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**Description**

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Combining-after-Decoding Turbo Hybrid ARQ by Utilizing Doped-Accumulator

Ade Irawan, Member, IEEE, Khoirul Anwar, Member, IEEE, and Tad Matsumoto, Fellow, IEEE

Abstract—This letter proposes a doped-accumulator assisted packet-combining-after-decoding (ACC-CAD) technique with different doping rates per transmission phases for hybrid automatic repeat request (ARQ). Horizontal iteration (HI) performed for decoding the serially concatenated codes (SCC) is followed by Vertical iteration (VI) to exchange extrinsic log-likelihood ratio (LLR) of the uncoded (systematic) bits, and the HI/VI chain is repeated. The doped-accumulator enables the two extrinsic information transfer (EXIT) curves of the SCC to match very well and the convergence tunnel to open until a point very close to the (1,0,1,0) mutual information point. Excellent performance of our technique is verified through EXIT analysis as well as frame-error-rate (FER) and throughput simulations.

Index Terms—Hybrid ARQ, turbo principle, doped-accumulator.

I. INTRODUCTION

EXCHANGING soft information in an iterative (turbo) fashion for packet combining in automatic repeat request (ARQ) systems has been intensively investigated in the last few years. Reference [1] first introduced the utilization of the Turbo encoder structure in hybrid ARQ (HARQ). The HARQ system forms parallel concatenation of multiple recursive convolutional codes, which is corresponding to multiple transmissions of the same information, if random interleaving is performed in the parallel branches of the encoder. At the receiver side, the packet combining-after-decoding (CAD) is performed to exploit the soft information expressed in the form of a priori log-likelihood ratio (LLR) of the uncoded (systematic) bits obtained in the last transmission for decoding the current transmission. It is shown in [1] that a considerable frame-error-rate (FER) performance gain can be achieved over conventional ARQ without packet combining.

The CAD concept has been adopted in various forms that can be found in the literatures. Reference [2] exploits the structure of [1] with systematic recursive convolutional code as the encoder instead of turbo code. In the technique shown in [2], only either systematic or parity bits are retransmitted, and hence a considerable throughput improvement can be achieved. Reference [3] considers rate compatible punctured turbo coded HARQ to provide higher throughput. A similar technique is proposed in [4], where the parity spreading interleaver (PSI) is employed to re-order the parity bits as a scheme for flexible puncturing.

An alternative way to packet combining in the framework of ARQ in multipath propagation environment is combining-before-decoding (CBD). The CBD technique combines all path energies of the transmitted signals to achieve diversity gain at the receiver.2 CBD can be performed by joint soft equalization and packet combining using a maximum a posteriori (MAP) equalizer, as introduced in [6]. The algorithm is an extension of the well-known turbo equalization to a single-input multiple-output (SIMO) channel where signal samples, received in each retransmission phase, are stored and combined by the turbo equalizer; this concept is referred to as integrated equalization (IEQ) in [6]. The same idea for packet combining by using MAP equalization is also proposed in [7]. Although the MAP algorithm can achieve the optimal performance, its computational complexity increases exponentially with the channel memory length. Most recently, the technique presented in [8] employs frequency domain turbo equalization with soft combining ARQ at the equalizer in a full-duplex system.

Another form of CBD is combining the interleaved LLRs of equalizers outputs, known as turbo-diversity transmit (TDT) in [5] or bit-interleaving diversity (BID) in [9]. Reference [5] introduces an improved turbo-diversity scheme to IEQ by exploiting different interleaver in every retransmission to reduce the Euclidean distance dispersion. As for IEQ, retransmission of the same codeword with an identical interleaver for every retransmission achieves only a path diversity. It can easily be expected that in frequency-selective fading channels, both CAD and CBD techniques can achieve a diversity order of multipath number \( k \) transmission(s). On the top of the diversity gain, both the techniques can achieve coding gain, where this letter shows that higher coding gain can be achieved by CAD. We show the capacities of the CAD and CBD techniques, and verify the achievable of their corresponding asymptotic performances via computer simulations. We then show that the introduction of doped-accumulator \( DA\text{cc} \) [10]–[11] with different doping rates in each transmission can improve the CAD performance while reducing the computational complexity.

The rest of this paper is organized as follows. The proposed turbo HARQ strategy is presented in Section II. Results of the extrinsic information transfer (EXIT) chart analyses provided in Section III are used to verify the simulation results presented in Section IV. Finally, Section V concludes this letter.
II. PROPOSED TURBO HARQ WITH DOPED-ACCUMULATOR

The transmitter of the turbo HARQ system proposed in this letter is depicted in Fig. 1. The maximum times of transmission attempts is set at $K$ (with $K-1$ retransmissions). The bit stream $b_0$ of the first transmission attempt is encoded by a rate $R$ non-systematic non-recursive convolutional codes (NSNRCC) $C_1$. The output of $C_1$ is then interleaved by a random interleaver $\Pi_1$. The output of $\Pi_1$ is fed into doped accumulator $DAcc$ with a generator $G = [3,2]_8$. $DAcc$ introduces no redundancy and its decoder requires only moderate additional complexity. The doped-accumulated bits are modulated by BPSK. Puncturing may be performed to achieve higher throughput as indicated in [3]. However, this paper leaves the issue of code optimization as a future study.

When the transmitter receives a positive acknowledgement (ACK), it indicates a successful decoding and thereby the transmitter moves on to the next frame transmission. If the transmitter receives a negative acknowledgement (NACK), it indicates an unsuccessful decoding at the receiver, and hence the transmitter retransmits the same information.

For the $k$-th attempt, $k = \{1, 2, \cdots, K\}$, $b_0$ is interleaved every $r$-th retransmission $r = \{1, 2, \cdots, k-1\} [k \neq 1]$, yielding $b_r = \Pi^r_x(b_0)$, where $\Pi^\nu_x(\cdot)$ is the function performing vertical interleaving. The transmitter transmits a vectorized signal having $N$ symbols, as $x_k = [x_k(1), x_k(2), \cdots, x_k(N)]^T \in \mathbb{C}^{N \times 1}$.

At the receiver side, the received signal $y_k$ of the $k$-th transmitted frame is given by $y_k = H_k x_k + \nu_k \in \mathbb{C}^{N \times 1}$, where $\nu_k$ is a zero mean complex additive white Gaussian noise (AWGN) vector with variance $\sigma^2$, corresponding to the specified signal-to-noise power ratio (SNR). The channel is assumed to be static within a frame, and statistically independent varies frame-by-frame. The channel matrix $H_k$ is a Toeplitz matrix with the dimensionality $(N + L - 1) \times N$, where $L$ is the channel memory length. With the cyclic prefix (CP) transmission, $H_k$ becomes an $N \times N$ circulant matrix with the multipath channel response on its first column: $[h(0), h(1), \cdots, h(L-1), 0, \cdots, 0]^T$. Then we can utilize the characteristic of the circularity to obtain a diagonal matrix of frequency domain channel matrix $\Psi_k = F^H H_k F$. This property is well utilized in the frequency-domain soft cancellation and minimum mean squared error (FD/SC-MMSE) turbo equalization ($EQ$). However, since the algorithm of the FD/SC-MMSE equalization technique is already well known [12]–[14], this letter does not provide its details. The results of log-likelihood ratio (LLR) are exchanged via horizontal iteration ($HI$) between the equalizer+deaccumulator ($EQ+DAcc$) and the decoder ($D$). For the decoders $D_{DAcc}$ and $D$, we use Bahl-Cocke-Jelinek-Raviv (BCJR) algorithm [15].

A. Packet Combining After Decoding

The $HI$ takes place independently in different phases of transmission, as shown in Fig. 2. Therefore the channel matrix size stays the same for every $HI$. The $HI$ is performed until no relevant improvement in mutual information (MI) is achieved, and then the obtained extrinsic LLR of the systematic information bits, $L_{e,D}u$, is combined into $L_u$ as

$$L_u = L_{e,D}u + \sum_{i=2}^{k} \Pi_{e,D}^{i-1}(L_{e,D}u).$$

$L_u$ is fed back to soft-input soft-output (SISO) channel decoders as the $a\ priori$ information, as depicted in Fig. 2, referred to as vertical iteration ($VI$). The ($VI$) can be seen as iterative decoding process of parallel concatenated code. Finally, by performing sufficient times of iterative $HI$-$VI$ decoding, the final hard decision, $\hat{b}$, is made on the $a\ posteriori$ LLR of the information (systematic) bits.

B. Doped-Accumulator

$DAcc$ is composed of a memory-1 systematic recursive convolutional code with octal generator of $[3,2][3]_8$ followed by heavy puncturing of the parity bits. Every $p$-th systematic
III. EXIT ANALYSIS

The structure of the CAD technique enables the use of different doping rates of the $D_{Acc}$ transmission-by-transmission to achieve better matching of the EXIT curves. The doping rate of the first transmission is determined by evaluating the EXIT curves of inner and outer code so that they are best matched among all possible values of the doping rates, while keeping the convergence tunnel open. In such parameter settings, no retransmission is required if the received SNR is larger than the threshold at which the convergence tunnel opens.

Fig. 3 shows the EXIT curves of $EQ + D_{DAcc}$, with a generator [3,2]$_8$ NSNRCC’s decoder, for a single snapshot channel realizations at the first transmission and the same channel for retransmission. The a priori LLR to the equalizer is set to zero for every $p$-th bit, as shown in Fig. 2. Hence, it is important to note that when $p = 1$, $DAcc$ is equivalent to a full accumulator; in this case, no LLR of the accumulated bits is fed back from the channel decoder to the equalizer.

IV. SIMULATION RESULTS

To evaluate the performances, computer simulations have been conducted in multipath Rayleigh fading channels. Randomly generated binary sequence with a length of 512 information bits per frame were used as $b_0$. Then, for ACC-CAD, $b_0$ and $b_r$ are independently coded by the same memory-1 rate 1/2 NSNRCC encoder with generator polynomial ([3 2])$_8$. For comparison, we also tested memory-2 rate 1/2 NSNRCC encoder with generator polynomial ([7 5])$_8$ for both CAD and CBD without $D_{Acc}$. Here, the total memory that used at the receiver for all the evaluated systems are the same. However, both memory-1 code NSNRCC and $D_{Acc}$ with the proposed system, having only two states in their trellis diagram, and hence decoding complexity is lower than the other cases used for comparison.

The channel of the second transmission is generally different from the first branch then followed by five $VI$s; the $HI$ and $VI$ process are repeated 50 times, referred as activation ordering pattern 50(H1V5). The activation ordering pattern for $k = 3$ and $k = 4$ are 43(H1V5) and 38(H1V5), respectively.

For the first transmission (without combining), the both CAD and CBD systems schemes achieve the same outage

\[ \text{FER}_{\text{CAD}} = \text{FER}_{\text{CBD}} \]
probability. In this case, the system performance is determined by the path diversity and coding gains that can be achieved by the HI only. It is found from Fig. 4 that the proposed CAD outperforms the systems without DAcc, as predicted from the EXIT analysis.\textsuperscript{7} With \( k > 1 \), the outage probability of CAD is lower than CBD; hence it is found that CAD clearly outperforms CBD. With ACC-CAD, the gap between FER and the outage probability, at FER = 10^{-3} for \( K = 2 \), is 2.74 dB whereas with the CBD the gap is 4.56 dB. Similarly, for \( K = 4 \), the gap between the FER curve and the outage probability with the ACC-CAD is 2.78 dB whereas the CBD is 4.90 dB.

The excellent performance of the proposed systems is also shown in terms of throughput efficiency at relatively low SNR in Fig. 5. With the ACC-CAD technique, as the throughput curves with every \( K \) value converge at SNR around 4 dB, we only need one retransmission, when SNR > 4 dB, to achieve the highest throughput. Fig. 5 also shows that ACC-CAD with only one retransmission outperforms the CBD with three retransmissions over the SNR value range of -2 dB \( \leq \) SNR \( \leq \) 8 dB in average.

V. CONCLUSION
This letter has proposed CAD HARQ technique using doped-accumulator (DAcc) and vertical iteration (VI) decoding. It has been shown that the proposed system outperforms the HARQ systems without DAcc. With the help of EXIT chart analysis, it has been shown that a better matching between \( EQ + D_{DAcc} \) and NRNSCC decoder’s EXIT curves, concatenated with VI decoding, can be achieved with the proposed technique, which results in excellent FER and throughput performances. The superiority of CAD over CBD has also been verified via computer simulations in multipath Rayleigh fading channels.

REFERENCES
\textsuperscript{7}Result for \( K = 3 \) is not shown to simplify the figure.