Hybrid ARQ with Incremental Redundant Index Assignments for Iterative Source-Channel Decoding

Thorsten Clevorn
Design Center NRW
Infineon Technologies AG
Duisburg, Germany
thorsten.clevorn@infineon.com

Laurent Schmalen, Peter Vary
Inst. of Comm. Systems and Data Processing
RWTH Aachen University
Aachen, Germany
{schmalen,vary}@ind.rwth-aachen.de

Marc Adrat
FKIE Communication Systems
Fraunhofer-Gesellschaft
Wachtberg, Germany
marc.adrat@fkie.fraunhofer.de

***Abstract*—Iterative source-channel decoding (ISCD) exploits the residual redundancy of source codec parameters by using the Turbo principle. In this paper we extend the excellent capabilities of ISCD to a hybrid automatic repeat request (HARQ) scheme by novel incremental redundant index assignments. The incremental redundancy for HARQ is supplied by the source encoder and not the channel encoder. Simulation results show an excellent performance over a wide range of channel conditions, with inherently adapted bandwidth and complexity.**

***Index Terms*—ISCD, Redundant Index Assignment, HARQ, Incremental Redundancy**

I. Introduction

In communications the transmission of information from a transmitter to a receiver is usually affected by distortions such as noise and interference. This can result in errors at the receiver. A common technique to increase the robustness of the transmission is the hybrid automatic repeat request (HARQ) [1, 2] protocol, which is, e.g., part of the high-speed packet access (HSPA) extension of UMTS for downlink (HSDPA) and uplink (HSUPA) [3]. With HARQ, the receiver checks, e.g., by a cyclic redundancy check (CRC), if a packet was received correctly. Upon detection of an error, a retransmission is requested. If the retransmission contains (artificial) redundancy differing from the original transmission, e.g., other parity bits of a rate-compatible punctured convolutional (RCPC) code [4], this is called incremental redundancy [1, 5].

HARQ can be applied to the transmission of source encoded data such as speech, audio, or video. For example, speech transmission via HSDPA and HSUPA is investigated in [6]. The task of source encoding is to remove natural source redundancy. However, the source encoded data such as scale factors or predictor coefficients for speech, audio, and video signals usually contains a considerable amount of residual (natural) redundancy due to imperfect source encoding resulting, e.g., from delay constraints [7].

With iterative source-channel decoding (ISCD), e.g., [8–10], this residual redundancy can be exploited by a Turbo process. ISCD is an extension of the Turbo principle for channel decoding, which made channel decoding close to the Shannon limit with moderate computational complexity possible. ISCD utilizes the a priori knowledge on the residual redundancy, e.g., non-uniform probability distribution or auto-correlation, for error concealment by a derivative of a soft decision source decoder (SDSD) [7, 11] and exchanges extrinsic reliabilities with a channel decoder.

In this contribution we combine the capabilities of HARQ with incremental redundancy and ISCD to a new powerful transmission scheme. In contrast to most known HARQ schemes, the incremental redundancy is not generated by the channel code, e.g., an RCPC code [4]. Instead, we extend the concept of redundant index assignments (RIA) for ISCD [12–14] to novel incremental redundant index assignments (IRIA), i.e., the incremental redundancy is generated directly in the source encoder and exploited by the SDSD. The channel code remains unmodified and is identical for all (re)transmissions. A rate $r = 1$ convolutional code is used for (inner) channel coding, as for a capacity-achieving serially concatenated system the inner code should be of rate $r \geq 1$ [15]. This last constraint is difficult to fulfill by varying channel codes, e.g., RCPC codes. With the proposed HARQ-ISCD, the Turbo principle based ISCD is automatically adapted to the current channel conditions by the retransmissions, yielding an excellent performance over a wide range of channel conditions. Also the computational complexity adjusts automatically.

This paper is organized as follows. In Section II-A the basic principles of ISCD are briefly reviewed. Next, in Section II-B the novel extension of ISCD to HARQ by incremental redundant index assignments is presented. The capabilities of HARQ extended ISCD are demonstrated by a simulation example in Section III. Finally, Section IV concludes the paper.

II. The Hybrid ARQ ISCD System Model

In Fig. 1 the baseband model of the proposed HARQ extension for iterative source-channel decoding is depicted. At first, we will describe the basic ISCD system[1]. In a second step the new HARQ scheme will be detailed.

[1]We will describe ISCD for source codecs with fixed-length coding (FLC). In the literature the term ISCD can be also found in the area of variable-length codes(VLC). However, it has already be shown in [13] that (for a given trade-off between coding efficiency and error robustness) a less complex system can be designed when using FLC.

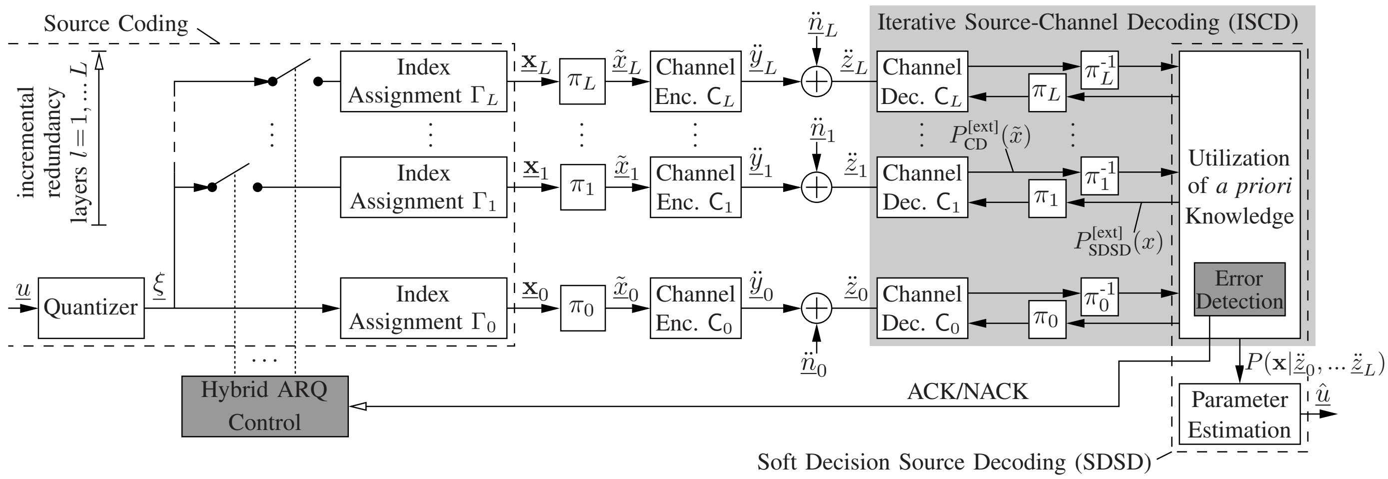

Fig. 1. Baseband model of proposed scheme with iterative source-channel decoding (ISCD) and Hybrid ARQ (HARQ).

A. Iterative Source-Channel Decoding (ISCD)

The basic ISCD system corresponds to the bottom path (Layer $l=0$) in Fig. 1. At time instant τ, a source encoder determines a frame $\underline{u}_\tau$ consisting of K_S source codec parameters $u_{\kappa,\tau}$ with $\kappa=1,\dots K_S$ denoting the position in the frame. The single elements $u_{\kappa,\tau}$ of $\underline{u}_\tau$ are assumed to be statistically independent from each other. By Q_κ-level scalar quantization each value $u_{\kappa,\tau}$ is individually mapped to a quantizer reproduction level $\bar{u}_\kappa^{(\xi_\kappa)}$ with index $\xi_\kappa=0,\dots Q_\kappa-1$. A unique bit pattern $\mathbf{x}_{\kappa,\tau}$ of $M_\kappa^\star \geq \lceil \log_2 Q_\kappa \rceil \doteq M_\kappa$ bits is assigned according to the index assignment (IA) Γ_κ, $\mathbf{x}_{\kappa,\tau}=\Gamma_\kappa(\xi_\kappa)$. The frame of K_S bit patterns is denoted by $\underline{\mathbf{x}}_\tau$. For simplicity, we assume an identical quantization and index assignment for all K_S source codec parameters $u_{\kappa,\tau}$, i.e., $Q_\kappa=Q$, $M_\kappa^\star=M^\star$, $\Gamma_\kappa=\Gamma$.

In the beginning, classic index assignments with $M^\star=\lceil \log_2 Q\rceil=M$ had been employed (see e.g., [7–9]). Later on, the concept of redundant index assignments (RIA) with $M^\star>\lceil \log_2 Q\rceil=M$ was proposed [10, 12, 14] to obtain performance improvements. The decreased resulting overall rate $r_\Gamma = M/M^\star < 1$ of the redundant index assignment is usually compensated by increasing the rate r_{C} of the applied channel code up to $r_{\mathsf{C}} = 1$. This matches with the findings in [15] that the inner code of a capacity-achieving serially concatenated system should be of rate $r \geq 1$.

The index assignment $\Gamma : \xi \mapsto \mathbf{x}$ can be considered as a (potentially non-linear) block code with the M-bit binary representation of the quantizer level index $\{\xi\}_2$, $\xi=0,\dots Q-1$, as input. The output is the $M^\star$-bit pattern $\mathbf{x}$. In case of an index assignment by a linear block code with a $M\times M^\star$ generator matrix $\mathbf{G}$ we get [12]

$$\mathbf{x} = \Gamma(\xi) = (\{\xi\}_2)\cdot \mathbf{G} \quad . \tag{1}$$

For example, if $M = 4$, $M^\star = 5$, and an even single parity check (SPC) code with

$$\mathbf{G}=\begin{pmatrix}1&0&0&0&1\\0&1&0&0&1\\0&0&1&0&1\\0&0&0&1&1\end{pmatrix} \qquad \begin{matrix}\text{corresponding index assignment}\\ \Gamma \mathrel{\hat{=}} \mathrm{SPC}_{M^\star=5}^{Q=16}\end{matrix} \tag{2}$$

is chosen, we get for $\xi=3$

$$\mathbf{x} = \Gamma(3) = (\{3\}_2)\cdot \mathbf{G} = (0011)\cdot \mathbf{G} = 00110 \quad . \tag{3}$$

Applications of this concept to non-iterative joint source-channel coding schemes can be found in [16, 17].

The bit interleaver π scrambles the incoming frame $\underline{\mathbf{x}}_\tau$ of data bits to $\tilde{\underline{x}}_\tau$ in a deterministic manner. Note that after interleaving there is usually no bit pattern structure anymore in the bits of a frame. Therefore, we do not use a bold face letter for $\tilde{\underline{x}}_\tau$. We restrict the interleaving to a single time frame with index τ and omit the time frame index τ in the following where appropriate. Furthermore, we also omit the layer index l (see Fig. 1) when possible. In general, all layers resemble basically similar ISCD systems.

For channel encoding C of $\tilde{\underline{x}}$ we can use, e.g., a standard terminated *recursive non-systematic convolutional* (RNSC) code of constraint length $J+1$ and rate r_{C}. The resulting codeword is mapped to a frame $\ddot{\underline{y}}$ of bipolar bits $\ddot{y}\in\{\pm 1\}$, e.g., for BPSK transmission with symbol energy $E_s=1$.

For simplicity and reproducibility additive white Gaussian noise (AWGN) $\ddot{\underline{n}}$ with a known power spectral density of $\sigma_n^2=N_0/2$ is applied as channel distortion, i.e., $\ddot{\underline{z}}=\ddot{\underline{y}}+\ddot{\underline{n}}$.

The received frames $\ddot{\underline{z}}$ are evaluated in a Turbo process, which exchanges *extrinsic* reliabilities between the channel decoder (CD) and the *soft decision source decoder* (SDSD). Such reliability information can either be evaluated in terms of probabilities $P(\cdot)$ or as *log-likelihood* ratios (L-values) $L(\cdot)$. The ISCD receiver is described in detail, e.g., in [8–10]. For convolutional codes the equations for the *extrinsic* reliabilities are well known. The SDSD determines *extrinsic* information mainly from the natural residual source redundancy which remains in the bit patterns $\mathbf{x}_{\kappa,\tau}$ after source encoding. Such residual redundancy appears on *parameter-level*, e.g., in terms of a non-uniform distribution $P(\mathbf{x}_\kappa)$, in terms of correlation, or in any other possible mutual dependency in time τ. The algorithm how to compute the *extrinsic* $P_{\mathrm{SDSD}}^{[\mathrm{ext}]}(x)$ has been detailed, e.g., in [8–10]. It may be interpreted as a modification of the well-known BCJR algorithm [18], operating on a fully developed trellis diagram. After the last iteration a soft estimate $\hat{u}$ is computed for each parameter in a frame based on the Q probabilities $P(\mathbf{x}|\underline{\ddot{z}}_0)$ of the possible bit patterns and the residual redundancy. The minimum mean squared error (MMSE) serves as fidelity criterion of the parameter estimation [7, 11].

Note that an ISCD scheme exploiting inter-frame correlation has been described. The adaptation to intra-frame correlation is straightforward by exchanging the position indices κ with time indices τ, see e.g. [10].

B. Hybrid ARQ extension of ISCD

For a redundant index assignment with $M^\star > M$ only 2^M out of the $2^{M^\star}$ possible bit patterns $\mathbf{x}$ are valid. Thus, it can be checked in each iteration if a valid bit pattern $\mathbf{x}$ is found. If a linear block code with a generator matrix $\mathbf{G}$ is used for a redundant index assignment according to (1), the corresponding parity check matrix $\mathbf{H}$ can be used to perform the check on each bit pattern $\mathbf{x}$. On the one hand this concept can be used as a stopping criterion for the iterations, i.e., the iterative process is terminated if all bit patterns $\mathbf{x}$ of a frame $\underline{\mathbf{x}}$ are valid [19]. On the other hand, if a feedback channel is available, we can inform the transmitter if the iterative process was successful, i.e., the receiver could obtain a frame $\underline{\mathbf{x}}$ with valid bit patterns $\mathbf{x}$ at all. This latter fact allows for the proposed HARQ extension of ISCD.

The baseband model of this novel HARQ extension for ISCD is depicted in Fig. 1. An error detection unit is added to the SDSD in the receiver to perform the checks on the decoded bit patterns $\mathbf{x}$. This unit acknowledges the successful reception of a frame $\underline{\mathbf{x}}$ by sending an acknowledge (ACK) via the feedback channel to the new HARQ controller in the transmitter. In case the receiver was not able to obtain a completely valid $\underline{\mathbf{x}}$ after its configured maximum number of iterations, it sends a not-acknowledge (NACK) to the transmitter. Another copy of the frame $\underline{\mathbf{x}}$ could now be transmitted. We propose the usage of the incremental redundancy concept, e.g., [1, 5], which is successfully used, e.g., for HSDPA and HSUPA in UMTS [3]. In the retransmission(s) different redundancy versions of the original data are transmitted to increase the diversity of the redundancy available in the decoding process.

The initial transmission, denoted as (redundancy) layer $l = 0$, can be found in the bottom path in Fig. 1. This is the known ISCD scheme. The retransmissions will be the layers $l = 1, \dots L$, with L being the maximum number of retransmissions. If the HARQ control unit receives a NACK for a frame it will activate and transmit the next higher not yet transmitted layer. Each layer l has an individual index assignment Γ_l with potentially different $M_l^\star$, an interleaver π_l of the required size, and a (again potentially different) channel code C_l. Similar to layer $l = 0$, AWGN $\underline{\ddot{n}}_l$ is applied to all layers $l = 1, \dots L$. All $\underline{\ddot{n}}_l$ shall have the same $\sigma_n^2 = N_0/2$ for simplicity. At the receiver, for each layer the corresponding channel decoder and (de)interleaver are instantiated. However, only a single SDSD is required for all layers because the trellis states of the SDSD correspond to the quantized parameters $\bar{u}$, which are common for all layers. Thus, the complexity of the SDSD does not increase significantly as the number of trellis states does not change. Each layer just provides different additional, i.e., redundant, information for the state transitions in the trellis. Thus, only the number of the usually much less complex channel decoders increases for the additional higher layers.

If all layers use a generator matrix $\mathbf{G}_l$ for their index assignment Γ_l and so far $\check{L}$ layers have been transmitted, the SDSD is based on a combined index assignment $\Gamma^{\text{HARQ}}_{[0,\check{L}]}$ with a $M \times (M_0^\star + \dots + M_l^\star + \dots + M_{\check{L}}^\star)$ generator matrix

$$\mathbf{G}^{\text{HARQ}}_{[0,\check{L}]} = \left(\mathbf{G}_0 | \cdots | \mathbf{G}_l | \cdots | \mathbf{G}_{\check{L}}\right) \quad . \tag{4}$$

Note that only for the initial layer $l = 0$ the index assignment must be redundant by itself, i.e., $M_0^\star > M$, to facilitate the validity checks of the bit patterns $\mathbf{x}$. For the retransmission layers, $l = 1, \dots L$, also $M_l^\star \leq M$ is possible. $\mathbf{G}^{\text{HARQ}}_{[0,\check{L}]}$ includes all lower layers and is sufficiently large for the validity check, which is using the parity check matrix $\mathbf{H}^{\text{HARQ}}_{[0,\check{L}]}$ of $\mathbf{G}^{\text{HARQ}}_{[0,\check{L}]}$.

Extending the example of (2) with $M = 4$ and the SPC with $M_0^\star = 5$ for layer 0 by 5 layers $l = 1, \dots 5$ with $M_l^\star = 2$ we can obtain, e.g., the following arbitrary overall generator matrix

$$\mathbf{G}^{\text{HARQ}} = \left(\mathbf{G}_0 \; | \mathbf{G}_1 | \mathbf{G}_2 | \mathbf{G}_3 | \mathbf{G}_4 | \mathbf{G}_5 \right) \tag{5}$$

$$= \left(\begin{array}{ccccc|cc|cc|cc|cc|cc} 1&0&0&0&1&1&1&1&0&1&1&1&0&0&0 \\ 0&1&0&0&1&1&1&0&1&1&0&0&1&1&0 \\ 0&0&1&0&1&1&0&1&1&0&1&0&1&0&1 \\ 0&0&0&1&1&0&1&1&1&0&0&1&0&1&1 \end{array}\right) \quad . \tag{6}$$

Thus, initially 5 bits are transmitted. In each of the up to 5 retransmissions 2 bits are transmitted on request by a NACK from the receiver. The bits to be transmitted in layer l are determined in analogy to (1) by

$$\mathbf{x}_l = \Gamma_l(\xi) = (\{\xi\}_2) \cdot \mathbf{G}_l \quad . \tag{7}$$

Each retransmission yields at the receiver an additional, i.e., incremental, set of redundancy. Consequently, we denote redundant index assignments like the Γ^{HARQ} of $\mathbf{G}^{\text{HARQ}}$ in (6) as incremental redundant index assignments (IRIA). Note, the bit patterns $\mathbf{x}_l$ and the $\underline{\ddot{y}}_l$ of the retransmission can be generated on demand, if the layer l is activated.

The single channel decoders C_l and (de-)interleavers π_l at the receiver are only active if the corresponding $\underline{\ddot{z}}_l$ has been received, i.e., a retransmission of the respective layer l was requested. Otherwise, depending on the implementation of the SDSD the inactive layers, e.g., are simply excluded from the SDSD processing or the corresponding $P^{[\text{ext}]}_{\text{CD}}(\tilde{x})$ are set as equiprobable, $P^{[\text{ext}]}_{\text{CD}}(\tilde{x}=0) = P^{[\text{ext}]}_{\text{CD}}(\tilde{x}=1) = 0.5$. The separation of the channel decoders C_l and (de-)interleavers π_l of the different layers is not disruptive for the Turbo process. The common SDSD which connects all layers facilitates the exchange of extrinsic information between the active layers. Only one Turbo component, decoder or (de-)interleaver, must work on all bits to enable the extrinsic information exchange. For example, in [12] numerous small codes are connected by a single large interleaver.

III. Simulation Results

The capabilities of the proposed novel HARQ scheme for ISCD with incremental redundant index assignments shall be demonstrated by simulation. Similar settings as in, e.g., [10, 12] are used.

At the transmitter $K_S = 250$ statistically independent parameters $u_{\kappa,\tau}$ per frame $\underline{u}_\tau$ are modeled by independent first order Gauss-Markov processes with $\sigma_u^2 = 1$ and auto-correlation $\rho = 0.9$, yielding an inter-frame correlation between frames $\underline{u}_\tau$ and $\underline{u}_{\tau-1}$. Each $u_{\kappa,\tau}$ is Lloyd-Max quantized to $Q = 16$ levels, i.e., $M = 4$ bits/parameter. As incremental redundant index assignment the Γ^{HARQ} with the generator matrix $\mathbf{G}^{\mathrm{HARQ}}$ of (6) is applied, with a maximum number of retransmissions $L = 5$. The used bandwidth in bits/parameter is $M_0^\star = 5$ for layer $l = 0$ and $M_l^\star = 2$ for layers $l = 1, \ldots 5$. Thus, the size of the random interleavers π_l is 1250 bits for $l = 0$ and 500 bits for $l = 1, \ldots 5$. Channel encoding is performed by identical terminated $r_{\mathsf{C}} = 1$ RNSC codes C_l with generator polynomial $\mathbf{G}^{\mathsf{C}} = (\frac{1}{1+D+D^2+D^3})$.

At the receiver at maximum $\Theta_l = 10$, $l = 0, \ldots L$, iterations are executed per (re)transmission. For example, when $\underline{\ddot{z}}_0$ is received $\Theta_0 = 10$ iterations are performed. Upon reception of $\underline{\ddot{z}}_1$, $\Theta_1 = 10$ are executed using $\underline{\ddot{z}}_0$ and $\underline{\ddot{z}}_1$. When a new retransmission $\underline{\ddot{z}}_l$ is received, the extrinsic information of the previous (re)transmissions is not resetted but reused and further refined. Of course, more complex iteration schemes could be developed, but we restrict the example to this simple one.

Note, for simplicity all control information such as the ACK/NACK on the feedback channel is assumed to be error free. Furthermore, no frames or retransmissions are discarded due to a failed validity check in the receiver even after the last retransmission. All frames are considered in the final parameter estimation and contribute to the parameter SNR between the original parameters u and the estimates $\hat{u}$ measured in the simulations. Also, no timing constraints occurring in duplex or streaming applications are considered.

The upper plot in Fig. 2 depicts the parameter SNR and the lower plot gives the corresponding symbol error rates (SER). The dash-dotted line is a transmission of the initial layer with $\mathbf{G}_0$ and a non-iterative receiver with SDSD. Note that today's systems with hard output channel decoding perform even worse. As further reference, the dashed lines mark the simulation results of a non-HARQ ISCD transmission with $\Theta = 10$ iterations and $\mathbf{G}_{[0,L']} = (\mathbf{G}_0 | \ldots | \mathbf{G}_{L'})$ as generator matrix for the redundant index assignment.

The bold solid lines show the performance of the proposed HARQ scheme with at maximum $L = 5$ or $L = 2$ retransmissions. For $L = 2$ an improvement of $\Delta_{E_s/N_0} \approx 3$ dB can be observed with respect to the also depicted transmission of the initial layer $l = 0$ alone. Thus, with up to $L = 2$ retransmissions a good quality can be achieved at a 3 dB smaller E_s/N_0. With three more retransmissions, i.e., $L = 5$, a further improvement of $\Delta_{E_s/N_0} \approx 1.5$ dB is possible, yielding a total improvement of about $\Delta_{E_s/N_0} \approx 4.5$ dB for $L = 5$.

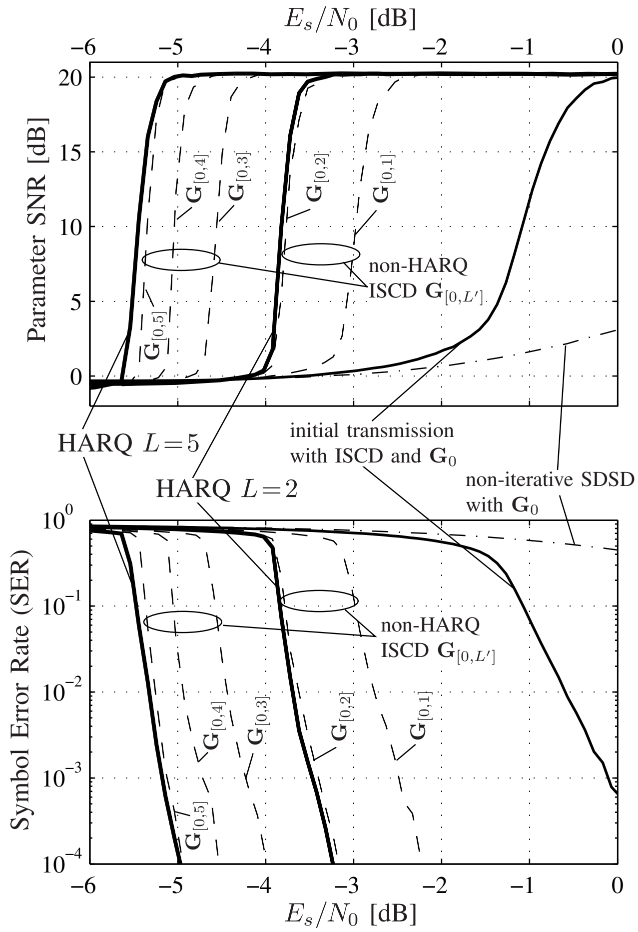

Fig. 2. Parameter SNR and symbol error rate (SER) simulation results.

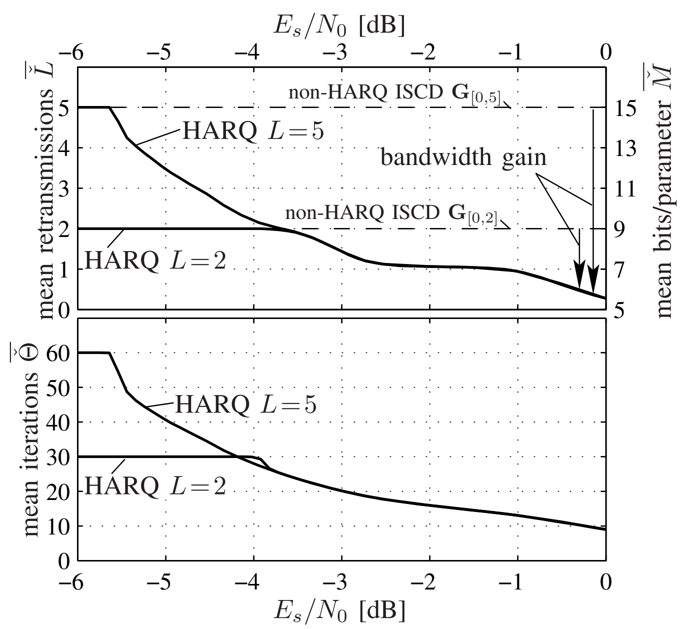

Fig. 3. Statistical analysis of the HARQ-ISCD simulation results in Fig. 2.

Both HARQ results are slightly superior to the respective non-HARQ results with $\mathbf{G}_{[0,5]}$ and $\mathbf{G}_{[0,2]}$. This can be explained by the higher number of effective iterations for the bits of the first (re)transmission layers, whose extrinsic information is improved in $\Theta_l = 10$ iterations after every retransmission. Nevertheless, we can observe that with the HARQ-ISCD scheme we can achieve the same performance as a non-HARQ ISCD scheme of the corresponding maximum index assignment size.

A statistical analysis of the HARQ-ISCD simulation results in Fig. 2 is presented in Fig. 3 and shows the real benefit of HARQ-ISCD.The excellent performance of standard ISCD is achieved by an automatically adapted and usually lower computational complexity and bandwidth usage. $\check{L}_\tau$ shall be the the number of retransmissions necessary for the frame at time instance τ until either the validity check at the receiver is passed or the maximum number of retransmission L is reached. The mean retransmissions $\overline{\check{L}}$ are depicted in the upper plot in Fig. 3. On the right vertical axis the corresponding mean $\overline{\check{M}}$ of the transmitted bits per parameter is shown. It can be observed that the required bandwidth of the HARQ-ISCD schemes adapts very well to the channel conditions.

In the lower plot in Fig. 3 the mean number $\overline{\check{\Theta}}$ of iterations executed for a frame is depicted. After each (re)transmission l, $\check{\Theta}_l$ iterations are executed until the SDSD terminates due to a successful validity check or the maximum number of iterations Θ_l is reached, i.e., $\check{\Theta}_l \leq \Theta_l$. Thus, $\check{\Theta}$ is defined as $\sum_0^{\check{L}} \check{\Theta}_l$. It can be observed, that the behavior of $\overline{\check{\Theta}}$ is quite similar to $\overline{\check{L}}$. Over a wide range of channel conditions the number of executed iterations are relatively low. Only for bad channel conditions the value $\overline{\check{\Theta}}$ increases up to the limit. Thus, the amount of computation adapts nicely to the channel conditions, similar to the required bandwidth discussed before.

IV. Conclusion

We presented a novel combination of HARQ with incremental redundancy and ISCD. Based on new incremental redundant index assignments the incremental redundancy for the retransmission is generated on the fly in the source encoder rather than in the channel encoder. At the receiver an extended SDSD detects erroneous frames and requests retransmission. The SDSD error detection incorporates inherently a stopping criterion for the iterative process. The simulation example demonstrates that the proposed HARQ-ISCD scheme adapts flexibly and automatically to different channel conditions. By retransmissions the maximum parameter SNR can be retained in bad channel conditions, while in good channel conditions only a small bandwidth and few iterations are necessary. Thus, compared to the existing transmission schemes, bandwidth as well as computational demands are used very efficiently.

Acknowledgment

This work was supported in part by the European Union under Grant FP6-2002-IST-C 020023-2 FlexCode and the UMIC research center.

References

[1] S. B. Wicker, *Error Control Systems for Digital Communication and Storage*. Prentice Hall, Englewood Cliffs, NJ, USA, 1995.

[2] R. A. Comroe and J. D. J. Costello, "ARQ Schemes for Data Transmission in Mobile Radio Systems," *IEEE J. Select. Areas Commun.*, vol. 2, pp. 472–481, July 1984.

[3] H. Holma and A. Toskala, *HSDPA/HSUPA for UMTS*. John Wiley & Sons, Ltd., Chichester, UK, 2006.

[4] J. Hagenauer, "Rate-compatible punctured convolutional codes (RCPC codes) and their applications," *IEEE Trans. Comm.*, vol. 36, pp. 389–400, Apr. 1988.

[5] D. M. Mandelbaum, "An Adaptive-Feedback Coding Scheme Using Incremental Redundancy," *IEEE Trans. Inform. Theory*, vol. 20, pp. 388–389, May 1974.

[6] 3GPP, TSG Services and System Aspects, "Packet-switched conversational multimedia applications; performance characterisation of default codecs, Technical Report TR 26.935," 2007.

[7] P. Vary and R. Martin, *Digital Speech Transmission - Enhancement, Coding & Error Concealment*. John Wiley & Sons, Ltd., Chichester, UK, 2006.

[8] M. Adrat, P. Vary, and J. Spittka, "Iterative Source-Channel Decoder Using Extrinsic Information from Softbit-Source Decoding," *IEEE ICASSP*, vol. 4, Salt Lake City, Utah, May 2001, pp. 2653–2656.

[9] N. Görtz, "On the Iterative Approximation of Optimal Joint Source-Channel Decoding," *IEEE J. Select. Areas Commun.*, vol. 19, pp. 1662–1670, Sept. 2001.

[10] R. Martin, U. Heute, and C. Antweiler, *Advances in Digital Speech Transmission*. John Wiley & Sons, Ltd., Chichester, UK, 2008.

[11] T. Fingscheidt and P. Vary, "Softbit Speech Decoding: A New Approach to Error Concealment," *IEEE Trans. Speech Audio Proc.*, vol. 9, pp. 240–251, Mar. 2001.

[12] T. Clevorn, P. Vary, and M. Adrat, "Iterative Source-Channel Decoding using Short Block Codes," *IEEE ICASSP*, vol. 4, Toulouse, France, May 2006, pp. 221–224.

[13] R. Thobaben, "A New Transmitter Concept for Iteratively-Decoded Source-Channel Coding Schemes," *IEEE SPAWC 2007*, Helsinki, Finland, June 2007, pp. 1–5.

[14] A. Q. Pham, L. L. Yang, and L. Hanzo, "Joint Optimization of Iterative Source and Channel Decoding Using Over-Complete Source-Mapping," *IEEE VTC-Fall*, Baltimore, MD, USA, Sept. 2007, pp. 1072–1076.

[15] A. Ashikhmin, G. Kramer, and S. ten Brink, "Extrinsic Information Transfer Functions: Model and Erasure Channel Properties," *IEEE Trans. Inform. Theory*, vol. 50, pp. 2657–2673, Nov. 2004.

[16] T. Fingscheidt, S. Heinen, and P. Vary, "Joint Speech Codec Parameter and Channel Decoding of Parameter Individual Block Codes (PIBC)," *IEEE SCW*, Porvoo, Finland, June 1999, pp. 75–77.

[17] S. Heinen and P. Vary, "Source-Optimized Channel Coding for Digital Transmission Channels," *IEEE Trans. Comm.*, vol. 53, pp. 592–600, May 2005.

[18] L. R. Bahl, J. Cocke, F. Jelinek, and J. Raviv, "Optimal Decoding of Linear Codes for Minimizing Symbol Error Rate," *IEEE Trans. Inform. Theory*, vol. 20, pp. 284–287, Mar. 1974.

[19] L. Schmalen, P. Vary, T. Clevorn, and B. Schotsch, "Efficient Iterative Source-Channel Decoding Using Irregular Index Assignments," *ITG SCC 2008*, Ulm, Germany, Jan. 2008.