Stop-and-Wait Hybrid-ARQ performance at IP level under imperfect feedback

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***Abstract*—We investigate several types of Stop and Wait HARQ schemes under imperfect feedback conditions. Performance are measured through the usual metrics, *i.e.* packet error rate, delay, and efficiency. The main novelties of this paper are twofold: i) the considered feedback undergoes the random arrival time of the acknowledgment. ii) the analysis is done at the network level (IP) which enlarges the vision of practical systems performance. In particular, our analysis enables us to consider a recent cross-layer MAC-IP allocation strategy. Finally our results provide a way to design the feedback link.**

I. Introduction

HARQ schemes improve mobile systems reliability since packet retransmissions are done upon packet error detection at the receiver side. The acknowledgement (ACK) or non-acknowledgement (NACK) of the packet decoding is done by means of a feedback channel. HARQ was investigated through numerous works under the assumption of ideal feedback, *i.e.* without errors in the acknowledgement messages and instantaneous return delay. For instance, [1–3] study HARQ performance at medium access (MAC) level, [4], [5] at network (IP) level and [6] at the application level. In this paper, we are interested in studying the effects of an unreliable feedback channel on the HARQ performance.

The main impairments on the feedback channel are twofold: *i)* the value of the acknowledgement message is not correctly decoded, *ii)* the acknowledgement message is not received instantaneously. In the last case, the round-trip time (RTT) defined as the time spent between a packet transmission and the reception of its corresponding acknowledgement at the transmitter side plays a great role. A (non-null) fixed/deterministic RTT leads to an efficiency/throughput reduction for the Stop-Wait (SW) protocol [7]. To overcome this fixed/deterministic RTT, the Go-Back-N (GBN) protocol [8] or the Selective-Repeat (SR) protocol [9], [10] may be of interest.

In the literature, only a small amount of analytical studies about the impact of non-ideal feedback on HARQ have been done. Actually, the case of null RTT only has been analyzed. In such a case, SW, GBN, and SR are equivalent even if the value of the acknowledgement is corrupted. Therefore only SW protocol was studied. Then, if the number of packet retransmissions is unlimited, delay and efficiency of a Type-I HARQ (that is fundamentally equivalent to an ARQ) are given in [7], [11]. Secondly, if the number of packet retransmissions is finite (referred to as *truncated* HARQ in the literature), an analytical expression of the efficiency is found in [12] for a Type-I HARQ and in [13] for a Type-II (only with Chase combining). When RTT is assumed to be non-zero but fixed/deterministic and known at the transmitter side, only [14] analyzed the influence on the delay of this unreliable and non-instantaneous feedback channel under SR protocol. Notice that all these existing works only focused on the performance at MAC level.

The purpose of this paper is to provide closed-form expressions for the packet error rate, the delay, and the efficiency associated with any type of truncated *SW* HARQ scheme in the context of the *IP layer* and the *random RTT*. Focusing on the IP layer is of great interest in order to have a better view of the whole system. Modeling RTT as a random variable can be especially well-adapted in the context of ad hoc networks. Moreover if TDD mechanism is employed (this is the case for UWB based ad hoc networks), the transmitter cannot send packet and listen to the reverse link simultaneously due to its half-duplex constraint. Consequently, GBN and SR cannot operate, and SW remains a relevant solution.

Notice that the proposed results extend those obtained in [4], [5], [15]. Indeed, in [4], [5], we only focused on HARQ performance (at the IP level) in the case of ideal reverse link. In [15], non-ideal reverse link (also at the IP level) was considered but with null RTT. The assumption of non-null and random RTT modifies dramatically the different proofs and closed-form expressions of the various metrics.

The rest of the paper is organized as follows. The HARQ schemes are introduced in Section II. The feedback model is described in Section III, and Section IV is devoted to the mathematical developments. Section V provides some numerical illustrations. Concluding remarks are drawn in Section VI.

II. HARQ schemes

We consider the same layer model as defined in [4]: at the MAC layer, we assume an IP packet is split into N fragments (FRAGs). These FRAGs are then transformed into MAC packets which are sent to the physical layer and thus which propagate through the channel. Let us denote by $p_n(k)$, $n, k \geq 1$, the probability of receiving n fragments in k MAC packets transmissions assuming perfect feedback. The closed-form expressions for $p_n(k)$ are available in [4].

Usually the maximum number of MAC packets transmitted per FRAG is finite and corresponds to the so-called *transmission credit*. Recently, [16] proposed a MAC-IP cross-layer improvement consisting in sharing the transmission credit amongst the set of fragments belonging to the same IP packet. This cross-layer approach will be called *IP-based strategy* (IBS), and the transmission credit shared by the N FRAGs is denoted by C. The standard one consisting in having the same value of transmission credit per fragment will be called *Fragment-based strategy* (FBS), and the transmission credit per FRAG is denoted by P.

The considered metrics are the packet error rate Π (PER), the average delay d defined as the average time for successfully decoding a packet [5], and the efficiency η. A subscript IP (resp. MAC) will stand for the performance at the IP (resp. MAC) level. A superscript F (resp. I) will be put for the metrics related to the FBS (resp. IBS) approach.

III. Imperfect feedback channel model

We consider an imperfect feedback with noisy channel and non-instantaneous random RTT. We assume that the feedback information integrity can be controlled at the transmitter side (by an error detection code for instance) in order to differentiate erroneous from error-free feedback frame (containing the acknowledgement message but also channel state information, etc). For instance, if the feedback information is detected with errors, we do not know what information is wrong, and thus all the feedback information will be wasted. We thus have the two following error events:

i) by assuming the error detection code powerful enough to neglect mis-detection, the ACK or NACK can be considered as error-free when no error detection occurs. Conversely, if an error is detected, we assume that a NACK is received. Such a model is in accordance with the literature [10], [13], [14]. Thus we get $\Pr\{\text{ACK} \to \text{NACK}\} = p_e$ and $\Pr\{\text{NACK} \to \text{ACK}\} = 0$.

ii) when the time for receiving a feedback is random, a time-out $\tau_0 > 0$ is usually introduced in order to prevent deadlock issues. To be more precise, if the RTT is larger than the time-out, then the feedback message is considered to be lost (seen as a NACK) [10].

We model the RTT as $T_0 + T$ where T_0 is the MAC packet duration and T is a continuous random variable defined by its density $\mathrm{d}F_T$. When ACK/NACK is erased, *i.e.*, $T_0 + T \geq \tau_0$, we have

$$p_c = \Pr\{T \geq \tau_0 - T_0\} = 1 - F_T(\tau_0 - T_0). \quad (1)$$

Hence, the considered model for the non-ideal feedback channel is the cascade of a binary erasure channel BEC and of a Z-channel with ternary input, as shown in Figure 1. This channel is equivalent to a Z-channel with a crossover probability

$$p_{\text{fb}} = p_c + (1 - p_c)p_e. \quad (2)$$

The transmitter receives NACK with an average transmission time depending on the initial feedback information

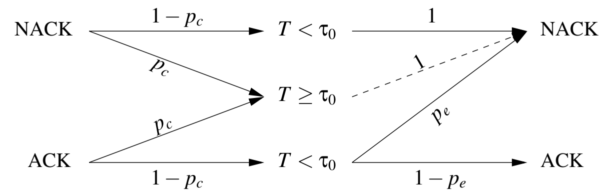

Figure 1. The reverse link modeled as a BEC-Z channel.

(ACK or NACK). So, the average time for receiving NACK given that an ACK has been sent is denoted by $\tau_{r,a} := T_0 + \mathbb{E}[T|\text{NACK Rx, ACK Tx}]$. The average time for receiving NACK given that a NACK has been sent is denoted by $\tau_{r,n} := T_0 + \mathbb{E}[T|\text{NACK Rx, NACK Tx}]$. Similarly, ACKs are received with a waiting time $\tau_a := T_0 + \mathbb{E}[T|\text{ACK Rx, ACK Tx}]$. After computing these expressions (proofs are omitted due to space limitation), one has

$$\tau_{r,a} = (p_c\tau_0 + p_e(1-p_c)\tau_a)/p_{\text{fb}}, \quad (3)$$

$$\tau_{r,n} = p_c\tau_0 + (1-p_c)\tau_a, \quad (4)$$

$$\tau_a = T_0 + \mathbb{E}[T|T < (\tau_0 - T_0)]. \quad (5)$$

IV. Performance evaluation

A. Preliminary results

Before going further, we introduce some useful terms in the context of imperfect feedback and we derive them.

For an integer $p \geq 1$, let $\alpha_{n,p}(i)$ be

- if $i < p$, the average time cost for receiving n FRAGs and their corresponding ACKs at the transmitter side in i MAC packet transmissions.
- if $i = p$, the average time cost for receiving $(n-1)$ first FRAGs and their corresponding ACKs at the transmitter side and for successfully decoding the n-th FRAG (whatever the acknowledgement message status) in i MAC packet transmissions.

Let $\beta_n(i)$ be the probability to receive n FRAGs and their corresponding ACKs in i MAC packet transmissions.

We are able to prove this proposition.

Proposition 1. *In the context of IBS, we have*

$$\begin{aligned}
\alpha_{N,C}(i) &= (1-p_{\text{fb}})^{N-\delta\{i=C\}} \sum_{k=N}^{i} \Big(i\tau_{r,a} - N(\tau_{r,n} - \tau_a) \\
&+ p_{\text{fb}}\delta\{i=C\}(\tau_{r,a} - \tau_a) - k(\tau_{r,a} - \tau_{r,n}) \Big) \\
&\times \binom{i-k+N-1}{N-1} p_N(k) {p_{\text{fb}}}^{i-k}, \\
\beta_n(i) &= \sum_{k=n}^{i} \binom{i-k+n-1}{n-1} p_n(k) {p_{\text{fb}}}^{i-k} (1-p_{\text{fb}})^n.
\end{aligned}$$

where $\delta\{A\}$ stands for the indicator function of A.

In the context of FBS, we will only need $\alpha_{1,P}(i)$ since we can work FRAG per FRAG. Then $\alpha_{1,P}(i)$ can be obtained by putting $N = 1$ and replacing C with P in Proposition 1.

Proof: Due to page limitation, we only provide a sketch of the proof for $\alpha_{1,P}(i)$. Similar derivations can be done for the other terms. When $i < P$, if the FRAG is decoded after k transmissions with any $k \in \{1, \cdots, i\}$, then the ACK is lost $(i-k)$ times before being received at the transmitter. Thus, $(k-1)$ NACKs were sent and received as NACKs for a duration cost $(k-1)\tau_{r,n}$. Moreover $(i-k)$ ACKs were sent and received as NACKs for a duration cost $(i-k)\tau_{r,a}$. Finally an ACK is necessarily received after the i-th transmission for a duration cost τ_a. Such an event has probability $p_1(k){p_{\text{fb}}}^{i-k}(1-p_{\text{fb}})$. For $i < P$, the proof is completed by adding all the previous events. When $i = P$, observe that $(P-1)$ NACKs are received but the last feedback message is an ACK with probability $(1-p_{\text{fb}})$ which leads to the slight modification in the given expression. ■

B. Performance for the (standard) FBS

Let us first remark that the PER *is not modified* by the noisy behavior of the reverse channel. Indeed, when a FRAG is correctly decoded at the receiver, all the possible subsequent retransmissions (coming from ACK erasures) of this packet are useless and are dropped whenever the reception is correct or not, until the transmitter correctly receives the ACK or until the transmission credit of the current FRAG is consumed. In [13], such a result has already been mentioned for the MAC level. Moreover the closed-form expression of Π_{IP}^F has been provided in [4].

Nevertheless, these useless transmissions due to the ACK erasures have a cost on the delay and on the efficiency. Under the assumption of i.i.d. FRAGs, like [5], the average delay (in time units) and the efficiency (in bits/symbol) are given by

$$d_{\text{IP}}^F = N d_{\text{MAC}} \text{ and } \eta_{\text{IP}}^F = \frac{T_0 \rho (1-\Pi_{\text{MAC}})^N}{\Pi_{\text{MAC}} \check{d}_{\text{MAC}} + (1-\Pi_{\text{MAC}}) d_{\text{MAC}}} \quad (6)$$

where d_{MAC} is the average delay at MAC level (*i.e.* when one FRAG is handled), and where $\check{d}_{\text{MAC}}$ is the average time spent when a FRAG reception failed, and ρ is the MAC overhead (coding rate, signaling, etc). The term T_0 appears in the efficiency numerator for homogeneity purpose since one MAC packet is sent over the channel within a time T_0.

The term d_{MAC} is derived as follows: we have to add the different average time costs for receiving one FRAG (and its associated ACK if this is not the last FRAG of the IP packet) over the number of transmit MAC packet. Since this delay only considers the successful fragments, we also have to divide by $(1-\Pi_{\text{MAC}})$. Therefore, we have

$$d_{\text{MAC}} = \frac{1}{1-\Pi_{\text{MAC}}} \sum_{i=1}^{P} \alpha_{1,P}(i). \quad (7)$$

Using Proposition 1 and Eq. (7) leads to

$$d_{\text{MAC}} = \frac{1}{1-\Pi_{\text{MAC}}} \sum_{i=1}^{P} \sum_{k=1}^{i} \big(i\tau_{r,a} - (\tau_{r,n} - \tau_a) + p_{\text{fb}} \delta\{i = P\} \\ (\tau_{r,a} - \tau_a) - k(\tau_{r,a} - \tau_{r,n}) \big) p_1(k) {p_{\text{fb}}}^{i-k} (1-p_{\text{fb}})^{\delta\{i<P\}}.$$

The term $\check{d}_{\text{MAC}}$ is derived as follows: the FRAG failed, thus the whole transmission credit P has been consumed and the receiver continuously sent NACK (note that it is impossible to receive ACK in that case) which costs $\tau_{r,n}$ for each MAC packet. Therefore we have $\check{d}_{\text{MAC}} = \tau_{r,n} P$.

C. Performance for the (cross-layer) IBS

Unlike FBS, the PER herein depends on the feedback channel quality since the i-th FRAG has a non-fixed credit depending on the number of transmissions used by the $(i-1)$ previous FRAGs. The probability of decoding the IP packet correctly with i MAC packet transmissions is equal to the probability that, for each $k \in \{N-1, \cdots, i-1\}$, $N-1$ FRAGs are correctly received in k MAC packet transmissions with their corresponding ACKs and the last FRAG is correctly received in $(i-k)$ MAC packet transmissions (independently of the correct reception of its associated ACK). Therefore, we have

$$\Pi_{\text{IP}}^I = 1 - \sum_{i=N}^{C} \sum_{k=N-1}^{i-1} \beta_{N-1}(k) p_1(i-k), \quad (8)$$

Similarly to the FBS case, we can obtain

$$d_{\text{IP}}^I = \frac{1}{1-\Pi_{\text{IP}}^I} \sum_{i=N}^{C} \alpha_{N,C}(i), \quad (9)$$

and

$$\eta_{\text{IP}}^I = \frac{T_0 \rho N (1-\Pi_{\text{IP}}^I)}{\check{d}_{\text{IP}} \Pi_{\text{IP}}^I + (1-\Pi_{\text{IP}}^I) d_{\text{IP}}^I}, \quad (10)$$

where $\check{d}_{\text{IP}}$ is the average delay given that the IP packet transmission has failed. It can be computed as:

$$\check{d}_{\text{IP}} = \frac{1}{\Pi_{\text{IP}}^I} \left(\sum_{n=1}^{N-1} \gamma_n(C) + \sum_{n=1}^{N} \theta_n(C) \right), \quad (11)$$

where $\gamma_n(C)$ is the average time cost for receiving $(n-1)$ FRAGs and their corresponding ACKs and for decoding the n-th FRAG in C transmissions, and where $\theta_n(C)$ is the average time cost for receiving $(n-1)$ FRAGs and their corresponding ACKs and not decoding the n-th FRAG in C transmissions.

The derivations for $\gamma_n(C)$ and $\theta_n(C)$ are rather tedious and are given without proof (due to the lack of space) in the next proposition.

Proposition 2.

$$\gamma_n(C) = (1-p_{\text{fb}})^{n-1} \sum_{\ell=n-1}^{C-1} \sum_{m=1}^{C-\ell} \Big((n-1)\tau_a + p_{\text{fb}} \tau_{r,a} \\ + (C-\ell-m)\tau_{r,a} + (\ell-n+m)\tau_{r,n} + (1-p_{\text{fb}})\tau_a \Big) \\ \times \binom{C-\ell-m+n-1}{n-1} p_{n-1}(\ell) {p_{\text{fb}}}^{C-\ell-m} p_1(m),$$

$$\theta_n(C) = (1-p_{\text{fb}})^{n-1} \sum_{\ell=n-1}^{C-1} \sum_{m=1}^{C-\ell} \Big((n-1)\tau_a + (C-\ell-m) \\ \times \tau_{r,a} + (\ell+m-n+1)\tau_{r,n} \Big) \binom{C-\ell-m+n-2}{n-2} \\ \times p_{n-1}(\ell) {p_{\text{fb}}}^{C-\ell-m} q(m),$$

where $q(k) = 1 - \sum_{i=1}^{k} p_1(i)$ *is the failure probability of a single FRAG after* k *transmissions.*

To our best knowledge, in the literature (see [11–13]), the analysis of SW HARQ schemes with imperfect feedback has been done with instantaneous noisy feedback only (*i.e.*, $T = 0$) and at the MAC level (*i.e.*, $N = 1$). In that case, we have $p_c = 0$ (so, $p_{\text{fb}} = p_e$) and $\tau_{r,n} = \tau_{r,a} = \tau_a = T_0$ (from Eqs. (2)-(5) respectively). These simplifications enable us to retrieve all the existing expressions given in the literature. So, the contribution of this paper is to focus on the IP level ($N \neq 1$) and on the non-instantaneous random acknowledgement delay ($T \neq 0$).

V. Numerical results

For the sake of presentation simplicity, we will only consider performance of a standard ARQ (corresponding to Type-I HARQ without FEC) and of a (Type-II) HARQ with Chase Combining (referred as CC-HARQ), both in FBS and IBS. The simulations are run through a Gaussian (AWGN) channel. Each MAC packet has 128 information bits, and the HARQ scheme is coded with a $1/2$-rate convolutional code with generators (35,23). Next, these bits are sent over a QPSK constellation. The imperfect feedback link is built as follows: T is exponentially distributed with parameter $\lambda > 0$, where $1/\lambda$ is the expected arrival time. After simple algebraic manipulations, we get $p_c = e^{-\lambda(\tau_0 - T_0)}$ and $\mathbb{E}[T | T < (\tau_0 - T_0)] = 1/\lambda - (\tau_0 - T_0)p_c/(1 - p_c)$.

In Figure 2 (resp. 3), we plot the theoretical delay and the empirical one (obtained through extensive simulations) at the IP level versus SNR for FBS (resp. IBS) when the ARQ and CC-HARQ are considered. The error rate for the reverse link is fixed to $p_e = 0.1$. We observe a very good agreement between the analytical and the simulation results. Similar results have been obtained with the other metrics (PER and efficiency).

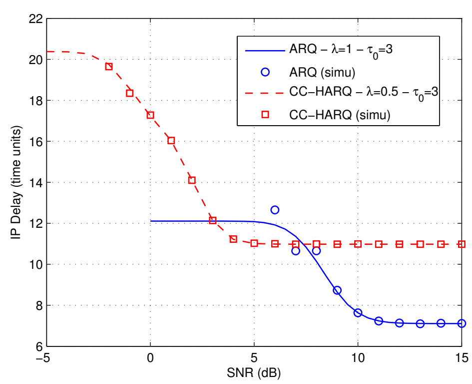

Figure 2. Delay (theoretical and empirical) versus SNR at IP level for various HARQ schemes. (FBS, $N = 3$, $P = 3$)

Now we would like to analyze the influence of the non-ideal feedback on the performance. Since the simulations and the theoretical results are close, we will plot the delays, PER and efficiency using the closed-form expressions only. Simulations with $p_e \neq 0$ but $T = 0$ are available in [15], thus hereafter we focus on the influence of the non-instantaneous feedback only ($p_e = 0$ but $T \neq 0$).

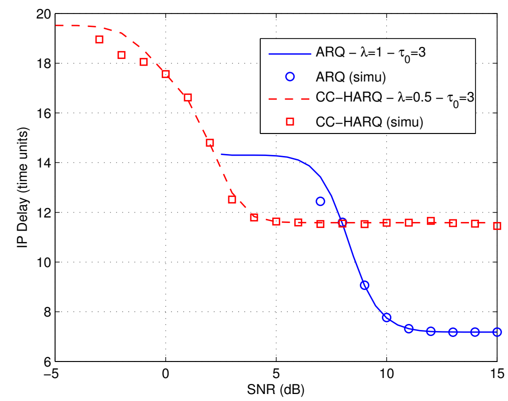

Figure 3. Delay (theoretical and empirical) versus SNR at IP level for various HARQ schemes. (IBS, $N = 3$, $C = 9$)

In Figure 4, the delay at the IP layer of the CC-HARQ scheme is displayed versus SNR for a given expected feedback arrival time λ and various time-out τ_0. The ideal feedback case is also displayed for benchmarking. The delay of IBS scheme is better than the FBS one at very low SNR (unlike observed in [5] for ideal feedback), and the time-out value has less influence on FBS scheme than on IBS at high SNR.

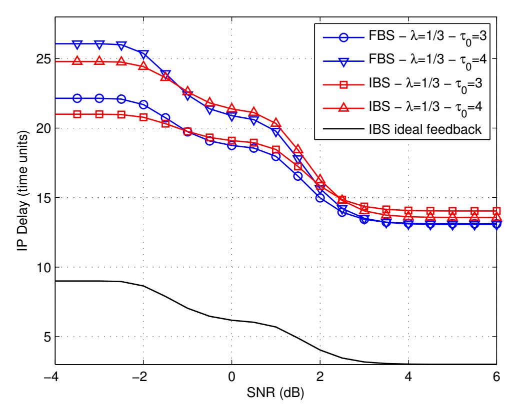

Figure 4. Delay versus SNR at IP level of CC-HARQ for FBS and IBS. ($\lambda = 1/3$ and various time-out values, $N = 3$, $P = 3$, $C = 9$).

In Figure 5, we plot the delay at the IP layer of the ARQ scheme versus the time-out τ_0 for different SNRs. Once again, the ideal feedback case is also considered. Finally, the time-out has to be chosen small enough for keeping moderate delay.

Nevertheless choosing the time-out too small will likely lead to an increase of the PER since we will accept less acknowledgement messages. Therefore, in Figure 6, the PER of the CC-HARQ scheme is plotted versus SNR for various time-out τ_0. As stated before, the PER is not modified for FBS. In contrast, for the IBS, the PER is significantly degraded and an error floor occurs, which is a drawback as the main

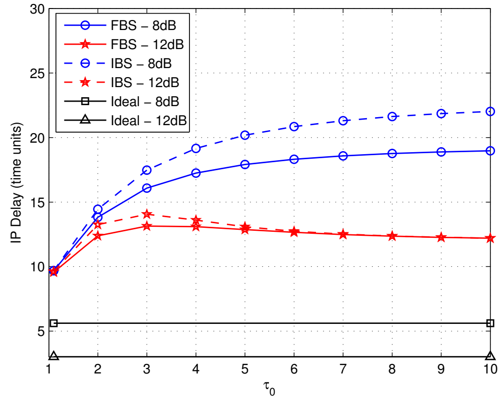

Figure 5. ARQ delay versus time-out at IP level for FBS and IBS. ($\lambda = 1/3$, $N = 3$, $P = 3$, $C = 9$)

interest of the IBS compared to the FBS was the gain in PER [16]. Moreover, the PER error floor decreases when the time-out increases. So, the time-out choice gives rise to a trade-off between the delay and the PER.

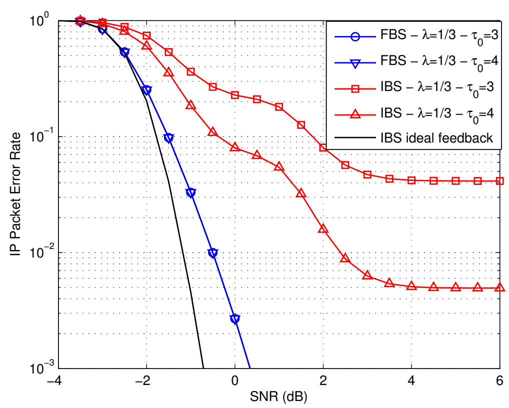

Figure 6. PER versus SNR at IP level of CC-HARQ for FBS and IBS. ($\lambda = 1/3$ and various time-out values, $N = 3$, $P = 3$, $C = 9$)

In Figure 7, we plot the efficiency versus the time-out for the ARQ scheme. It is observed that a large time-out leads to a lower efficiency for FBS, but leads to a little increase for the IBS efficiency. However, for increased time-out values, the efficiency quickly becomes quiet independent of the time-out for the two strategies.

It is finally seen that IBS performs less than FBS in terms of efficiency: this can be explained by the high sensitivity of the PER if the IBS to feedback erasures.

VI. Conclusion

In this paper we analyzed the effect of an unreliable feedback channel (error and random delay on this channel) on HARQ performance at IP level. Closed-form expressions were derived for the main metrics, *i.e.*, PER, delay and efficiency for two different retransmission strategies (a standard one and

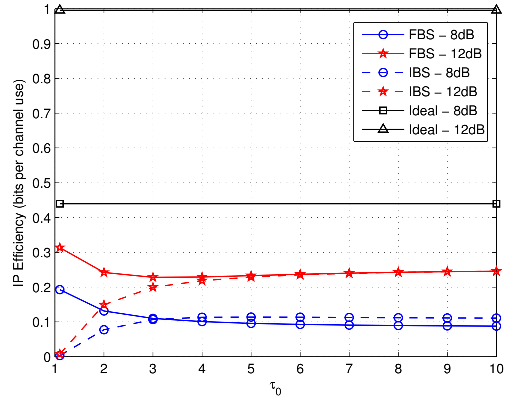

Figure 7. ARQ efficiency versus time-out, at IP level, for FBS and IBS. ($\lambda = 1/3$, $N = 3$, $P = 3$, $C = 9$).

a cross-layer one). Numerical analysis have been done in order to analyze the merits of each strategy when imperfect feedback occurs. Actually, the cross-layer one offers a better delay at low SNR while the standard one leads to a better efficiency.

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