A Cross-Layer HARQ Scheme Robust to Imperfect Feedback

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***Abstract*—Some recent cross-layer HARQ schemes have been designed in order to enhance the system performance at network level. However, these schemes suffer from high performance loss as soon as the feedback is imperfect. Therefore the purpose of this paper is to develop a new cross-layer HARQ scheme that is more robust to imperfect feedback, and that still has a cross-layer gain.**

I. INTRODUCTION

Hybrid Automatic Repeat reQuest (HARQ) provides a good trade-off between channel coding and packet retransmission. It is a well suited solution to enforce the link quality at the Medium Access Control (MAC) layer in wireless environments, and has been adopted in some towards-4G standards (3GPP LTE Release 8, for instance). Future 4G communications standards plan an all-IP oriented infrastructure by use of Internet Protocol (IP) to manage the network (NET) layer. Therefore, it is of interest: i) to analyze the retransmission schemes (like HARQ) at NET level, *i.e.*, when the IP packet is the figure of merit, and ii) to design such HARQ schemes to improve the performance at IP level. In [1], a cross-layer ARQ scheme (between the MAC and NET layers) has been designed, that improves the Packet Error Rate (PER) at NET level, and has been extended to HARQ in [2].

HARQ is based upon a feedback mechanism that informs the transmitter whether the packet is correct (ACK) or not (NACK). In wireless systems, this feedback message can be subject to errors: it will be assumed, as usual (see [3], [4] and references therein), that the ACK may be erroneous whereas the NACK is always correctly received. Under this assumption, [3] has remarked that the HARQ PER at MAC level was unaffected by feedback errors. When not using a cross-layer retransmission scheme, this is also true for the NET level PER. However, it has been shown in [4] that the PER of the cross-layer scheme introduced in [1] was dramatically degraded by erroneous feedback, and so loses its main interest.

In the spirit of [1], this paper contributes to the development of a new cross-layer HARQ scheme that still enhances NET level performance, and that is robust to feedback impairments. This is achieved thanks to a new way of handling the HARQ transmission credit within an IP packet. Analytical expressions for various performance metrics (PER, delay, efficiency) are provided for the proposed HARQ scheme when the feedback is imperfect.

The paper is organized as follows: the system model (the system layers and existing HARQ schemes) and notations are described in Section II. Section III is devoted to the proposed cross-layer HARQ scheme description. Its performance are derived in closed-form in Section IV. Finally, Section V gives some numerical results.

II. SYSTEM MODEL

The model encompasses the three lowest layers of the ISO model, *i.e.* the PHY, the MAC and the NET layers. Without loss of generality the NET protocol is assumed to be the IP.

We assume that the incoming IP packets are split into N fragments of equal length at the MAC layer. Next, each fragment is transmitted following a given HARQ scheme. A fragment is firstly transformed into MAC packet(s) according to the considered HARQ scheme: all the MAC packets are identical and correspond to the fragment (plus MAC overhead) in ARQ, whereas the MAC packets arise from a punctured version of the encoded fragment (using a forward error correcting code) in Incremental Redundancy HARQ. At PHY layer, the first MAC packet of the resulting sequence is inserted into a frame, modulated according to a given constellation, and sent through the wireless channel. At the receiver side, the MAC packet is decoded and the HARQ process checks if the fragment can be recovered without errors (with CRC control for instance) or not. The receiver sends back to the transmitter an acknowledgment (ACK) or a negative ACK (NACK) accordingly. If an ACK is received, the transmitter restarts the HARQ process with the next fragment. Otherwise, it sends the next MAC packet in the sequence, and so on. The number of MAC packets transmission per fragment is usually limited to a finite value M in order to bound the maximum transmission delay (M is also referred to as *maximum transmission credit*). If the M-th transmission fails the fragment is dropped and the retransmission process is started again with the next fragment. Finally, once the N fragments have been correctly received, the receiver concatenates them into an IP packet that is sent to the NET layer. If at least one fragment is missing, the resulting IP packet is dropped by the NET layer.

The conventional retransmission scheme described above is usually applied at MAC layer where HARQ manages the fragments one after the other independently. The main drawback of this approach lies in the fact that if the M-th MAC packet transmission fails, the corresponding fragment is dropped and so the corresponding IP packet too. The PER can be improved at IP level as proposed in [1] by granting the total transmission credit $C = NM$ to the set of fragments belonging to the same IP packet. So if a fragment does not use the C transmissions, then the remaining credit can be used by the next ones, and the IP packet is only dropped if all the corresponding fragments are not received correctly in at most C transmissions.

In the sequel we will refer to the conventional strategy (transmission credit per fragment) as Fragment-Based Strategy (FBS) and to the cross-layer strategy of [1] as IP-Based Strategy (IBS).

III. PROPOSED HARQ SCHEME

Actually, the analysis conducted in [4] shows that the IBS performs quite poorly when the feedback is imperfect, and there are some case where the FBS outperforms it. Indeed, if the first fragment has been correctly received, but the acknowledgment is lost during the feedback, then a lot of transmission credits may be wasted. Therefore the transmitter could not have enough credits left to transmit the $N-1$ last fragments, resulting into the IP packet loss.

Therefore, although it is interesting to share the transmission credit amongst the fragments belonging to a same IP packet (as done in IBS), it is crucial in the imperfect feedback case to also bound the number of transmissions per fragment (as done in FBS). To combine these two dual approaches, we suggest to keep a maximum transmission credit per fragment, while allowing the unused credit of a given fragment to be carried forward to the next fragment. More

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precisely, let M_n be the maximum transmission credit for the n-th fragment of a given IP packet. The proposed approach, called Report Credit Strategy (RBS), consists in applying the following rule:

$$M_n \leftarrow M_n + (M_{n-1} - k_{n-1}),\ \forall n > 1, \tag{1}$$

where $k_n \leq M_n$ denotes the number of transmissions consumed by fragment n.

IV. PERFORMANCE CLOSED-FORM EXPRESSIONS

As long as HARQ is considered, there are various performance metrics of interest at IP level:

- the PER denoted by P;
- the average delay, denoted by d, is the average number of MAC transmissions for successfully received an IP packet [4];
- the efficiency, denoted by η, is the average number of information bits received when a bit is transmitted.

According to the usual imperfect feedback models [3], [4], we assume that the ACK can be changed into NACK with a probability p_{fb} whereas the NACK cannot become an ACK.

Let $p_1(k)$, $k \geq 1$, be the probability of correctly receiving a single fragment in k MAC packet transmissions assuming perfect feedback ($p_{\text{fb}} = 0$). Closed-form expressions for $p_1(k)$ are available in [2]. In the sequel, we provide the closed-form expressions for the above mentioned metrics for RCS when imperfect feedback is assumed ($p_{\text{fb}} \neq 0$). The proofs will be given in the final version. Let $\tilde{p}_n(k)$, $n, k \geq 1$ be the probability of correctly receiving n fragments in k MAC packet transmissions when using RCS. We obtain

$$\tilde{p}_n(i) = \sum_{\boldsymbol{x} \in \chi_{i,n}} \prod_{j=1}^{n} \sum_{k_j=1}^{q_j} p_1(k_j) p_{\text{fb}}^{q_j - k_j} (1 - p_{\text{fb}})^{\delta\{Aj\}},$$

where $\chi_{i,n} = \{\boldsymbol{x} \in \mathbb{N}_*^n \,|\, \sum_{\ell=1}^{n} x_\ell = i \text{ and } x_\ell \in A_\ell\}$ with $A_j = \{x_j \,|\, x_j < \sum_{m=1}^{j} M_m - \sum_{m=1}^{j-1} x_m\}$, and δ denotes the Kronecker symbol.

Let us denote by $C = \sum_{n=1}^{N} M_n$ the total transmission credit for the IP packet. By following the approach of [2], [4], we obtain

$$P_{\text{RCS}} = 1 - \sum_{i=N}^{C} \tilde{p}_N(i), \tag{2}$$

$$d_{\text{RCS}} = \frac{1}{1 - P_{\text{RCS}}} \sum_{i=N}^{C} i \tilde{p}_N(i), \tag{3}$$

$$\eta_{\text{RCS}} = \frac{\rho N (1 - P_{\text{RCS}})}{C P_{\text{RCS}} + (1 - P_{\text{RCS}}) d_{\text{RCS}}}, \tag{4}$$

where $\rho \in [0, 1]$ denotes the MAC overhead (coding rate).

V. NUMERICAL RESULTS

HARQ with Chase Combining based on a $1/2$-rate convolutional code is considered. Each IP packet is split into $N = 4$ fragments, and we put $M = 2$ for FBS, $C = 8$ for IBS, and $M_n = 2$, $n = 1, \ldots, 4$ for RCS.

In Fig. 1, we plot the IP level PER versus SNR for FBS, IBS, and RCS when $p_{\text{fb}} = 0$ and $p_{\text{fb}} = 0.1$. As claimed before, the PER is insensitive to imperfect feedback for FBS. However, the PER is dramatically degraded for IBS and even performs poorer than FBS. The proposed RCS not only performs better than FBS when $p_{\text{fb}} = 0$, but still performs better with imperfect feedback. Furthermore, RCS is only slightly degraded by imperfect feedback.

In Fig. 2, we plot the IP level efficiency versus SNR for FBS, IBS, and RCS when $p_{\text{fb}} = 0$ and $p_{\text{fb}} = 0.1$. All the schemes offer very close performance. Nevertheless, the proposed RCS performs slightly better than IBS for medium SNR.

In Fig. 3, we plot the required SNR to achieve a PER at IP level equal to p^0, versus p_{fb} for FBS, IBS and RCS. The proposed RCS performs better than FBS and is insensitive to imperfect feedback. On the other hand, the IBS performance strongly degrades and cannot achieve the required PER beyond a certain p_{fb} value due to the existence of error floors (see Fig. 1).

Notice that the transmission credits M_n may influence the performance and will be analyzed deeply in the final version.

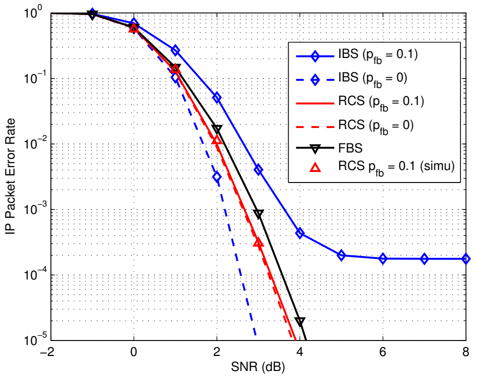

Figure 1. HARQ PER at IP level.

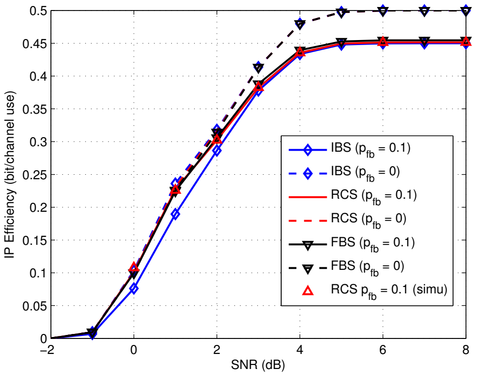

Figure 2. HARQ Efficiency at IP level.

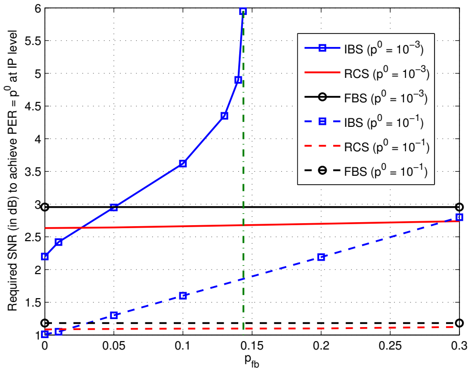

Figure 3. SNR versus p_{fb}.

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