Inter-Layer Turbo Coded Unequal Error Protection for Multi-Layer Video Transmission

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Abstract—In layered video streaming, the enhancement layers (ELs) must be discarded by the video decoder, when the base layer (BL) is corrupted or lost due to channel impairments. This implies that the transmit power assigned to the ELs is wasted, when the BL is corrupted. To combat this effect, in this treatise we investigate the inter-layer turbo (IL-turbo) code, where the systematic bits of the BL are implanted into the systematic bits of the ELs at the transmitter. At the receiver, when the BL cannot be successfully decoded, the information of the ELs may be utilized by the IL-turbo decoder for the sake of assisting in decoding the BL. Moreover, for providing further insights into the IL technique the benefits of the IL-turbo scheme are analyzed using extrinsic information transfer (EXIT) charts in the scenario of unequal error protection (UEP) coded layered video transmission. Finally, our data partitioning based experiments show that the proposed scheme outperforms the traditional turbo code based UEP scheme by about an E_b/N_0 of 1.1 dB at a peak signal-to-noise ratio (PSNR) of 36 dB or 3 dB of PSNR at an E_b/N_0 of -5.5 dB at the cost of a complexity increase of 13%.

I. INTRODUCTION

Layered video coding [1] was proposed for encoding the video into multiple layers of unequal importance, namely into the base layer (BL) and the enhancement layers (ELs). The technique has been widely employed in existing video standards. The moving picture expert group (MPEG) [2] developed a multiview profile (MVP) [3] based stereoscopic video compression technique as part of the MPEG-2 standard, where the left view is encoded as the BL and the right view is encoded as an EL. Furthermore, the technique referred to as scalable video coding (SVC) [4], [5], is an extension of the H.264/AVC standard [5] and is capable of generating spatially or temporally layered video. This enables the transmitter to adapt the transmitted video quality “on-the-fly” to meet the specific preferences of different users. Moreover, the data partitioning mode of H.264/AVC [5] splits each slice into a maximum of three bitstreams/partitions [6], namely type A, type B and type C partitions according to their semantic importance. Specifically, the type A partition may be deemed to be the BL. Correspondingly, the B and C partitions may be interpreted as ELs, since they depend on the A partition for decoding.

The concept of linear unequal error protection (UEP) codes was proposed as early as 1967 [7]. The authors of [8] proposed UEP low-density parity-check (LDPC) coded transmissions over the binary erasure channel (BEC). The system performance of data-partitioned [5] video transmission using recursive systematic convolutional (RSC) coded UEP was investigated in [9]. On the other hand, UEP turbo coded modulation was investigated in [10], where both the channel capacity and the cutoff rates of the different protection levels were derived. The authors of [11] proposed a cross-layer optimization aided SVC for the robust delivery of scalable video over error-prone channels.

The traditional UEP encodes each layer separately using different forward error protection (FEC) codes. However, when the BL is corrupted, the ELs depending on the BL must be discarded by the video decoder, implying that the transmit power of the ELs is wasted. To counteract this problem, the authors of [12] proposed the so-called layer-aware forward error protection (LA-FEC) philosophy based on

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raptor codes employed at the upper layer for transmission over the BEC, where the parity bits are generated across different layers. As a further enhancement, we proposed the inter-layer FEC (IL-FEC) principle in [13], where a recursive systematic convolutional (RSC) code was employed. Specifically, the systematic bits of the BL were implanted into the systematic bits of the ELs at the transmitter. As a benefit, the receiver may invoke the ELs for assisting in the correction of the errors within the BL. Against this background, in this treatise we develop an IL-turbo [14] coded UEP aided video system for transmission over a layered steered space-time coded (LSSTC) [15] structure. Furthermore, extrinsic information transfer (EXIT) charts [16] are employed for analyzing the performance of our proposed system.

More explicitly, our novel contributions are:

- 1) *We conceive an IL-turbo codec for layered video streaming, which is combined with cutting-edge UEP and LSSTC schemes for the sake of improving the attainable performance, where our proposed IL-turbo system outperforms the traditional turbo code based UEP system by about an E_b/N_0 gain of 1.1 dB or a peak-signal to noise ratio (PSNR) gain of 3 dB.*
- 2) *We use the novel EXIT technique to design and analyze our proposed IL-turbo coded UEP system, where we show that the IL-turbo coded system exhibit an open tunnel at a lower SNR value than the traditional turbo coded system.*
- 3) *Our IL-turbo coded system imposes a 13% complexity increase, which guarantees the practical feasibility of our proposed technique.*

We use the H.264/AVC data partitioning mode of [6] in our simulations, but our proposed scheme is not limited to partitioning-based video. It may be readily applied in any arbitrary layered video system [13]. The rest of this paper is organized as follows. Section II briefly introduces our IL-turbo-LSSTC system model, then the performance of our proposed system is analyzed using EXIT charts in Section III. The performance of our IL-turbo-LSSTC scheme is benchmarked in Section IV followed by our conclusions in Section V.

II. SYSTEM OVERVIEW

In this section, we will briefly introduce the IL-turbo system conceived for partitioned video streaming over our LSSTC scheme, which is capable of simultaneously achieving both a multiplexing- and diversity-gain, as well as a beamforming gain [13]. The system’s architecture is displayed in Fig. 1, while the variable node decoder (VND) and check node decoder (CND) are defined in [13]. Furthermore, data-partitioning aided H.264 [5] encoding is employed, which generates the BL A and the ELs B , C . Below, we assume that layers A , B and C contain the same number of n bits for the sake of conceptual simplicity, noting that our solution is not limited to this specific scenario as we have shown in [13].

A. Transmitter Model

At the transmitter of Fig. 1, the video source signal s is firstly compressed by the data-partitioning mode of the H.264 encoder, resulting in the binary sequences of x_a , x_b and x_c , which represent the partitions A , B and C , respectively. Then the resultant layers are IL-turbo encoded as follows:

Fig. 1: IL-turbo encoding architecture of H.264 data partitioning mode coded video.

- 1) The BL x_a will be encoded by the turbo encoder A of Fig. 1, resulting in the encoded bits containing the systematic bits x_a and parity bits $x_{a,p}$.
- 2) The EL x_b will firstly be encoded into the systematic bits x_b and the parity bits $x_{b,p}$ by the turbo encoder B. Then IL encoding is performed by the XOR operation which implants the systematic bits x_a into the systematic bits x_b . Specifically, the implantation process generates the check bits $x_{ab}^i = x_a^i \oplus x_b^i$. After this procedure, the check bits x_{ab}^i and the parity bits $x_{b,p}$ are output as encoded bits of the EL x_b . Note that the interleaver π^{-1} of Fig. 1 is employed for interleaving the bits x_a before their XOR-based implantation into the EL x_b .
- 3) Similar to the encoding process of EL B, the bit sequence of the EL x_c will be encoded into the check bits $x_{ac}^i = x_a^i \oplus x_c^i$ and the parity bits $x_{c,p}$.

Finally, the binary sequences x_a , $x_{a,p}$, x_{ab} , $x_{a,p}$, x_{ac} and $x_{c,p}$ are output as the resultant bits of the IL-turbo encoder. Following the IL-turbo encoding procedure, the output bits are modulated by the quadrature phase-shift keying (QPSK) modulator and then transmitted over the LSSTC transmitter scheme of Fig. 1.

B. Receiver Model

At the receiver of Fig. 1, LSSTC detection is performed, which generates the relevant input for the QPSK demodulator. Then the QPSK demodulator generates the log-likelihood ratios (LLR), containing the soft information y_a , y_{ab} , y_{ac} , $y_{a,p}$, $y_{b,p}$ and $y_{c,p}$, for the A, B and C partitions, respectively.

Below, we briefly introduce the IL decoding process using BL A and EL B, while the decoding process of BL A and EL C is similar [13]. In each iteration, the IL-turbo decoder A of Fig. 1 will firstly decode the BL A using the input y_a and $y_{a,p}$. Then a typical cyclic redundancy check (CRC) is employed to detect whether the estimated bits $\hat{x}_a$ of BL A are error-free or not, which results in the following two decoding processes.

- 1) When the estimated bits $\hat{x}_a$ are error-free, the hard-bits $\hat{x}_a$ are converted to infinite LLRs, which will be subjected to the process "VND2-VND3-CND2-VND4" [13]. Then the LLRs $L_a(x_b)$ of EL B may be generated. Afterwards, the turbo decoder B of Fig. 1 decodes the EL B. Finally, the bits $\hat{x}_b$ will be estimated from the output of VND4 of Fig. 1.

- 2) When the estimated bits $\hat{x}_a$ are corrupted, the LLRs $L_e(x_a)$ of the BL will be input to the process "VND2-VND3-CND2-VND4" [13] for generating the LLRs $L_a(x_b)$ for the EL B. Afterwards, the turbo decoder B of Fig. 1 decodes the EL B. Finally, the process "VND4-CND2-VND3-VND2" will feed back the improved LLRs $L_a(x_a)$ to turbo decoder A, which terminates the current iteration. In the next iteration, turbo decoder A will use the improved $L_a(x_a)$ as a-priori information for obtaining an enhanced decoder output.

The iterative decoding process may be terminated, when the BL A is successfully recovered or the affordable complexity has been reached.

III. EXIT CHART ANALYSIS

Parameters	Value	Parameters	Value
FEC	turbo-[111, 101]	Number of Tx antennas	4
Modulation	QPSK	Elements Per AA	4
Channel	Narrowband Rayleigh Fading Channel	Number of Rx antennas	4
		Overall Coding Rate	1/2

TABLE I: Parameters employed in our systems, where "AA" indicates antenna array.

Error Protection Arrangements	Code Rates		
	L_0	L_1	Average
EEP	0.5	0.5	0.5
UEP1	0.54	0.46	0.5
UEP2	0.47	0.53	0.5

TABLE II: Coding rates of turbo codec error protection arrangements for the BL L_0 and the EL L_1 . The code-rates were adjusted by variable-rate puncturers.

In this section, we analyze our proposed system using EXIT charts. For the sake of simplifying the analysis, we assume that there are two layers: a BL L_0 and an EL L_1 . Furthermore, we employed a 1/3 rate turbo codec consisting of two identical RSC codec with the generator of [111, 101]. The system parameters used in our simulations are summarized in Table I. In the following analysis, where two layers are considered, the BL L_0 is protected by the IL-turbo codec. Hence, we consider the convergence behavior of the BL. For the sake of analyzing our IL-turbo codec, different error protection arrangements were considered, as shown in Table II, where EEP stands for equal error protection and UEP is unequal error protection.

Fig. 2: Comparison of the upper RSC and lower RSC EXIT curves at $E_b/N_0 = -8.5$ dB for all error protection arrangements of Table II.

Fig. 3: Trajectory comparison of the upper RSC and lower RSC EXIT curves at $E_b/N_0 = -8.5$ dB for the systems employing EEP.

In Fig. 2, we plot the EXIT chart for the turbo coded system using the coding arrangements of Table II, where the Lower-UEP1-IL for example characterizes the lower RSC decoder of the IL-turbo-LSSTC system utilizing the UEP1 arrangement of Table II. Observe from Table II, the error correction capability of the BL L_0 increases in the order of UEP1, EEP and UEP2, while the width of the open EXIT tunnel increases in the same order, as observed from Fig. 2. Observe in Fig. 2 that at $E_b/N_0 = -8.5$ dB, the IL-turbo coded system has a wider open EXIT tunnel than the system dispensing with the IL-turbo. More explicitly, if we consider the UEP2 aided system, then it is clear from Fig. 2 that the IL-turbo coded system has a wider open EXIT tunnel. In other words, the IL-turbo coded system requires a lower E_b/N_0 than its counterpart dispensing with IL-turbo in order to attain an open tunnel. This implies that the IL-turbo system is capable of attaining a better BER performance for the BL than its counterpart dispensing with IL-turbo coding. The reason for attaining a wider EXIT tunnel by our proposed scheme is due to the fact that extra MI is fed back to the BL from the EL.

An EXIT trajectory comparison of the EEP-turbo-LSSTC system and of the EEP-IL-turbo-LSSTC system is displayed in Fig. 3, which is based on Monte-Carlo simulations. Observe from Fig. 3 that the EEP-IL-turbo-LSSTC system has a wider open tunnel than the EEP-turbo-LSSTC system, as discussed in the previous paragraph. The stair-case-shaped decoding trajectory of the EEP-IL-turbo-LSSTC system reaches the point (0.93, 0.93), while that of the EEP-turbo-LSSTC system is curtailed around (0.83, 0.83) point. Hence our proposed system has a better convergence behavior than the EEP technique, which results in a better BER performance [15]. Observe in Fig. 3 that, although there is an open EXIT tunnel between

	Football	Foreman
Representation	YUV 4:2:0	YUV 4:2:0
Format	CIF	CIF
Bits Per Pixel	8	8
FPS	15	30
Number of Frames	30	30
Video Codec	H.264 PM	H.264 PM
Bitrate	1522 kbps	655 kbps
Error-Free PSNR	37.6 dB	38.4 dB

TABLE III: The parameters of the video sequences employed.

the curves “Lower-EEP” and “Upper-EEP”, the trajectory fails to converge to the (1, 1) point of perfect convergence to a vanishingly low BER due to the fact that we employ short interleavers. The length of the interleaver is constrained in real-time video streaming application for the sake of delay control. Therefore, it can be inferred from Figs. 2 and 3 that employing the IL-turbo coding results in a better BER performance, which is demonstrated by the wider open EXIT tunnel shown in Figs. 2 and 3.

IV. PERFORMANCE STUDY

This section benchmarks our proposed IL-turbo-LSSTC system against the UEP aided turbo-LSSTC system. The JM H.264 reference software configured in its partitioning mode (PM) is employed for encoding two 30-frame video clips, namely the Foreman and Football sequences, which are represented in their (352 × 288)-pixel common intermediate format (CIF), 4:2:0 YUV mode and are scanned at 30 and 15 frame per second (FPS), respectively. Moreover, both of the video sequences were encoded into an intra-coded (I) frame, followed by 29 predicted (P) frames, where the bi-directionally predicted (B) frame was disabled for the sake of preventing any error propagation and for avoiding the associated delay. All the above configurations result in a bitrate of 655/1522 kbps and in an error-free PSNR of 38.4/37.6 dB for the Football/Foreman sequence. The above configurations are listed in Table III, while the remaining system parameters are included in Table I.

The H.264-PM compressed video was encoded and transmitted on a network abstraction layer unit (NALU) [5] basis, which is the smallest element to be interpreted by the video decoder. Furthermore, each NALU may be protected by a CRC code, which must be discarded by the video decoder if errors are detected at the receiver. All experiments were repeated 100 times for the sake of generating statistically reliable curves.

Our error-protection arrangements are presented in Section IV-A. Then we will characterize both the attainable BER versus E_b/N_0 performance and the PSNR versus E_b/N_0 performance in Section IV-B. Finally, in Section IV-C the system’s complexity will be quantified in terms of the number of decoding operations executed.

A. Error Protection Arrangements

Error Protection Arrangements	Code Rates			
	Type A	Type B	Type C	Average
EEP	0.5/0.5	0.5/0.5	0.5/0.5	0.5/0.5
UEP1	0.35/0.40	0.57/0.65	0.57/0.65	0.5/0.5
UEP2	0.45/0.55	0.52/0.46	0.52/0.46	0.5/0.5
UEP3	0.65/0.60	0.47/0.43	0.47/0.43	0.5/0.5
UEP4	0.75/0.70	0.45/0.39	0.45/0.39	0.5/0.5

TABLE IV: Coding rates of different error protection arrangements for the Football/Foreman sequence. The code-rates were adjusted by variable-rate puncturers.

For all the arrangements, an overall coding rate of 1/2 was chosen. Let us assume that the A, B and C partitions carry N_a , N_b and N_c bits and have coding rates of r_a , r_b and r_c , respectively. Then the following constraint must apply for the sake of guaranteeing the

Fig. 4: BER, PSNR and complexity versus E_b/N_0 performance for *Football* and *Foreman* sequences, where the systems used all the parameters of Table IV for transmission over uncorrelated Rayleigh channels.

overall coding rate:

$$2 \times (N_a + N_b + N_c) = \frac{N_a}{r_a} + \frac{N_b}{r_b} + \frac{N_c}{r_c}. \quad (1)$$

The B and C partitions may be treated as equally important ELs [6], since they are independent of each other. Hence we have $r_b = r_c$ in all the error protection arrangements. More specifically, given r_a then the value $r_b = r_c$ is calculated as follows:

$$r_b = \frac{N_b + N_c}{2 \times (N_a + N_b + N_c) - \frac{N_a}{r_a}}. \quad (2)$$

Based on the above discussions, the error protection schemes tested for the *Football* and *Foreman* sequences are listed in Table IV, where variable-rate puncturers were employed for achieving a specific coding rate.

B. System Performance

In this section, we benchmark our proposed system using a turbo codec, which consists of two identical RSC codec relying on the generator polynomials of $G = [111, 101]$. Furthermore, all the FEC arrangements of Section IV-A will be utilized.

Firstly, we present the BER versus E_b/N_0 performance employing the turbo codec for the *Football* sequence, noting that similar trends were observed for the *Foreman* sequence. The BER versus E_b/N_0 curves for the A partition are displayed in Fig. 4a, comparing the performance of the different schemes of Table IV. Observe in Fig. 4a that the IL-turbo scheme achieved a reduced BER compared to the benchmarkers. Specifically, the EEP-IL-turbo-LSSTC scheme

outperforms the EEP-turbo-LSSTC benchmarker by about 2 dB at a BER of 10^{-5} . Furthermore, among all the error protection arrangements, the UEP1-turbo-LSSTC scheme achieves the best BER performance due to the high error protection assigned to the A partition. Hence, we may conclude that the UEP aided IL-turbo scheme is capable of providing an improved system performance compared to the traditional UEP aided turbo codec.

The BER versus E_b/N_0 performance of the type B partition for the *Football* sequence is presented in Fig. 4b, noting that similar trends were observed also for the C partition. Observe in Fig. 4b that the performance of the schemes using the IL-turbo arrangements is worse than that of their benchmarkers. This is due to the fact that more errors may be introduced into the type B partition, when the A partition cannot be correctly decoded. Note however that extra bit errors are introduced only if the A partition is corrupted and in this scenario the B partition must be dropped in the traditional UEP aided turbo-LSSTC schemes. Hence the error propagation to the B partition does not degrade the performance further.

The PSNR versus E_b/N_0 performance recorded for the *Football* sequence is shown in Fig. 4c, where the UEP2-turbo-LSSTC scheme is seen to achieve the best performance amongst the systems not employing IL coding, albeit it has a limited gain compared to the EEP-turbo-LSSTC system. The reason for this trend is that the A partition predominantly carries the video header information and fails to assist the H.264 decoder to conceal the residual errors, when the B and C partitions are corrupted. On the other hand, the systems using our proposed IL-turbo-LSSTC model outperform their corresponding benchmarkers. Specifically, the UEP3-IL-turbo-LSSTC is the best

protection arrangement among all IL-turbo schemes, which achieves a power reduction of 1.1 dB compared to the UEP2-turbo-LSSTC scheme at a PSNR of 36 dB. Alternatively, about 3 dB of PSNR video quality improvement may be observed in Fig. 4c at a channel SNR of -5.5 dB.

For providing further insights for video scenes exhibiting different motion-activity, the PSNR versus E_b/N_0 performance of the IL-turbo-LSSTC model is presented in Fig. 4d using the Foreman sequence, when using the protection arrangements of Table IV. Similar to the Football sequence, the traditional UEP technique can hardly benefit from assigning different protections to the different layers. By contrast, about 1.1 dB of power reduction is achieved by the UEP2-IL-turbo-LSSTC arrangement over the EEP-turbo-LSSTC scheme at a PSNR of 37 dB. Alternatively, about 2 dB of PSNR video quality improvement may be observed at a channel SNR of -6 dB. A subjective comparison of the EEP-IL-turbo-LSSTC and EEP-turbo-LSSTC arrangements is presented in Fig. 5, where frames of both Football and Foreman sequences are given.

Fig. 5: Video comparison at $E_b/N_0 = -6$ dB for the Football sequence and Foreman sequence. The three columns (left to right) indicate the original frames, the EEP-turbo-LSSTC decoded frames, the EEP-IL-turbo-LSSTC decoded frames, respectively.

C. Complexity Analysis

We benchmark the complexity of our IL-turbo-LSSTC scheme in Fig. 4e using the Football sequence. Note that if the BL A is corrupted, the decoding of the ELs B and C is unnecessary, since they would be discarded by the H.264-PM decoder. Therefore, the complexity of benchmarking systems is proportional to the E_b/N_0 value. Again, in the simulations each NALU was encoded into a single packet by the turbo code. Since the turbo decoding operation dominates the computational cost, it was used as the basis of comparing the system's complexity. The y-axis of Fig. 4e indicates the average number of turbo decoding operations¹ per NALU, which was averaged over 2221 NALUs of the H.264-PM encoded Football bitstream.

Observe from Fig. 4e that each complexity curve of the IL-turbo-LSSTC schemes has a peak value, which distinguishes the trends of the complexity upon increasing the E_b/N_0 . For example, the complexity of the UEP3-IL-turbo-LSSTC scheme peaks at E_b/N_0 of -7.5 dB, where the IL decoding technique was activated for correcting the A partition when it cannot be correctly decoded without IL decoding. Furthermore, the complexity of the turbo-LSSTC schemes increases upon increasing the E_b/N_0 due to the fact that the decoding of the ELs B and C was disabled when the BL A was corrupted. Since low E_b/N_0 values results in high video distortion, here we focus on higher E_b/N_0 values. Observe from Fig. 4e that the UEP3-IL-turbo-LSSTC scheme achieves an E_b/N_0 gain of 1.1 dB by imposing about 13% higher complexity compared to the UEP2-turbo-LSSTC scheme

¹The turbo decoder may decode each packet more than once, where each time of the turbo decoding is referred to as one turbo decoding operation.

at a video quality of 36 dB. Viewed from a different perspective, the UEP3-IL-turbo-LSSTC scheme has a PSNR gain of 3 dB at the cost of a 13% complexity increase compared to the UEP2-turbo-LSSTC scheme at an E_b/N_0 of -5.5 dB.

V. CONCLUSIONS

An IL-turbo coded layered video streaming scheme conceived with multi-functional MIMOs was proposed, where the partitioned H.264/AVC video coding mode was employed and the information of the BL was implanted into the information of the ELs by an XOR operation. At the receiver, our IL-turbo decoding technique of Fig. 1 was invoked for the sake of improving the attainable system performance. The system advocated was analyzed using EXIT charts for providing insights into the gain attained using our IL-turbo coding scheme. Our experiments demonstrated that the proposed system substantially outperforms the traditional UEP turbo systems.

In our future work, we will incorporate the IL-turbo scheme into multiview video coding. Moreover, we will also carry out further investigations for optimizing the IL-turbo coded system performance.

REFERENCES

- [1] T. Zhang and Y. Xu, "Unequal packet loss protection for layered video transmission," *IEEE Transactions on Broadcasting*, vol. 45, pp. 243–252, June 1999.
- [2] L. Hanzo, P. Cherriman, and J. Streit, *Video Compression and Communications: From Basics to H.261, H.263, H.264, MPEG2, MPEG4 for DVB and HSDPA-Style Adaptive Turbo-Transceivers*. New York: John Wiley, 2007.
- [3] H. Imaizumi and A. Luthra, *Three-Dimensional Television, Video and Display Technologies*, ch. MPEG-2 Multiview Profile, pp. 169–181. Berlin, Heidelberg, and New York: Springer Verlag, 2002.
- [4] H. Schwarz, D. Marpe, and T. Wiegand, "Overview of the scalable video coding extension of the H.264/AVC standard," *IEEE Transactions on Circuits and Systems for Video Technology*, vol. 17, pp. 1103–1120, September 2007.
- [5] Joint Video Team (JVT) of ISO/IEC MPEG and ITU-T VCEG, *ITU-T Rec. H.264/ISO/IEC 14496-10 AVC: Advanced Video Coding for Generic Audiovisual Services*, March 2010.
- [6] S. Wenger, "H.264/AVC over IP," *IEEE Transactions on Circuits and Systems for Video Technology*, vol. 13, pp. 645–656, July 2003.
- [7] B. Masnick and J. Wolf, "On linear unequal error protection codes," *IEEE Transactions on Information Theory*, vol. 13, pp. 600–607, October 1967.
- [8] N. Rahnavard and F. Fekri, "New results on unequal error protection using LDPC codes," *IEEE Communications Letters*, vol. 10, pp. 43–45, January 2006.
- [9] Nasruminallah, M. El-Hajjar, N. Othman, A. Quang, and L. Hanzo, "Over-complete mapping aided, soft-bit assisted iterative unequal error protection H.264 joint source and channel decoding," *IEEE 68th Vehicular Technology Conference, VTC 2008-Fall*, pp. 1–5, September 2008.
- [10] M. Aydinlik and M. Salehi, "Turbo coded modulation for unequal error protection," *IEEE Transactions on Communications*, vol. 56, pp. 555–564, April 2008.
- [11] E. Maani and A. Katsaggelos, "Unequal error protection for robust streaming of scalable video over packet lossy networks," *IEEE Transactions on Circuits and Systems for Video Technology*, vol. 20, pp. 407–416, March 2010.
- [12] C. Hellge, D. Gomez-Barquero, T. Schierl, and T. Wiegand, "Layer-aware forward error correction for mobile broadcast of layered media," *IEEE Transactions on Multimedia*, vol. 13, pp. 551–562, June 2011.
- [13] Y. Huo, M. El-Hajjar, and L. Hanzo, "Inter-layer FEC aided unequal error protection for multi-layer video transmission in mobile TV," *IEEE Transactions on Circuits and Systems for Video Technology*, early access, 2013.
- [14] C. Berrou, A. Glavieux, and P. Thitimajshima, "Near Shannon limit error-correcting coding and decoding: Turbo codes," in *Proceedings of the International Conference on Communications*, (Geneva, Switzerland), pp. 1064–1070, May 1993.
- [15] L. Hanzo, O. Alamri, M. El-Hajjar, and N. Wu, *Near-Capacity Multi-Functional MIMO Systems: Sphere-Packing, Iterative Detection and Cooperation*. John Wiley & Sons, IEEE press, 2009.
- [16] S. ten Brink, "Convergence behavior of iteratively decoded parallel concatenated codes," *IEEE Transactions on Communications*, vol. 49, pp. 1727–1737, October 2001.