LA-FEC without taking media coding dependencies into account, the sheer FEC decoding probability for the enhancement layer decreases since it can only be corrected if the base layer can also be corrected. Therefore, the condition for a successfully decodable enhancement layer without taking media coding dependencies into account changes from (2) to (11):

$$(r_1 \geq k_1) \cap (r_0 + r_1 \geq k_0 + k_1). \tag{11}$$

The number of non-decodable constellations $\Delta|\Omega_{1-LA}|$ enabled by the LA-FEC can be determined by (12):

$$\Delta|\Omega_{1-LA}|(r|k_0 + k_1 > r \geq k_1) = \sum_{\mathrm{x}=\max(r-n_1,0)}^{\min(r-k_1,k_0-1)} \binom{n_0}{x}\binom{n_1}{r-x} \tag{12}$$

TABLE I
DECODING PROBABILITIES

	Base layer	Enh. layer	LA-FEC	Media dependencies
$P(\Omega_0)$	X	-	-	-
$P(\Omega_1)$	-	X	-	-
$P(\Omega_{1de0})$	-	X	-	X
$P(\Omega_{0-LA})$	X	-	X	-
$P(\Omega_{1-LA})$	-	X	X	-
$P(\Omega_{1de0-LA})$	-	X	X	X

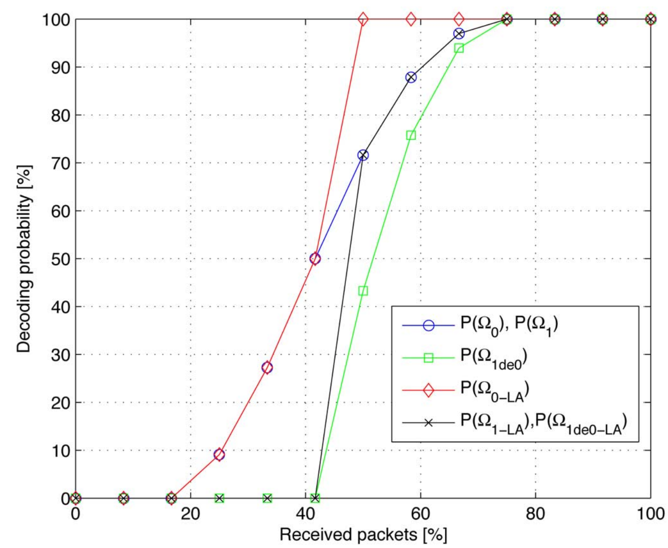

Fig. 7. Decoding probability (cf. Table I) for "Layer 0" and "Layer 1" over the ratio of received packets for ST-FEC and LA-FEC.

and the decoding probability of the enhancement layer $P(\Omega_1)$ in (4) decreases for the case using the LA-FEC to $P(\Omega_{1-LA})$ following (13):

$$P(\Omega_{1-LA})(r) = \frac{|\Omega_1|(r|r \geq k_1) - \Delta|\Omega_{1-LA}|(r|k_0 + k_1 > r \geq k_1)}{|\Omega|(r)}. \tag{13}$$

Taking media coding dependencies into account, the decoding probability of the enhancement layer $P(\Omega_{1de0-LA})$ is equal to $P(\Omega_{1-LA})$, since all non-decodable cases are already taken into account due to the dependencies introduced by the LA-FEC. Therefore, equation (14) is true for the decoding probability $P(\Omega_{1de0-LA})$:

$$P(\Omega_{1de0-LA})(r) = P(\Omega_{1-LA})(r). \tag{14}$$

All discussed decoding probabilities are summarized in Table I.

The decoding probability for the different cases is shown in Fig. 7 over the ratio of received symbols. For ST-FEC, taking the media coding dependency into account, the enhancement layer decoding probability $P(\Omega_{1de0})$ compared to the base layer decoding probability $P(\Omega_0)$ is significantly reduced. Using LA-FEC instead, the base layer decoding probability $P(\Omega_{0-LA})$ is increased from 43% to 75% of ratio of received packets and already reaches 100% decoding probability after reception of 50% of all transmitted symbols. On the other side, the sheer enhancement layer FEC decoding probability $P(\Omega_{1-LA})$ decreases compared to $P(\Omega_1)$ due to the additional

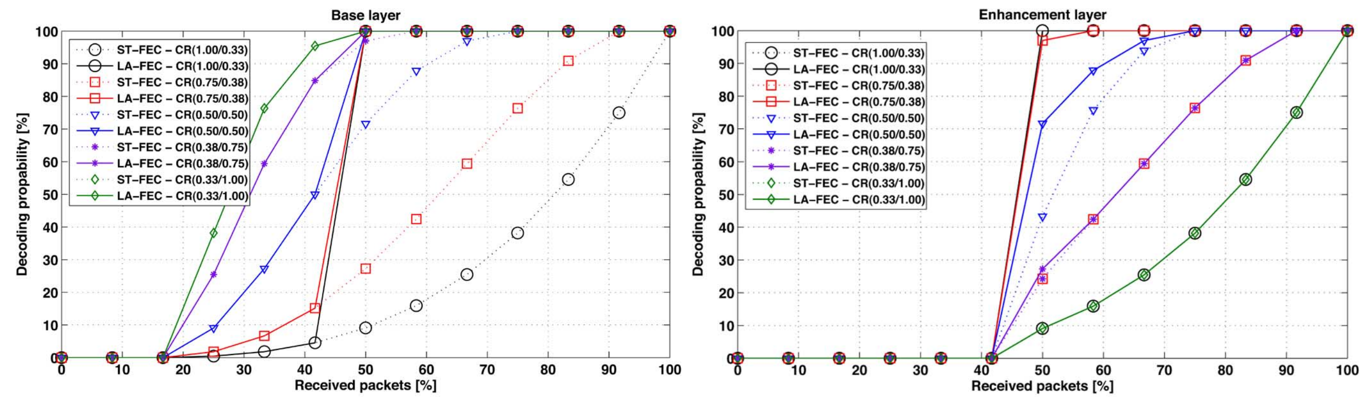

Fig. 8. Decoding probability of base and enhancement layer using different parity distributions $CR(c_0/c_1)$ for ST-FEC and LA-FEC taking media dependencies into account.

FEC dependencies introduced by LA-FEC. However, taking the media coding dependency into account using the LA-FEC, even the enhancement layer shows a higher decoding probability $P(\Omega_{1de0-LA})$, which is due to the higher FEC decoding probability of the base layer.

The presented decoding probabilities are calculated for one exemplary distribution of parity data within the toy example with $p_1, p_2 = 3$, which is referred to as equal error protection (EEP). We further analyze the influence of the distribution of the parity symbols among the media layers on the decoding probability. The distribution of parity symbols is indicated by the code rate (CR) c_l for each layer l, which is calculated by the number of source symbols k_l of layer l to the number of transmitted symbols per layer $n_l = k_l + p_l$ following equation (15):

$$c_l = \frac{k_l}{n_l}. \tag{15}$$

For the enhancement layer, we assume a successful decoding only if the base layer can be decoded as well. The results for both media layers are shown in Fig. 8.

For ST-FEC, the base layer decoding probability (left plot) solely depends on its code rate c_0. It should be noted here that the selection of the code rate distribution for layered media is given by the target application and needs to take the decoding probability of both media layers into account. For the base layer decoding probability (left plot), the best performance is given by applying all protection symbols to the base layer with setting $CR(0.33/1.00)$ and the worst performance when applying all protection symbols to the enhancement layer $CR(1.00/0.33)$. Also in the case using LA-FEC, the best base layer performance can be achieved by setting $CR(0.33/1.00)$. The influence of the enhancement layer code rate when using LA-FEC on the decoding probability of the base layer can be easily seen in the plot. Independent of the code rate distribution among layers, the maximum decoding probability is reached by receiving 50% of all symbols and all code rate distributions show an additional gain for lower reception ratios. It can be noticed that the gain introduced by LA-FEC increases with a stronger enhancement layer protection.

The enhancement layer performance (right plot) is calculated taking the media dependency to the base layer into account (comp. Fig. 7). Therefore, the performance for ST-FEC and LA-FEC is affected by both the base layer and the enhancement layer robustness. It is obvious that the best performing base layer code rate distribution $CR(0.33/1.00)$ gives the worst results for the enhancement layer. Shifting all protection to the enhancement layer $CR(1.00/0.33)$ gives the best performance for LA-FEC but the worst performance for ST-FEC. Again, the gain over ST-FEC achieved by the LA-FEC depends on the amount of protection symbols within the enhancement layer.

To analyze the LA-FEC performance, it is important to consider the video quality in terms of peak signal-to-noise ratio (PSNR), which is affected by the FEC decoding probabilities of both media layers. The results shown in Fig. 9 are based on the following assumptions: A non-decodable constellation, which would result in a freeze of the video, gives a video quality in terms of PSNR of 14 dB. It should be noted that values of PSNR significantly below 20 dB are typically not acceptable from the user point of view. A constellation, where the base layer is decodable, results in a PSNR value of about 30 dB and an additional decodable enhancement layer results in a PSNR of 35 dB. Fig. 9 shows the average PSNR over the ratio of received packets. The plot shows that LA-FEC outperforms ST-FEC for all code rate distributions except for $CR(0.33/1.00)$, which performs equal, and never performs worse. Shifting all protection to the enhancement layer $CR(1.00/0.33)$ allows to reach the highest quality at 50% symbol reception rate. However, such a code rate distribution would put a hard burden on receiving the base layer only. It is also interesting to see that LA-FEC allows reaching performance areas, which are not possible with ST-FEC independent of the code rate distribution. The presented theoretical results lack in a realistic channel model for mobile broadcast which typically shows a tendency towards burst errors, which have not been part of the experiments conducted in this section. More realistic performance measurements are given in Section V.

C. Implementation of Layer-Aware Raptor Code

The LA-FEC scheme can be applied on both physical layer FEC, as similarly shown for LDPC in [40], and upper layer FECs [8], [9]. This paper focuses on an exemplary integration of the LA-FEC to an upper layer FEC. The upper layer FEC considered here is the Raptor FEC.

The application of the LA-FEC to the Raptor code has already been presented in [27]. This section gives a brief summary of

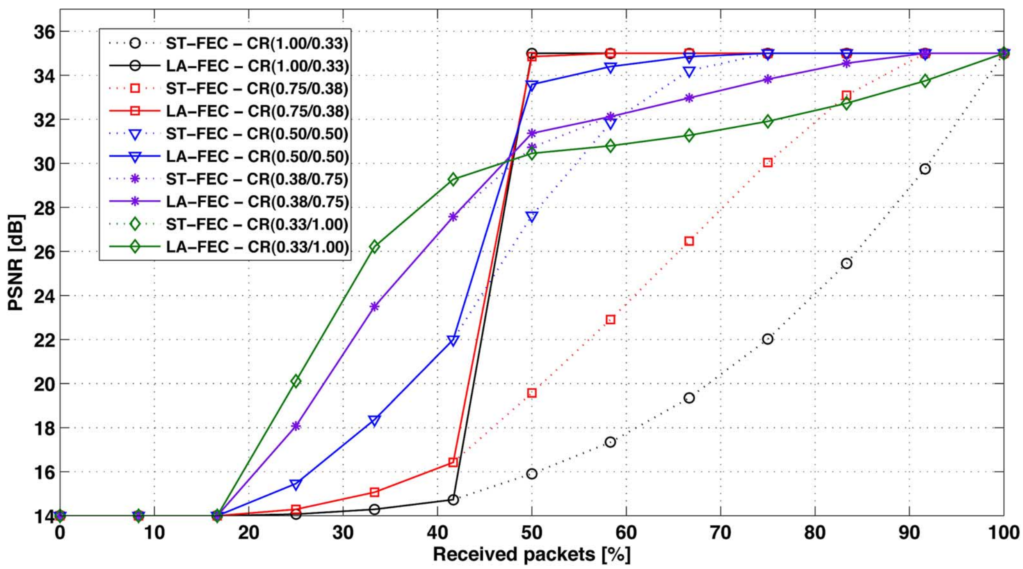

Fig. 9. Average PSNR using different parity distributions $CR(c_0/c_1)$ for ST-FEC and LA-FEC assuming PSNR 14 dB for a non decodable constellation, 30 dB for a decodable base layer, and 35 dB for decodable enhancement layer.

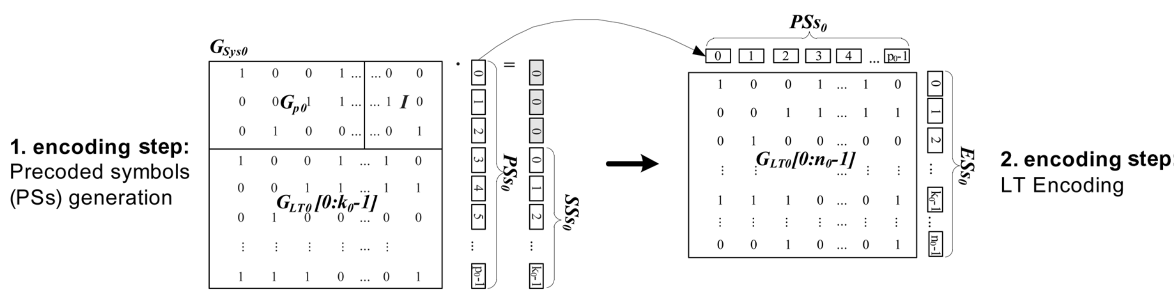

Fig. 10. Raptor encoding process for one layer $(\mathrm{L}=0)$ as specified in [10]. The first encoding step generates the precoding symbols (PSs_0) from the source symbols (SSs_0) by use of an erasure code like LDPC. In the second step, the encoded symbols (ESs_0) are generated from the PSs_0 by use of a fountain code, e.g., LT code. The code is systematic, since the first k encoding symbols consist of the k source symbols.

[27]. The required extensions for a systematic Raptor code as, e.g., specified in 3GPP MBMS [12] and or DVB-SH (for MPE-iFEC) [11]. A full specification based on [26] can be found in the Annex D of the DVB Upper layer FEC overview [5], which discusses the possibility to integrate LA-FEC within DVB. Note that the extension could be applied in a similar way to the more efficient RaptorQ FEC [9] codes.

Raptor codes are in general one of the first known classes of fountain code with linear time encoding and decoding [8]. In preparation of the encoding, a certain amount of data is collected within a source block. The data of a source block are further divided in k source symbols (SSs) of a fixed symbol size. Fig. 10 illustrates the Raptor encoding process for a single media "Layer 0", which consists of two encoding steps [26]. In the first step, a fixed rate "precode" step, here typically any erasure code like, e.g., LDPC, can be applied on the SSs_0 to generate the so-called precoding symbols (PSs_0). The values of the PSs_0 are determined by the matrix G_{Sys0}, which consists of the precode matrix G_{P0}, the identity matrix I, and the LT matrix $G_{LT0}[0 : k_0 - 1]$, where the latter is identical to the first k_0 rows of $G_{LT0}[0 : n_0 - 1]$ in the second encoding process. The values within the brackets denote the number of rows. The integration of the matrix G_{LT0} assures that the first k_0 encoding symbols (ESs_0) after LT encoding are identical to the SSs_0. After finalizing the first step, the PSs_0 are forwarded to the second step. The fountain of n_0 encoding symbols ESs_0 are calculated by XORing PSs_0 following the connection given by the LT code and illustrated by the $G_{LT0}[0 : n_0 - 1]$ matrix. Note, that also with LA-FEC, the generation of base layer ESs_0 follows the original Raptor process.

For the enhancement "Layer 1", the LA-FEC approach needs to be integrated into the Raptor coding process [26], which requires on one hand the extension of the G_{LT} matrix of the LT-encoding step of the PSs in the dependent media layers and on the other hand the extension of the G_{LT} matrix of the precoding process to preserve the systematic behavior of the code. Fig. 11 shows the required extensions, highlighted in green, for generation of ESs_1.

In the first encoding step, the generation of the matrices G_{p1}, I, and $G_{LT1}[0 : k_1 - 1]$ is identical to the related matrices shown in Fig. 10. LA-FEC requires the extension of the matrix G_{Sys1} by the matrix $G^*_{LT0}[n_0 : n_0 + k_1 - 1]$ which is the continuation of the $G_{LT0}[0 : n_0 - 1]$ matrix in Fig. 10. G_{Sys1} represents the first k_1 rows of the $G^*_{LT0}[n_0 : n_0+n_1-1]$ matrix in the second encoding step. Furthermore, the PSs_0 symbols from the "Layer 0" processing are included in the encoding process. These extensions assure that the output symbols PSs_1 still lead to a systematic code after the second encoding step.

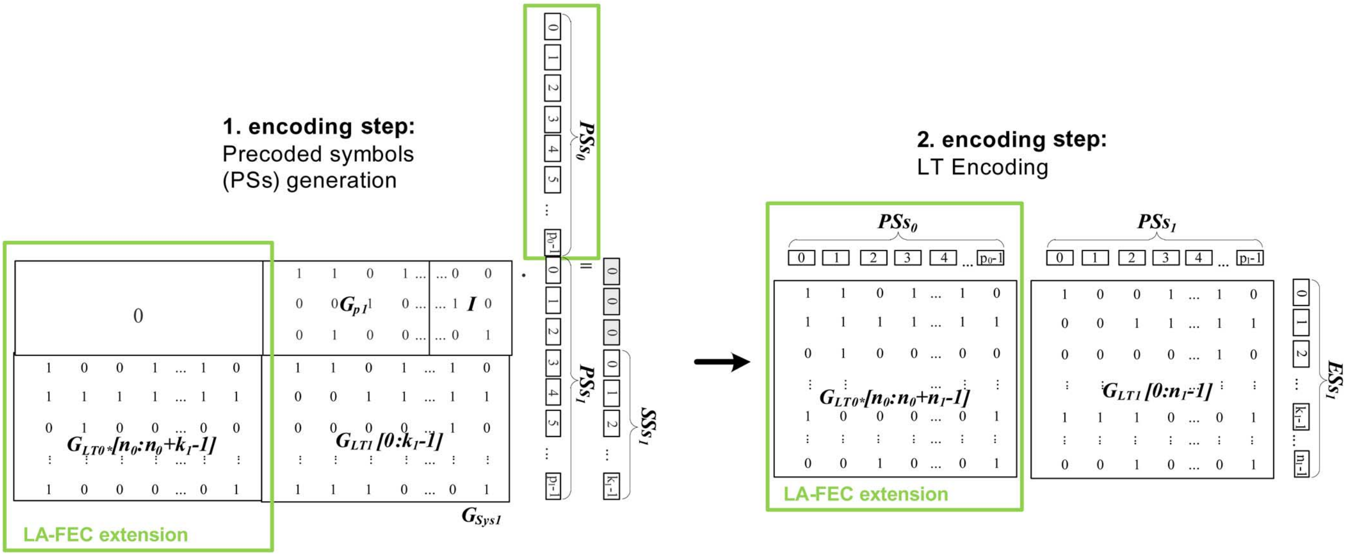

Fig. 11. LA-FEC extended Raptor encoding process. The required extensions for LA-FEC are marked in green. Extending the first encoding step keeps the systematic code. The extension for the LT-Encoding connects enhancement layer to base layer. Note, the extension matrices $(\mathrm{GLT0}^*)$ are generated by standard Raptor algorithm.

The generation of the ESs_1 symbols in the second step is extended to the PSs_0 through extending the $G_{LT1}[0:n_1-1]$ matrix by $G^*_{LT0}[n_0 : n_0+n_1-1]$. Therefore, the ESs_1 symbols can be used in the LA-FEC together with the ESs_0 symbols for joint decoding. This is also shown in the example in Section IV. The extensions required by the LA-FEC use the algorithms for precode generation and LT Encoding as already specified in [25], leaving the specification and the defined constraints of the algorithms untouched. In case of a successful decoded "Layer 0", the introduced connections across the layers by the LA-FEC extension are not required anymore and can be removed by XORing the PSs_0 in the FEC process of "Layer 1". In such a case, "Layer 1" can be corrected following the standard Raptor coding process [26], enabling its full correction performance.

D. Signaling and Transport of Layer-Aware FEC

The usage of the LA-FEC in transmission systems requires specific signaling and transport techniques to support the multi-layer approach in combination with LA-FEC coding. The integration of the LA-FEC Raptor extension on link or application layer is assumed to be applied for real-time transmission over RTP [32]. For real-time applications, typically RTP is used over UDP [33] due to its connectionless and non-reliable nature it allows for minimal delay in transport. RTP provides basic features such as media synchronization, transmission order recovery, multiplexing, source identification, and reception feedback information. For SVC, the RTP Payload Format for Scalable Video Coding [34] is required for media payload packetization and for MVC, the RTP Payload Format for Multiview Video Coding [35]. In particular, these payload formats for SVC and MVC define the transmission of the layered SVC and MVC data in multiple RTP sessions, which allows a transmission system using the LA-FEC coding process to simply differentiate between SVC layers and MVC

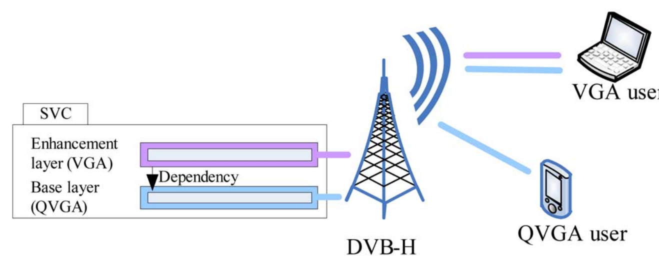

Fig. 12. Support of different device capabilities $(\mathrm{QVGA}+\mathrm{VGA})$ using SVC in a DVB-H broadcast system.

views based on the transport address, such as an IP address, the UDP port, or the synchronization source identifier in the RTP packet header (SSRC) [32]. Signaling of session related information is defined in the Session Description Protocol [37]. In order to signal the dependency of RTP sessions containing layers or views of the same codec, the SDP extensions in [36] are required.

For transporting the FEC coded data, the IETF created the generic FECFRAME framework defining basic means for FEC-based content delivery protocols, which can be also used in RTP. This framework defines beside other features how multiple media and repair flows are treated and further provides an identification mechanism for source symbols as a part of the payload packetization information. To use this framework with the Raptor code, [38] is intended to be used.

In order to make this framework applicable to the LA-FEC the Raptor FEC scheme [39] and the Raptor RTP Payload format [40] can be used without modifications for packetizing the repair flow. The signaling for the Raptor FEC scheme is defined in [38], where the indication of depending repair flows is already defined in [41], as required for LA-FEC base layer protection and LA-FEC enhancement layer protection.

V. Simulation Results for SVC LA-FEC at the Application Layer in DVB-H

A. Simulation Setup

The simulations in this section are based on a mobile Broadcast scenario where two device capabilities, QVGA and VGA, are supported by a single DVB-H service using SVC [cf. Fig. 12]. For increasing the robustness of the whole service, the link layer FEC defined in DVB-H, MPE-FEC, and the proposed Raptor-based LA-FEC solution is evaluated on the application layer using different code rate distributions across media coding layers.

B. Channel Model

The simulation scenario consists on a Typical Urban 6-taps (TU6) channel model with a constant Doppler (i.e., user velocity). The TU6 channel models the time variant small-scale fluctuations of the received signal due to receiver mobility (fast fading), and it was proven to be representative for DVB-H mobile reception for Doppler frequencies above 10 Hz (i.e., vehicular reception) [31]. We consider the DVB-H physical layer transmission mode: FFT size 8 K, OFDM symbol guard interval (GI) 1/4, modulation 16-QAM, and code rate 1/2, which provides a channel capacity of about 10 Mbps.

C. Media Encoding

The video encoding was performed using the SVC reference software version JSVM 9.1. A simple rate control was employed to achieve an approximately constant service rate. The video was encoded in small chunks, where each chunk consists of a preceding IDR frame followed by three groups of picture of size 8 (GOP8), i.e., 25 frames. Each chunk was encoded multiple times with different quantization parameters (QP) values. Depending on the selected video rate, the chunk with QP value providing the target bitrate was selected and the different chunks were concatenated to one video stream. The chunk wise encoding gives a random access point (RAP) interval of 1 s at 25 frames per second (fps).

The test sequence "Soccer"[1] with a duration of 10 s was selected for the simulations. An SVC bit stream with two scalable layers was encoded using the scalable high profile of H.264/AVC. In particular the stream contained a base layer which provides QVGA at 12.5 fps, and an enhancement layer increasing the quality to VGA at 25 fps. Freeze frame error concealment was used, where in case of frame loss, the last decoded picture is copied for output. In cases where only the enhancement layer was lost, the up-scaled picture of the QVGA layer was used for PSNR calculation. A summary of the encoding parameters can be found in Table II.

D. DVB-H Transmission Scheduling

DVB-H applies a so-called time slicing approach, where data are transmitted in bursts in order to save battery power by switching off the receiver between bursts. Therefore, the two SVC layers were transmitted in two different time-sliced bursts, the second containing the enhancement layer directly following the first containing the base layer. Fig. 13 illustrates such a transmission scheduling, where the red arrows show the SVC layer coding dependencies, the black arrows the protection by ST-FEC, and the green arrows the protection added by LA-FEC.

[1]Other sequences have been tested which show a different rate-distortion performance but similar performance in the comparison of LA-FEC and ST-FEC.

TABLE II
Encoding Parameters for SVC Bitstream With Temporal and Spatial Scalability

	Quality	Bitrate	PSNR VGA
H.264/AVC Base layer	QVGA 12.5fps	225 kbps	31.3 dB (upscaled)
SVC Enhancement layer	VGA 25fps	647 kbps	35.4 dB

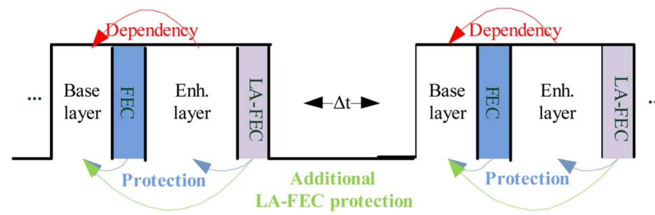

Fig. 13. SVC transmission of base (QVGA@12.5 fps) and enhancement layer (VGA@25 fps) in different time-sliced bursts, the second immediately following the other.

The source block size for FEC generation is aligned to the chunk size, i.e., each source block starts with an IDR RAP and incorporates all GOP8 s of the chunk, equivalent to 1 s of media data.

E. FEC Settings

The overall service bitrate (including media data and parity bits) was fixed to 1300 kbps. The code rates for base and enhancement layer are adjusted to reach this bitrate. For example, the EEP scheme allows for a code rate of 0.68 for each media layer. Furthermore, different UEP schemes were applied with either stronger protection in base layer or stronger protection in the enhancement layer. It should be noted here that with ST-FEC, typically UEP with a stronger protection for the enhancement layer is a not a reasonable setting. The selected video streams are encapsulated in RTP packets according to their specific RTP payload format [34] and the FEC symbols are encapsulated within the related RTP payload format [40] and subsequently into IP streams.

F. Results

The plots in Fig. 14 show the IP packet error rate for the SVC base (left) and enhancement layer (right) and Fig. 15 shows the resulting video quality in terms of average PSNR (right) and the number of freeze frames (left) over different reception conditions in terms of C/N for the different transmission schemes. Note that there are in total 250 frames.

The IP packet error plot in Fig. 14 illustrates the effect of the LA-FEC scheme compared to the ST-FEC scheme. Although the total amount of protection packets is the same for the different coding schemes, the number of lost base layer IP packets is for all code rate distributions significantly lower when aplying LA-FEC. All LA-FEC schemes show a similar base layer decoding probability whereas the ST-FEC decoding probability strongly depends on the assigned code rate. As expected from the theoretical analysis in Section IV-B, the effective IP packet error rate of enhancement layer data after FEC correction is increased due to the introduced dependency to the base layer data

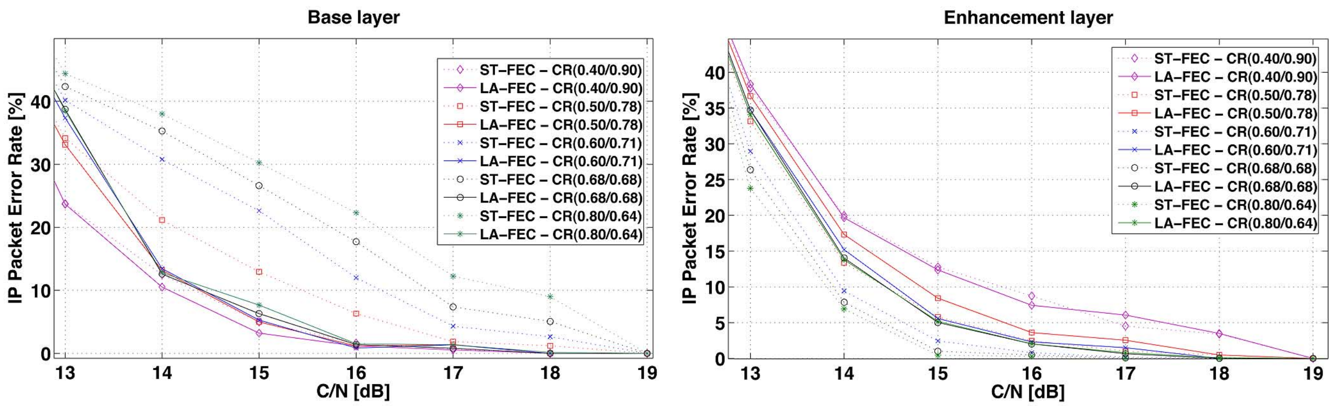

Fig. 14. IP packet error rate for (left) base and (right) enhancement layer using ST-FEC and LA-FEC with different code rate distributions across SVC layers at a fixed service bitrate of 1300 kbps.

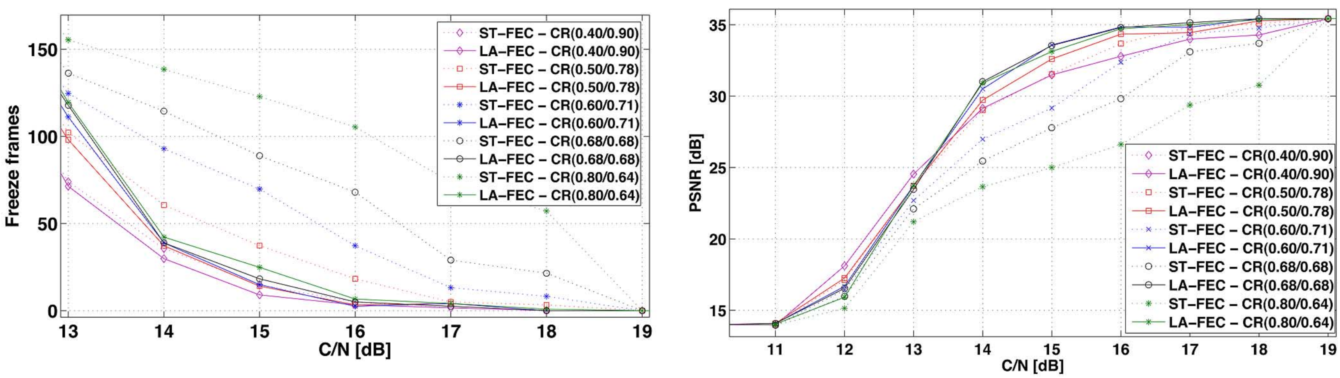

Fig. 15. Average number of freeze frames of (left) 250 frames and the (right) average PSNR value for a VGA receiver using ST-FEC and LA-FEC with different code rate distributions across SVC layers at a fixed service bitrate of 1300 kbps.

when applying LA-FEC. However, due to the fact that enhancement layer data are useless without the reception of the respective base layer data, the increased IP packet error rate has no negative impact on the perceived video quality.

Considering the video quality in Fig. 15, all LA-FEC settings show a better performance compared to ST-FEC. The best ST-FEC scheme has a strong UEP spreading [cf. CR(0.50/0.78) in the figure]. However, further increasing the base layer protection in the ST-FEC case decreases the overall performance [cf. CR(0.40/0.90) in the figure]. Although there is not a significant performance difference between the tested LA-FEC settings, the best LA-FEC scheme is the one using EEP code rate setting [cf. (CR(0.68/0.68) in the figure]. The LA-FEC EEP scheme outperforms the best ST-FEC scheme by approximately 2 dB in terms of PSNR for the C/N value range from 14 dB to 16 dB. Within this area, the video service with LA-FEC achieves a video quality in terms of PSNR over 30 dB, which can be assumed as an acceptable quality from a users point of view. It is further interesting that the difference in performance between the different LA-FEC schemes is not as big as between the ST-FEC schemes. Even a stronger protection for the enhancement layer shows a relatively better performance than the ST-FEC schemes when applying LA-FEC. This also allows for applying new operation points using stronger protections in the enhancement layer, which might be useful in applications such as conditional access. With LA-FEC and conditional access, a service could be applied with a free base layer providing low quality and low robustness, e.g., CR 0.80. With additionally receiving the enhancement layer of the premium service would not only increase the video quality but also the service robustness [cf. CR(0.80/0.64) in Fig. 15]. Taking into account that LA-FEC with EEP gives the best performance, LA-FEC eases the adjustment of the code rates for a multi-layer transmission system. Considering freeze frames, LA-FEC gives a significant improvement to the number of frozen frames, which is due to the lower base layer IP packet error rate. All LA-FEC schemes show a lower number of freeze frames than the related ST-FEC scheme and all LA-FEC schemes reach at least the performance of the best ST-FEC scheme. Thereby, LA-FEC significantly increases the service reliability. This is in general interesting, since increasing the service robustness with layered-media by UEP compared to single layer typically comes at the cost of a reduced enhancement layer protection. Using LA-FEC allows to achieve a similar effect without reducing the enhancement layer robustness [cf. CR(0.68/0.68) in Fig. 15].

VI. Conclusion

In this work, we present the LA-FEC concept for improving performance in broadcast of multi-layered media. The LA-FEC concept can be implemented either on the physical or any upper communication system layer. We present a theoretical model, which shows the gain introduced by LA-FEC compared to standard FEC schemes. We described the application of the LA-FEC concept to the Raptor code at the link or application layer. We further describe the application means for transport and signaling of LA-FEC. Simulations results for application layer LA-FEC in a DVB-H scenario showed that the theoretical gain can also be translated to a real channel. Future work will be the investigation of the performance of LA-FEC on physical layer. We further plan to analyze the performance of combinations of LA-FEC with related schemes.

REFERENCES

[1] H. Schwarz, D. Marpe, and T. Wiegand, "Overview of the scalable video coding extension of the H.264/AVC standard," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 17, no. 9, pp. 1103–1120, Sep. 2007.

[2] P. Merkle, Y. Morvan, A. Smolic, D. Farin, K. Müller, P. H. N. de With, and T. Wiegand, "The effects of multiview depth video compression on multiview rendering," *Signal Process.: Image Commun.—Special Issue on Advances in Three-Dimensional Television and Video*, vol. 24, no. 1–2, pp. 73–88, Jan. 2009.

[3] DVB TM-H NGH, Call for Technologies (CfT) v 1.0, DVB TM 4270r2, Nov. 2009.

[4] ATSC, ATSC-Mobile DTV Standard, Part 7—AVC and SVC Video System Characteristics, Document A/153 Part 7:2009, Oct. 2009.

[5] ETSI TR 102 993 V1.1.1, Digital Video Broadcasting (DVB); Upper Layer FEC for DVB Systems, Feb. 2011.

[6] D. J. C. MacKay and R. M. Neal, "Near Shannon limit performance of low density parity check codes," *Electron Lett.*, vol. 33, no. , pp. 457–458, Mar. 1997.

[7] C. Berrou, "The ten-year-old turbo codes are entering into service," *IEEE Commun. Mag.*, vol. 41, no. 8, pp. 110–116, Aug. 2003.

[8] A. Shokrollahi, "Raptor codes," *IEEE Trans. Inf. Theory*, vol. 52, no. 6, pp. 2551–2567, 2006.

[9] M. Luby, A. Shokrollahi, M. Watson, T. Stockhammer, and L. Minder, RaptorQ Forward Error Correction Scheme for Object Delivery, IETF RMT draft-ietf-rmt-bb-fec-raptorq-04, Aug. 2010. [Online]. Available: http://tools.ietf.org/html/draft-ietf-rmt-bb-fec-raptorq-04.

[10] ETSI TS 102 472 v1.3.1, Digital Video Broadcast (DVB); IP Datacast Over DVB-H: Content Delivery Protocols, Jun. 2009.

[11] ETSI TS 102 584 v1.2.1, Digital Video Broadcasting (DVB); DVB-SH Implementation Guidelines, Jan. 2011.

[12] 3GPP TS 26.346 V9.4.1, Multimedia Broadcast/Multicast Service (MBMS); Protocols and codecs (Release 9).

[13] C. Hellge, S. Mirta, T. Schierl, and T. Wiegand, "Mobile TV with SVC and hierarchical modulation for DVB-H broadcast services," in *Proc. IEEE Int. Symp. Broadband Multimedia Systems and Broadcasting (BMSB)*, Bilbao, Spain, May 2009.

[14] S. Mirta, "HD video broadcasting using scalable video coding combined with DVB-S2 variable coding and modulation," in *Proc. ASMA and SPSC*, Sep. 2010.

[15] B. Masnick and J. Wolf, "On linear unequal error protection codes," *IEEE Trans. Inf. Theory*, vol. IT-13, no. 4, pp. 600–607, 1967.

[16] C. C. Kilgus and W. C. Gore, "A class of cyclic unequal-error-protection codes," *IEEE Trans. Inf. Theory*, vol. IT-18, no. 5, pp. 687–690, Sep. 1972.

[17] I. Boyarinov and G. Katsman, "Linear unequal error protection codes," *IEEE Trans. Inf. Theory*, vol. 27, no. 2, pp. 168–175, 1981.

[18] N. Rahnavard and F. Fekri, "New results on unequal error protection using LDPC codes," *IEEE Communications Lett.*, vol. 10, no. 1, pp. 43–45, 2006.

[19] N. Rahnavard, B. N. Vellambi, and F. Fekri, "Rateless codes with unequal error protection property," *IEEE Trans. Inf. Theory*, vol. 53, no. 4, pp. 1521–1532, 2007.

[20] A. Bouabdallah and J. Lacan, "Dependency-aware unequal erasure protection codes," *J. Zhejiang Univ. SCIENCE A 2006 7 (Suppl. I):27–33*, 2006.

[21] M. Bogino, P. Cataldi, M. Grangetto, E. Magli, and G. Olmo, "Gliding-window digital fountain codes for streaming of multimedia contents," in *Proc. ISCAS 2007*, May 2007.

[22] D. Sejdinovic, D. Vukobratovic, A. Doufexi, V. Senk, and R. Piechocki, "Expanding window fountain codes for unequal error protection," *IEEE Trans. Commun.*, vol. 57, no. 9, pp. 2510–2516, 2009.

[23] D. Vukobratovic, V. Stankovic, D. Sejdinovic, L. Stankovic, and Z. Xiong, "Scalable video multicast using expanding window fountain codes," *IEEE Trans. Multimedia*, vol. 11, no. 6, pp. 1094–1104, 2009.

[24] H. Zimmermann, OSI Reference Model, *IEEE Trans. Commun.*, vol. COMM-28, no. 4, p. 425, Apr. 1980.

[25] M. Luby, "LT-codes," in *Proc. ACM Symp. Foundation of Computer Science (FOCS)*, 2002.

[26] M. Luby, A. Shokrollahi, M. Watson, and T. Stockhammer, Raptor Forward Error Correction Scheme for Object Delivery, IETF RFC 5053, Internet Engineering Task Force (IETF), Network Working Group, Sep. 2007. [Online]. Available: http://tools.ietf.org/html/rfc5053.

[27] C. Hellge, T. Schierl, and T. Wiegand, "Mobile TV using scalable video voding and layer-aware forward error correction," in *Proc. IEEE Int. Conf. Multimedia and Expo (ICME'08)*, Hanover, Germany, Jun. 2008.

[28] C. Hellge, T. Schierl, and T. Wiegand, "Multidimensional layered forward error correction using rateless codes," in *Proc. IEEE Int. Conf. Communication (ICC)*, Bejing, China, 2008.

[29] C. Hellge, T. Schierl, and T. Wiegand, "Receiver driven layered multicast with layer-aware forward error correction," in *Proc. ICIP 2008*, 2008, pp. 2304–2307.

[30] C. Hellge, D. Gomez-Barquero, T. Schierl, and T. Wiegand, "Intra-burst layer aware FEC for scalable video coding delivery in DVB-H," in *Proc. ICME 2010*, Singapore, Jul. 2010.

[31] G. Faria, J. A. Henriksson, E. Stare, and P. Talmola, "DVB-H: Digital broadcast services to handheld devices," *Proc. IEEE*, vol. 94, no. 1, pp. 194–209, Jan. 2006.

[32] H. Schulzrinne, S. Casner, R. Frederick, and V. Jacobson, RTP: A Transport Protocol for Real-Time Applications IETF STD 0064, RFC 3550, Jul. 2003. [Online]. Available: http://tools.ietf.org/html/rfc3550.

[33] J. Postel, User Datagram Protocol, IETF STD 6, RFC 768, Sep. 1981. [Online]. Available: http://tools.ietf.org/html/rfc768.

[34] S. Wenger, Y.-K. Wang, T. Schierl, and A. Eleftheriadis, RTP Payload Format for SVC Video work in progress, Internet Engineering Task Force (IETF), Audio Video Transport Group (avt), draft-ietf-avt-rtp-svc-21, Apr. 2010. [Online]. Available: http://tools.ietf.org/html/draft-ietf-avt-rtp-svc.

[35] Y.-K. Wang and T. Schierl, RTP Payload Format for MVC Video, work in progress, IETF AVT, draft-ietf-avt-rtp-mvc-01.txt, Oct. 2010. [Online]. Available: http://tools.ietf.org/html/draft-ietf-avt-rtp-mvc-01.

[36] T. Schierl and S. Wenger, Signaling Media Decoding Dependency in Session Description Protocol (SDP), IETF MMUSIC, Apr. 2009. [Online]. Available: http://tools.ietf.org/html/rfc5583.

[37] M. Handly, V. Jacobson, and C. Perkins, SDP: Session Description Protocol, IETF RFC 4566, Jul. 2006. [Online]. Available: http://tools.ietf.org/html/rfc4566.

[38] M. Watson, Forward Error Correction (FEC) Framework, IETF FECFRAME draft-ietf-fecframe-framework-09, Jul. 2010. [Online]. Available: http://tools.ietf.org/html/draft-ietf-fecframe-framework.

[39] M. Watson, Raptor FEC Schemes for FECFRAME, IETF FECFRAME, draft-ietf-fecframe-raptor-02, Mar. 2010. [Online]. Available: http://tools.ietf.org/html/draft-ietf-fecframe-raptor.

[40] M. Watson, RTP Payload Format for Raptor FEC, IETF FECFRAME, draft-ietf-fecframe-rtp-raptor-03, Mar. 2010. [Online]. Available: http://tools.ietf.org/html/draft-ietf-fecframe-rtp-raptor.

[41] A. Begen, SDP Elements for FEC Framework, IETF FECFRAME, draft-ietf-fecframe-sdp-elements-07, Jul. 2010. [Online]. Available: http://tools.ietf.org/html/draft-ietf-fecframe-sdp-elements-04.

[42] DVB TM-H, Response to DVB-NGH Call for Technologies, Layer-Aware FEC for Layered Media Transmission, TM-NGH092, Feb. 2010.

[43] T. Wiegand, G. J. Sullivan, G. Bjontegaard, and A. Luthra, "Overview of the H.264/AVC video coding standard," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 13, no. 7, pp. 560–576, Jul. 2003.

[44] ETSI EN 302 583 V1.1.2, Digital Video Broadcasting (DVB); Framing Structure, Channel Coding and Modulation for Satellite Services to Handheld Devices (SH) Below 3 GHz, Feb. 2010.

[45] ETSI EN 302 755 V1.1.1, Digital Video Broadcasting (DVB); Frame Structure Channel Coding and Modulation for a Second Generation Digital Terrestrial Television Broadcasting System (DVB-T2), Sep. 2009.

[46] C. Berrou, "The ten-year-old turbo codes are entering into service," *IEEE Commun. Mag.*, vol. 41, no. 8, pp. 110–116, Aug. 2003.

Cornelius Hellge received the Dipl.-Ing. degree (M.Sc.) in media technology from the Ilmenau University of Technology, Ilmenau, Germany, in July 2006.

He has been with Fraunhofer HHI since 2005. Since 2009, he has worked in parallel as a researcher in the Image Communication Laboratory at the Berlin Institute of Technology, Berlin, Germany. He contributed to different standardization bodies (e.g., DVB, 3GPP) and has done different research works on reliable real-time transmission of H.264/AVC and scalable video coding (SVC) in mobile point-to-point, multicast, broadcast, IPTV, and P2P environments. His main research interests are in the area of reliable video transmission and signaling, in particular in forward error correction and in the joint use of channel and source coding. Currently, he is working on media delivery in CDNs in the context of the European research project of the FP7 program OCEAN. He was a Co-editor of the DVB bluebook on upper layer forward error correction. Currently, he is actively participating in the standardization process of the next-generation handheld standard DVB-NGH and the 3GPP SA4 group.

David Gómez-Barquero received the double M.Sc. degree in telecommunications engineering from the Universidad Politécnica de Valencia (UPV), Valencia, Spain, and the University of Gavle, Gavle, Sweden, in 2004 and the Ph.D. degree in telecommunications from UPV in 2009.

He is a post-doc guest researcher at the Fraunhofer Heinrich Herzt Institute (HHI) in Berlin, Germany. During his doctoral studies, he was a guest researcher at the Royal Institute of Technology, Sweden, the University of Turku, Finland, and the Technical University of Braunschweig, Germany. He also did an internship at Ericsson Eurolab, Aachen, Germany. His main research interests are in the area of mobile multimedia broadcasting, in particular radio resource management, forward error correction, and network planning issues in both DVB and 3GPP MBMS systems. He chaired the special interest group on hybrid cellular and broadcasting networks in the European COST2100 cooperation action, and co-edited the DVB bluebook on upper layer forward error correction as an invited expert. Currently, he is actively participating in the standardization process of the next generation handheld mobile broadcasting standard DVB-NGH.

Thomas Schierl (M'07) received the Dipl.-Ing. (M.Sc.) degree in computer engineering from the Berlin Institute of Technology, Berlin, Germany, in December 2003 and the Dr.-Ing. (Ph.D) degree in electrical engineering and computer science from Berlin Institute of Technology in October 2010.

Since 2010, he has been head of the Multimedia Communications Group in the Image Processing Department of Fraunhofer HHI, Berlin. Since September 2004, he has been a Senior Researcher in the Image processing department, where he is responsible as a project manager for various scientific as well as industry-funded research projects. He is the co-author of various IETF RFCs; beside others, he is author of the IETF RTP Payload Format for H.264 SVC (Scalable Video Coding), the IETF RTP Payload for Multi View Coding (MVC), as well as of the IETF RFC on Rapid Synchronization of RTP flows (RFC 6051). In the ISO/IEC MPEG group, he is co-editor of the MPEG Standard on Transport of H.264 SVC as well as H.264 MVC over MPEG-2 Transport Stream. He is also a co-editor of the AVC File Format. Typically, he is participating MPEG, IETF, 3GPP, and DVB meetings. In 2007, he visited the Image, Video, and Multimedia Systems group of Prof. B. Girod at Stanford University, Stanford, CA, for different research activities. His research interests include real-time media delivery over IP networks, which may be mobile or wired, with or without infrastructure [e.g., Mobile Ad Hoc Networks (MANETs)], or based on traditional as well as on overlay/Peer-to-Peer (P2P) mobile IPTV approaches. Currently, he is working on mobile media content delivery over HTTP.

Thomas Wiegand (M'05–SM'08–F'11) received the Dipl.-Ing. degree in electrical engineering from the Technical University of Hamburg-Harburg, Germany, in 1995 and the Dr.-Ing. degree from the University of Erlangen-Nuremberg, Germany, in 2000.

He is a Professor at the Department of Electrical Engineering and Computer Science at the Berlin Institute of Technology, Berlin, Germany, chairing the Image Communication Laboratory, and is jointly heading the Image Processing Department of the Fraunhofer Institute for Telecommunications—Heinrich Hertz Institute, Berlin. He joined the Heinrich Hertz Institute in 2000 as the head of the Image Communication group in the Image Processing Department. His research interests include video processing and coding, multimedia transmission, as well as computer vision and graphics. From 1993 to 1994, he was a Visiting Researcher at Kobe University, Kobe, Japan. In 1995, he was a Visiting Scholar at the University of California at Santa Barbara. From 1997 to 1998, he was a Visiting Researcher at Stanford University, Stanford, CA, and served as a consultant to 8 × 8, Inc., Santa Clara, CA. From 2006–2008, he was a consultant to Stream Processors, Inc., Sunnyvale, CA. From 2007–2009, he was a consultant to Skyfire, Inc., Mountain View, CA. Since 2006, he has been a member of the technical advisory board of Vidyo, Inc., Hackensack, NJ. Since 1995, he has been an active participant in standardization for multimedia with successful submissions to ITU-T VCEG, ISO/IEC MPEG, 3GPP, DVB, and IETF. In October 2000, he was appointed as the Associated Rapporteur of ITU-T VCEG. In December 2001, he was appointed as the Associated Rapporteur/Co-Chair of the JVT. In February 2002, he was appointed as the Editor of the H.264/MPEG-4 AVC video coding standard and its extensions (FRExt and SVC). From 2005–2009, he was Co-Chair of MPEG Video.

Dr. Wiegand received the SPIE VCIP Best Student Paper Award in 1998. In 2004, he received the Fraunhofer Award and the ITG Award of the German Society for Information Technology. The projects that he co-chaired for development of the H.264/MPEG-4 AVC standard have been recognized by the 2008 ATAS Primetime Emmy Engineering Award and a pair of NATAS Technology & Engineering Emmy Awards. In 2009, he received the Innovations Award of the Vodafone Foundation, the EURASIP Group Technical Achievement Award, and the Best Paper Award of the IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS FOR VIDEO TECHNOLOGY. In 2010, he received the Eduard Rhein Technology Award. He was a Guest Editor for the IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS FOR VIDEO TECHNOLOGY for its Special Issue on the H.264/AVC Video Coding Standard in July 2003, its Special Issue on Scalable Video Coding-Standardization and Beyond in September 2007, and its Special Section on the Joint Call for Proposals on High Efficiency Video Coding (HEVC) Standardization. Since January 2006, he has been an Associate Editor of the IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS FOR VIDEO TECHNOLOGY.