Title	Lossy Forwarding Techniques for Parallel Multihop-Multirelay Systems
Author(s)	Irawan, Ade; Anwar, Khoirul; Matsumoto, Tad
Citation	2015 IEEE 82nd Vehicular Technology Conference (VTC Fall): 1-5
Issue Date	2015-09
Type	Conference Paper
Text version	author
URL	http://hdl.handle.net/10119/14224
Rights	This is the author's version of the work. Copyright (C) 2015 IEEE. 2015 IEEE 82nd Vehicular Technology Conference (VTC Fall), 2015, 1-5. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.
Description	

Lossy Forwarding Technique for Parallel Multihop-Multirelay Systems

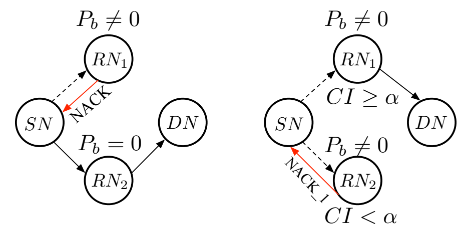
Ade Irawan*, Khoirul Anwar* and Tad Matsumoto*§
*School of Information Science
Japan Advanced Institute of Science and Technology (JAIST), 1-1 Asahidai, Ishikawa 923-1292, JAPAN
Email: {ade.irawan, anwar-k, matumoto}@jaist.ac.jp
§Center for Wireless Communications, University of Oulu, Finland
Email: tadashi.matsumoto@ee.oulu.fi

***Abstract*—This paper proposes a Partial Hybrid Automatic Repeat reQuest (P-HARQ) scheme where the relaying nodes select either forwarding the erroneous packets or requesting retransmission. In contrast to the conventional technique where the erroneous packets is always discarded, the packets found to have errors after decoding are interleaved, re-encoded, and forwarded if relay selects the forwarding mode. This technique is refer to as lossy forwarding. In this paper, the mode selection (either forwarding or requesting retransmission) is based on the confidence indicator (CI). Since the channels are assumed to suffer from block Rayleigh fading, the CI is calculated via online mutual information measurements, block-by-block. Results of computer simulations conducted to confirm the superiority of the proposed P-HARQ technique in terms of bit-error-rate, packet-error-rate and throughput performances in parallel multihop wireless multirelaying systems, are presented.**

I. Introduction

Multihop relaying systems have gained considerable interest from both academia and industry due to their capability of reducing the overall path loss between the source node and the destination node. In a cellular system, the multihop relaying systems can dynamically balance the traffic among cells, increase the system capacity, improve the throughput, and extend the system coverage [1]. Furthermore, the power used by the source node can be saved because the communication distance becomes closer than single hop communications. However, the end-to-end delay may be larger compared to that of single-hop communication due to processing in each hop. Moreover, there is still no guarantee that shorter hop always reliable due to the time-varying nature of wireless channels.

Automatic repeat request (ARQ) can be used to improve the reliability of multihop relaying systems with the mechanisms as shown in [2]. Reference [2] has classified the ARQ mechanisms into three categories: end-to-end ARQ, hop-by-hop ARQ, and relay ARQ. The conventional end-to-end ARQ is a very simple mechanism to ensure the successful recovery of the packets at the destination node. However, long transmission delay is a detrimental drawback, and hence additional techniques initiated by the relay nodes are needed, for instance the hop-by-hop ARQ proposed by [3], and the relay ARQ by [4]. Ref. [2] shows that delay increases exponentially as the packet-error-rate (PER) per link in two-hop transmission increases, and the hop-by-hop ARQ as well as the relay ARQ mechanism performs similarly, even though they outperform the end-to-end ARQ in term of throughput. The superiority of the hop-by-hop ARQ and the relay ARQ over the end-to-end ARQ is shown in [2], also in term of throughput.



(a) Conventional HARQ (b) Proposed HARQ

Fig. 1. Multihop relaying comparison between the conventional and the proposed HARQ.

Every time a packet is retransmitted, either from a new node or from the same node, the receiving node will increase the amount of information. Hence, by accumulating sufficient information, the node will be able to decode the message. In this case, combining the ARQ with forward error correction (FEC) in a hybrid ARQ (HARQ) scheme can achieve not only the time diversity through the ARQ itself, but also the spatial diversity through the relays which retransmit the source information, as described in [5]. Therefore, employing HARQ in multihop relaying systems can further improve the reliability.

Many different schemes of HARQ for multihop relaying systems have been proposed in the literatures, for example, the HARQ for one-relay-per-hop systems in [6]–[8]. Those protocols may not be optimal for a system with more than one relay per hop, since the spatial diversity is not taken into consideration. The system becomes more complex as the number of relay per hop increases as shown in [9]–[11].

The relay nodes of all those schemes do not forward erroneous packets, but instead request for retransmissions, and hence the end-to-end latency increases. Furthermore, they do not consider the correlation between more than two information sequences[1] so that further potential improvement using

[1]The correlation among packets from parallel links exist since they were originally sent from the same source.

correlation property between the received sequences is not exploited.

To improve the performance of multihop multirelaying systems, in this paper we propose Partial HARQ (P-HARQ) shown in Fig. 1, where erroneous packets are forwarded to preserve as many parallel links as possible to exploit the correlation among the erroneous messages, resulting in larger diversity gain. Furthermore, the end-to-end throughput can be enhanced because P-HARQ improves the reliability retransmission-by-retransmission. In particular, P-HARQ utilizes the knowledge of the correlation between the information sequences received in the previous transmissions. Therefore, the correlation knowledge or the redundancy among packets coming from different links is significantly beneficial. However, the more hops in transmission, the larger the distortion in the forwarded packet, which results in decreased redundancy hop-by-hop. To solve this problem, we introduce a confidence indicator (CI) as a threshold by which a relay node selects either forwarding the erroneous packets or requesting retransmission.[2] Therefore, P-HARQ is initiated by the relay nodes, depending on the CI value, to reduce the number of end-to-end retransmissions, and hence it increases the end-to-end throughput.

The remainder of this paper is organized as follows. The system model considered in this paper is presented in Section II. In Section III, the proposed P-HARQ mechanism is introduced, where the brief mathematical expression for the CI calculation is provided. The numerical results are presented in Section IV, where we evaluate the impact of introducing the CI to bit-error-rate (BER), PER and throughput performances. Finally, Section V concludes this paper.

II. System Model

Throughout this paper, vectors are expressed with bold, and scalars with standard text notation. We consider a multihop multirelaying network where a source node SN aims to transmit information sequence to a destination node DN through two relay nodes RN_1 and RN_2 that are located physically separate in parallel links, as shown in Fig. 1. There are three time slots in one transmission cycle. In the first time slot, the node SN broadcasts its coded sequences $\boldsymbol{x}_S$ to the node RN_1 and RN_2. The rest time slots, both relays transmit their coded sequence $\boldsymbol{x}_{RN_l}, l \in \{1, 2\}$ to the destination DN, sequentially. We consider static channel within one block but varying link-by-link as well as transmission-by-transmission during HARQ rounds.[3] We use the terminologies transmitting nodes and receiving nodes for referring to the source node and the relay nodes on transmit phase, and relay nodes and destination node on receive phase, respectively.

A. Transmit Phase

Fig. 2 depicts the transmitter structure of the source node and the relay node RN_1. The structure of RN_2 is similar to RN_1. With m (re)transmissions, $m \in \{1, 2, ..., M\}$, where the maximum number of retransmissions is $M-1$, the binary information sequence $\boldsymbol{u}^m$ is first encoded by the channel encoder C_m. For the retransmit phases, at relay node, $\boldsymbol{u}^m$ is first random-interleaved by inner interleaver $\Pi_{0,m+1}$ before encoded.[4] The relay node discards the old packet whenever receiving a new packet.[5] The same process is performed at the tandem relay of the first transmission. The encoded bit sequence is then randomly interleaved by outer interleaver[6] $\Pi_{1,m}$ followed by doped-accumulator[7] DA_m with doping ratio $\rho = \rho_m$. The doped-accumulated bits are mapped in the *Map* box in Fig. 2 to constellation points for modulation. In this paper, we use binary phase shift keying (BPSK), which follows the mapping rule $0 \rightarrow -1, 1 \rightarrow +1$, and then transmitted over frequency-flat block Rayleigh fading channel with the complex channel gain $h_q, q \in \{SN-RN_1, SN-RN_2, RN_1-DN, RN_2-DN\}$. The transmitter transmits the modulated signal having N symbols, as

$$\boldsymbol{x}_i^m = [x_i^m(1), x_i^m(2), \cdots, x_i^m(N)]^T \in \mathbb{C}^{N\times 1}, \quad i \in \{SN, RN_1, RN_2\}. \tag{1}$$

B. Receive Phase

The received signal of the transmitted packet can be formulated as

$$\boldsymbol{y}_j^m = h_{ij}\boldsymbol{x}_i^m + \boldsymbol{\nu}_j^m \in \mathbb{C}^{N\times 1}, j \in \{RN_1, RN_2, DN\}, \tag{2}$$

where $\boldsymbol{\nu}$ is a zero mean complex additive white Gaussian noise (AWGN) vector with variance σ^2 (double sided). The average signal-to-noise power ratio (SNR) is $\langle |h_{ij}|^2\rangle/\sigma^2$ since $E[\boldsymbol{x}_i^m] = 1$.

The conditional log-likelihood ratios (LLRs) based on the probability that the receiver's matched filter output $y_j^m(n)$ for the n-th bit in $\boldsymbol{x}_i^m$ is defined as

$$L(y_j^m(n)|h_{ij}, x_i^m(n)) = \ln\frac{Pr(y_j^m(n)|h_{ij}, x_i^m(n)=+1)}{Pr(y_j^m(n)|h_{ij}, x_i^m(n)=-1)}, \tag{3}$$

where $n = \{0, 1, 2, ..., N\}$. Hence, with

$$Pr(y_j^m(n)|h_{ij}, x_i^m(n)) = \frac{1}{\sqrt{\pi\sigma^2}}\exp\left[-\frac{|y_j^m(n) - h_{ij}\cdot x_i^m(n)|^2}{\sigma^2}\right], \tag{4}$$

it is straightforward to calculate the soft output of the channel $\boldsymbol{L}_c$, for BPSK over a block fading additive white Gaussian noise (block fading AWGN) channel as

$$\boldsymbol{L}_{c,j}(n) = \frac{4}{\sigma^2}\cdot\Re\{h_{ij}^*\cdot\boldsymbol{y}_j^m(n)\}, \tag{5}$$

[2] In contrast with CRC, error detection using CI introduces no additional redundancy attached to the packet.

[3] This condition is valid for indoor environments, where all nodes experience low mobility.

[4] It should be noticed that the use of the different interleaver for each round of transmission by the relays converts the system into a distributed Turbo code.

[5] Combining the packets at the relay node should further improve the performance, but it is out of the scope of this paper for the sake of simplicity.

[6] The outer interleaver enables extrinsic LLR exchanging of systematic bits via vertical iteration at the receiver side, likewise, the inner interleaver plays important function of extrinsic LLR exchanging via horizontal iteration.

[7] DA is a rate-1 systematic recursive convolutional code where every ρ-th systematic bits is replaced with the accumulated coded bits [12].

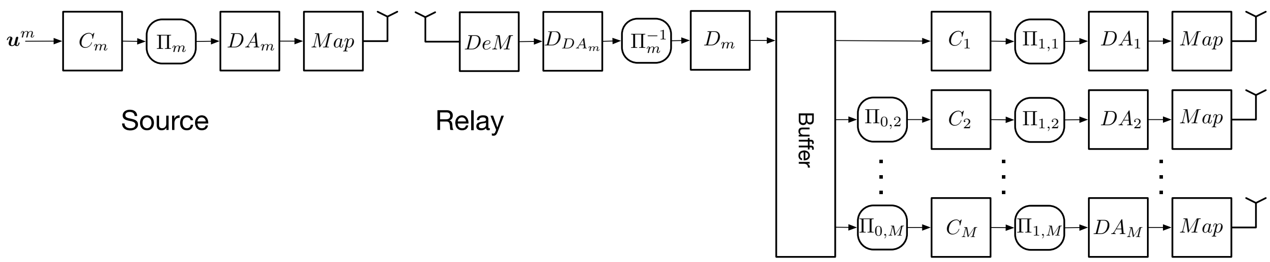


Fig. 2. Block diagram of the source and the relay node RN_1. The structure of the relay node RN_2 is similar with RN_1.

where $\Re\{\cdot\}$ is the real value of its argument.

Fig. 3 depicts the structure of the destination node. The block diagram only shows the structure of receiving the packet from the same relay node. However, the similar structure also can be used for decoding the packets coming from another relay. The combiner $\sum$ combines all the *extrinsic* LLRs, output of channel decoder of the each HARQ round. The soft output vector of the channel $\boldsymbol{L}_c^m$, the LLRs obtained by (5), is first input to the demapper *DeM* followed by DA_m decoder (D_{DA_m}), and its output extrinsic LLR is forwarded to the inner-deinterleaver prior to the channel decoder D_m. The subtraction of *a priori* LLR $\boldsymbol{L}_a$ from *a posteriori* LLR $\boldsymbol{L}_p$ is not shown in the figure for the sake of simplicity. The CI of the received packet is then calculated, which is equivalent to the mutual information between the *a posteriori* LLR and the uncoded systematic bits. The CI can be calculated online, as described in Section III. If the value of the CI is lower than the predetermined threshold, the extrinsic LLR obtained as the output of D_m are exchanged via horizontal iteration (*HI*) between the $DeM + D_{DA_m}$ and D_m.[8] The incorrectly decoded packet is stored in order to first update it to reflect the correlation knowledge, and then to combine with the retransmitted packet(s) in the following time slots.

When the retransmitted packet is received, the *HI* is performed independently, as in the first transmission, and then the obtained *extrinsic* LLRs of the systematic information bits, $\boldsymbol{L}_e^{u,m}$, are propagated crosswise between the soft-input soft-output (SISO) channel decoders, as depicted in Fig. 3, of which process is referred to as vertical iteration (*VI*). *VI* can be seen as iterative decoding process of parallel concatenated code. $\boldsymbol{L}_e^{u,m}$ is updated by the function f_c defined by (8). The function f_c is utilized to help the decoder eliminate the errors in the packets received by the relays, by exploiting the correlation knowledge between the relays. The correlation value is indicated by the error probability p_e, block-by-block, which can be estimated by using a pair of *a posteriori* LLRs, $\boldsymbol{L}_{p,D_\mathcal{I}}^u$ and $\boldsymbol{L}_{p,D_\mathcal{J}}^u$, $\mathcal{I} \neq \mathcal{J}$, the uncoded (systematic) bits output from the decoders $D_\mathcal{I}$ and $D_\mathcal{J}$, respectively, as [12]

$$\hat{p}_e = \frac{1}{K}\sum_{k=1}^{K} \frac{\exp(L_{p,D_\mathcal{I}}^u) + \exp(L_{p,D_\mathcal{J}}^u)}{(1+\exp(L_{p,D_\mathcal{I}}^u)) \cdot (1+\exp(L_{p,D_\mathcal{J}}^u))}, \tag{6}$$

[8]Threshold is set adaptively while determining the threshold value of the *a posteriori* LLR.

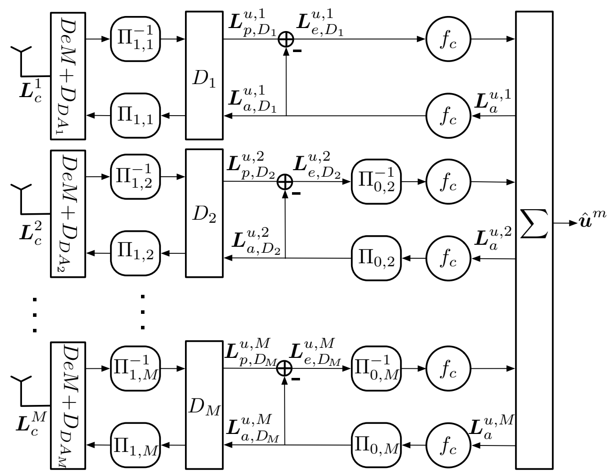


Fig. 3. Block diagram of the destination node when receiving RN_1 packets. The similar structure applied when receiving RN_2 packets.

where K denotes the number of the *a posteriori* LLR pairs obtained by the decoders for the packets transmitted from RN_1 and RN_2, with sufficient reliability. The updated *extrinsic* LLR of $L_{e,D_\mathcal{I}}^{u,m}$ can then be obtained by [12]

$$L_{e,D_\mathcal{I},updated}^u = f_c(\tilde{L}_{e,D_\mathcal{I}}^u, \hat{p}_e) \tag{7}$$

$$= \ln \frac{(1-\hat{p}_e)\cdot \exp(\tilde{L}_{e,D_\mathcal{I}}^u) + \hat{p}_e}{(1-\hat{p}_e) + \exp(\tilde{L}_{e,D_\mathcal{I}}^u)\cdot \hat{p}_e}, \tag{8}$$

where $\tilde{\boldsymbol{L}}_{e,D_\mathcal{I}}^u = \boldsymbol{L}_{e,D_\mathcal{I}}^u$ for the first transmission, and $\tilde{\boldsymbol{L}}_{e,D_\mathcal{I}}^u = \Pi_{0,m}^{-1}(\boldsymbol{L}_{e,D_\mathcal{I}}^u)$ for the retransmissions. The *a priori* LLR $\boldsymbol{L}_a^{u,m}$ is then

$$\boldsymbol{L}_a^{u,m} = \sum_{q\in\omega\backslash m} \boldsymbol{L}_{e,D_{\mathcal{I},updated}}^{u,m}, \tag{9}$$

with $\omega = \{1, 2, ..., M\}$ being the set of retransmission number. Finally, by performing sufficient rounds of iterative *HI-VI-HI-VI* decoding processes, the final hard decisions, $\hat{\boldsymbol{u}}^m$ is made on the *a posteriori* LLR originated by summing up all the deinterleaved and f_c-updated versions of the *a posteriori* LLR $\boldsymbol{L}_{p,D_m}^{u,m}$.

III. Partial HARQ Mechanism

In this section, we explain the general mechanism of P-HARQ. Suppose that there is a network composed of one source node and one destination node with arbitrary number of relay nodes constructing multihop multirelaying network. Initially, the packet from the source node is forwarded to the destination node through the (multiple) relay(s), even though it still contains errors. The receiving nodes calculate values CI, to be used when deciding either requesting retransmission or forwarding the packet. The online technique for calculating the mutual information between the *a posteriori* LLR output of the channel decoder and the information sequence from the previous node [13] is used, and the calculated mutual information

$$CI = I(L_n; U) = 1 - \frac{1}{N}\sum_{n=1}^{N} H_b\left(\frac{e^{+|L_n|/2}}{e^{+|L_n|/2} + e^{-|L_n|/2}}\right), \quad (10)$$

is utilized as CI, where $H_b(\cdot)$ is a binary entropy function. The CI calculation is beneficial since the receiving nodes do not need to know the original information sequence. The probability of error corresponding to the CI value can be calculated by

$$P_b \approx \frac{1}{2} erfc\left(\frac{J^{-1}(CI)}{2\sqrt{2}}\right), \quad (11)$$

where $J^{-1}(\cdot)$ is the inverse of function $J(\cdot)$ [14]. It is worth noting that P_b is the BER per link, not the BER of original source information, except the CI value calculated at the relay(s) of the first hop.

The receiving nodes send negative acknowledgement (NACK) to their previous nodes to indicate an unsuccessful decoding, and hence request for retransmission. There are two types of NACK in P-HARQ: NACK_1 to indicate a retransmission required from the node in one-hop back, and NACK_2 for retransmission required from the node in two-hop back. Therefore, if a transmitting node receive NACK_1, it will retransmit the packet to the next node. On the other hand, if a transmitting node receive NACK_2, it will transmit NACK_1 to the node one-hop back.

The destination node initially requests retransmission from its previous node(s) if the decoded packet does not satisfy the required BER, calculated from the CI value. The destination prioritizes combining the packets received from all relays, including retransmissions, according to the block diagram shown in Fig. 3, instead of combining the retransmitted packets from one relay. If the (re)transmissions can reduce the BER estimated by (11), the smaller the CI value is set as the threshold α_D. Then, even if the forthcoming packets have smaller CI than α_D, α_D is not changed so far as the required BER calculated from the final *VI* results is satisfied. However, if the packet quality does not meet the BER requirement, the destination node will send NACK_1 even if the CI is larger to α_D, otherwise send NACK_2.

As for the relay node, the threshold α_R is set equal to CI when receiving NACK_1. After the initial transmission, the relay node will always forward the packets which have CI larger than α_R, otherwise it requests retransmission from its previous node. The relay nodes will also evaluate and update their own α_R whenever receiving NACK_2.

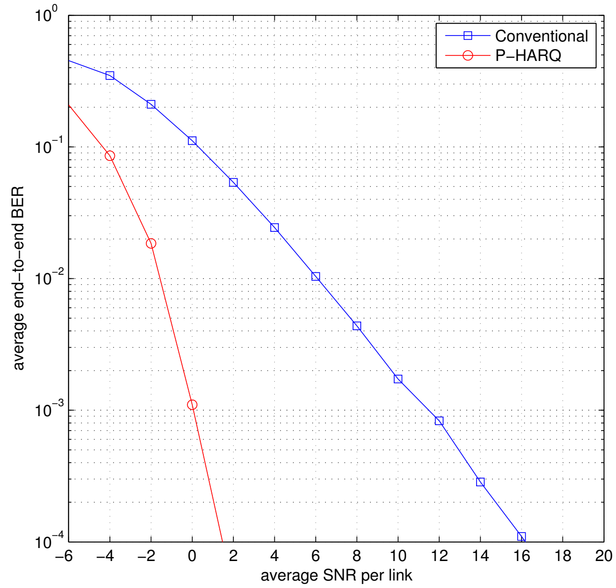


Fig. 4. BER performances.

IV. Numerical Results

We evaluate BER, PER, and throughput performances by simulations that consider the transmission of 100,000 packets with size 2,048 bits per packet. The maximum number of retransmissions per node is set to 4 ($M = 5$). For the fair comparison, we set the same total number of retransmission for all evaluated system in each SNRs. All nodes use the same channel coding, where a half-rate non-systematic non-recursive convolutional coding (NSNRCC) with a generator polynomial $G = [7, 5]$ is considered. They all also use the same varying doping ratio ρ (re)transmission-by-(re)transmission, where $\rho \in \{2, 10, 15, 20, 25\}$.

We assume no delay constraints for the overall transmission of information from the source to the destination nodes, and hence the relay nodes can decode the packet before they forward. We also assume an ideal medium access control protocol, where each node can transmit and receive a packet independently. Each node is allowed to transmit and receive only one packet simultaneously, and every packet transmitted from nodes is received without collisions.

We compare P-HARQ with the conventional scheme. In the conventional scheme, the relay nodes forward only error-free packets and the retransmissions occur either between the source node and the relay nodes or between the relay nodes and the destination node. As stated in footnote 5, we perform no packet combining at the relay nodes for all the schemes.

Figs. 4 and 5 show that P-HARQ outperforms the conventional scheme in terms of BER and PER performances, respectively. Fig. 5 shows that the conventional scheme fails in combining all transmitted packet to achieve large diversity gain while it can be achieved by P-HARQ. This is because P-HARQ is able to carefully combine the most reliable packets by employing the CI. P-HARQ has 6.2 dB degradation from

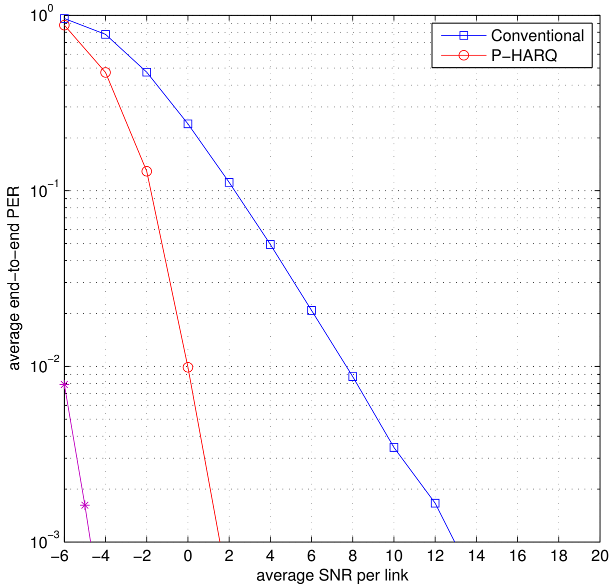


Fig. 5. PER performances.

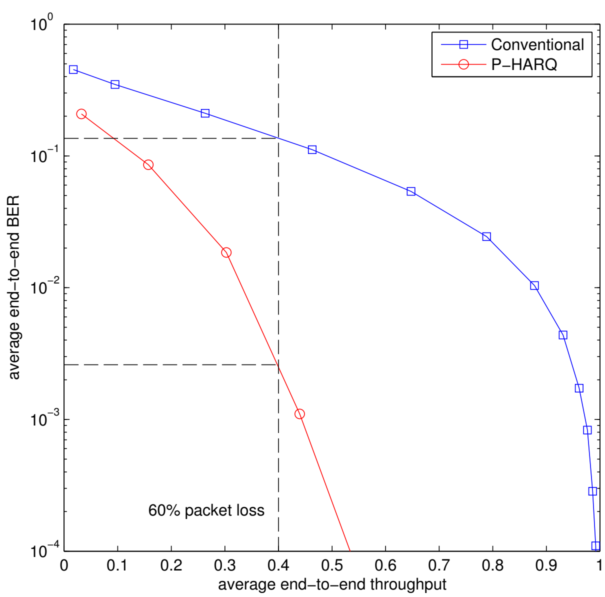


Fig. 6. Corresponding BER of throughput performances.

MRC because the relay nodes forward even erroneous packet to the destination while MRC assumes no error at the relay nodes.

The throughput is defined as the ratio of the average number of successfully recovered packets at the destination node per time slot, to the total number of transmitted packets per time slot. We normalized the throughput over two time slots, which means that the throughput of one is achieved whenever the packet is successfully recovered within two time slots. Hence, the packet loss rate can be calculated as $P_{loss} = 1 - T$, with T being the throughput of the system. Fig. 6 shows that for the same ratio of end-to-end packet loss, the BER performance of the proposed P-HARQ is lower than the conventional scheme. For the example, the 60% of end-to-end packet loss corresponds to BER of 0.0026 for P-HARQ, but 0.1360 for the conventional scheme.

V. Conclusion

Partial HARQ has been proposed to improve the system throughput of parallel multihop relaying systems. The improvement is obtained by: (i) allowing lossy forwarding at the relay, and (ii) exploiting the correlation among received packets at the destination node. Results of computer simulations verified the significant improvement on BER, PER and throughput performances over frequency-flat block Rayleigh fading channels.

Acknowledgment

This work has been performed in part, in the framework of the FP7 project ICT-619555 RESCUE (Links-on-the-fly Technology for Robust, Efficient and Smart Communication in Unpredictable Environments) by the European Union, and in part under Academy of Finland NETCOBRA Project.

References

[1] H. Wu, C. Qiao, S. De, and O. Tonguz, "Integrated cellular and ad hoc relaying systems: iCAR," *Selected Areas in Communications, IEEE Journal on*, vol. 19, no. 10, pp. 2105–2115, Oct 2001.

[2] S.-Y. Jeon and D.-H. Cho, "Modelling and analysis of ARQ mechanisms for wireless multi-hop relay system," in *IEEE VTC Spring 2008*, May, pp. 2436–2440.

[3] H. Wiemann, M. Meyer, R. Ludwig, and C. P. O, "A novel multi-hop ARQ concept," in *IEEE VTC 2005-Spring*, vol. 5, May, pp. 3097–3101.

[4] S.-Y. Jeon, K.-Y. Han, K. Suh, and D.-H. Cho, "An efficient ARQ mechanism in multi-hop relay systems based on IEEE 802.16 OFDMA," in *IEEE VTC 2007 Fall*, Sept 2007, pp. 1649–1653.

[5] T. Tabet, S. Dusad, and R. Knopp, "Achievable diversity-multiplexing-delay tradeoff in half-duplex ARQ relay channels," in *ISIT 2005*, Sept, pp. 1828–1832.

[6] D. Chiarotto, O. Simeone, and M. Zorzi, "Throughput and energy efficiency of opportunistic routing with type-i HARQ in linear multihop networks," in *IEEE GLOBECOM 2010*, Dec, pp. 1–6.

[7] W. Fu, Z. Tao, J. Zhang, and D. Agrawal, "Error control strategies for WiMAX multi-hop relay networks," in *IEEE GLOBECOM 2009*, Nov, pp. 1–6.

[8] S. H. Kim and B. C. Jung, "On the optimal link adaptation in linear relay networks with incremental redundancy HARQ," *Communications Letters, IEEE*, vol. 18, no. 8, pp. 1411–1414, Aug 2014.

[9] M. Levorato, F. Librino, and M. Zorzi, "Integrated cooperative opportunistic packet forwarding and distributed error control in MIMO ad hoc networks," *Communications, IEEE Transactions on*, vol. 59, no. 8, pp. 2215–2227, August 2011.

[10] B. Zhao and M. Valenti, "Practical relay networks: a generalization of hybrid-ARQ," *Selected Areas in Communications, IEEE Journal on*, vol. 23, no. 1, pp. 7–18, Jan 2005.

[11] A. Bhamri, F. Kaltenberger, R. Knopp, and J. Hamalainen, "Smart Hybrid-ARQ (SHARQ) for cooperative communication via distributed relays in LTE-advanced," in *SPAWC, 2011 IEEE 12th International Workshop on*, June, pp. 41–45.

[12] K. Anwar and T. Matsumoto, "Accumulator-assisted distributed turbo codes for relay systems exploiting source-relay correlation," *Communications Letters, IEEE*, vol. 16, no. 7, pp. 1114–1117, 2012.

[13] J. Hagenauer, "The EXIT chart - introduction to extrinsic information transfer in iterative processing," *European Signal Processing Conference*, p. 1541–1548, September 2004.

[14] S. ten Brink, "Convergence behavior of iteratively decoded parallel concatenated codes," *Communications, IEEE Transactions on*, vol. 49, no. 10, pp. 1727–1737, Oct 2001.