Analysis of a cross-layer Hybrid-ARQ scheme: application to unequal packet protection

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***Abstract*— In order to improve the reliability of any HARQ technique at the IP level, a cross-layer strategy between the MAC and the IP levels has been recently developed in [1]. This strategy consists in replacing a retransmisssion credit per MAC packet with a retransmission credit per IP packet. In other words, the transmission credit is shared by the MAC packets belonging to the same IP packet. Packet Error Rate, throughput, delay and jitter for this new approach have been extensively analyzed in [1], [2]. In this paper, we remark and theoretically prove that the first MAC packets are better protected than the last ones. This leads to a natural "unequal packet loss protection" that can be useful in many applications, such as video streaming, compressed image transmission, audio and protocols (TCP/IP). Exploiting this novel manner of protecting packets unequally may not exclude the use of the standard manners, such as different feedforward error correcting codes (FEC), modulation size, or hybrid ARQ scheme per required quality of protection. Finally, our claims are supported by numerical simulations.**

I. Introduction

In real systems, in order to protect the data against transmission errors, it is usual to carry out Feedforward Error Coding (FEC) at the PHY layer and to add an Automatic ReQuest (ARQ) mechanism at the MAC layer. To still improve the transmission reliability, a combination of both approaches can be done and leads to the so-called Hybrid ARQ (HARQ) scheme [3]. This HARQ scheme is located at the MAC layer. By taking into account the presence of the IP layer (in the context of TCP-IP protocol), it is possible to optimize the HARQ scheme in the following way [1]: instead of having a transmission credit per MAC packet, it is of interest to share the total transmission credit among all the MAC packets belonging to the same IP packet. This technique enables us to improve the Packet Error Rate (PER) at the IP level significantly. In this paper, focusing on the MAC level, we will see and prove that the MAC packets belonging to the same IP packet are inherently unequally protected if the above-mentioned cross-layer optimization is considered.

Before going further, we recall that it is worthy of protecting the data, and thus the packets, differently for some applications. For instance, in the video streaming context, the data associated with the first image (called usually I-Frame where I stands for Intra-coded) have to be more protected than the data associated with the other images (called usually P-Frames where P stands for Prediction) representing the motion in the video sequence [4], [5]. Similar issue has to be addressed in the context of scalable image where the image is decomposed through a discrete-cosine transform or a wavelet transform for which the data associated with the low-frequency image decomposition are more important than the data corresponding to the high-frequency image decomposition [7], [8]. Equivalent issues arise in voice transmission [9]. Lastly, in IP context, the IP header has to be read correctly. As a corollary, for some other applications (such as the voice), some MAC packets (actually the less important ones) belonging to the same IP packet can be lost without affecting significantly the system performance [10], [11] and thus it can be interesting to forward these partially corrupted IP packets to the upper layer [13].

In the literature, one can find various ways to do unequal packet protection: for instance, a more robust coding scheme is applied to the packets that have to be more protected. If HARQ scheme is carried out, the packet to be more protected is protected with a more powerful HARQ scheme in which the transmission credit may be higher or the underlying coding scheme may be stronger [14]. As already explained before, we exhibit an additional (and so complementary) way for protecting the packets in an unequal manner by using the cross-layer HARQ scheme introduced in [1].

Therefore, we consider that it is of interest to inspect the following problems:

- what is the error probability of each MAC packet belonging to the same IP packet in the framework of [1]? Once the derivations have been done, is each MAC packet really unequally protected?
- what is the probability to get a certain number of erroneous MAC packets out of all the MAC packets belonging to the same IP packet?

This paper is organized as follows : in Section II, we introduce the system model and we remind some basic results about derivations of packet error rate. In Section III, we derive the probability to erroneously receive each MAC packet belonging to the same IP packet for the XO strategy. We prove that this probability depends on the location of the considered MAC packets in the IP packet which lead to an unequal packet protection. In Section IV, we derive the probability to successfully receive a given number of MAC packets among the whole set of MAC packets belonging to the same IP packet. Section V is devoted to numerical illustrations. Conclusions are drawn in Section VI.

II. System model

A. HARQ scheme and cross-layer optimization

For the sake of clarity, we consider i) an IP protocol based communication, ii) a single user context. Only the three first ISO layers are taken into account: the PHY layer, the MAC layer, and the IP layer. At the transmitter side, the MAC layer has to transmit several IP packets of length L_{IP}. Each IP packet is split into N MAC packets of length $L_{\mathrm{MAC}} = L_{\mathrm{IP}}/N$. From each MAC packet, some subblocks are generated in order to be transmitted by the PHY layer [3], [12].

The way to generate the subblocks enables us to partially distinguish the different kinds of HARQ from each other. Due to the lack of space and for the sake of simplicity, we hereafter only introduce the so-called IR-HARQ (where IR stands for Incremental Redundancy). Notice that our later derivations actually hold for any kind of HARQ.

Let us move on to a brief IR-HARQ description. Each MAC packet for which an header and a CRC have been added is encoded by a Forward Error Correcting Code of rate R_0 (known as *mother code*). The encoded MAC packet is then split into t_0 PHY packets, usually thanks to a puncturing technique of the mother code. The PHY packets (denoted $\mathrm{PPACKET}$) associated with the same MAC packet are then numbered as $\{\mathrm{PPACKET}(i)\}_{i=1}^{t_0}$. The transmitter starts to transmit $\mathrm{PPACKET}(1)$, then $\mathrm{PPACKET}(2)$ (if a NACK is received), then $\mathrm{PPACKET}(3)$ (if a second NACK is received) and so on up to $\mathrm{PPACKET}(t_0)$. If the MAC packet is still not received after the transmission of the last PHY packet $\mathrm{PPACKET}(t_0)$, the first PHY packet $\mathrm{PPACKET}(1)$ is transmitted again and so on. These PHY packets are sent through a propagation channel (that may be Gaussian one, Rayleigh one Frequency-Selective one, etc).

At the receiver side, the incoming PHY packet is decoded and sent to the MAC layer which decides to send back an ACKnowledgment (ACK) or a Negative ACKnowledgment (NACK) to the transmitter accordingly. To make a decision on the MAC packet, the receiver has the following sequential process: checking the CRC for $\mathrm{PPACKET}(1)$; if $\mathrm{PPACKET}(1)$ is not correctly received, it sends a NACK and it receives afterwards $\mathrm{PPACKET}(2)$. Then checking the CRC of the both previous PHY packets concatenation (associated with a FEC of lower rate), and so on until the reception of $\mathrm{PPACKET}(t_0)$ which is concatenated with the $(t_0 - 1)$ previous PHY packets and then decoded with mother code of rate R_0 followed by the CRC checking. Then, if the MAC packet is not received after $\mathrm{PPACKET}(t_0)$ decoding and the transmission credit is not reached, the received packet memory is flushed (put to zero) and the process starts again.

We recall that, in a conventional manner, the PHY packet transmission credit is the same for each MAC packet and is denoted by $P_{\max}$. But one can remark that each correctly received MAC packet is sent to IP layer, and the IP packet corresponding to N MAC packets is considered to be correctly received only if each associated MAC packet is correctly received. For instance, as soon as one MAC packet is not correctly received, the associated IP packet is dropped. Based on this statment, [1] has proposed to enhance the ARQ scheme by providing a global transmission credit, noted C, to the set of MAC packets belonging to the same IP packet. Notice that a straightforward extension to HARQ scheme to this principle has been given in [2]. Thus, rather than allowing each of the N MAC packets (belonging to the same IP packet) to be transmitted $P_{\max}$ times, the new scheme allocates C transmissions to the set of the N MAC packets. This strategy constitutes a cross-layer optimization between MAC and IP layers. In the later we will refer the conventional one to as Non Optimized strategy (NO) and the cross-layer one to as Cross-layer Optimized-based Strategy (XO). We remind that the main goal of this paper is to prove that XO strategy offers inherently unequal packet protection.

B. Brief review about packet error rate derivations

As we mainly focus on XO strategy, we need to give some existing results about the packet error rate derivations at the IP level (and not at the MAC level) [2]. This paragraph also enables us to introduce some useful notations. We hereafter assume for the sake of simplicity that the ACK/NACK transmissions are delay-free and error-free. All the closed-form expressions about the PER only depend on the elementary packet error rate π_j defined as the PER corresponding to the $(j+1)$-th PHY packet transmission when the j previous PHY transmissions associated with the same MAC packet have failed. Notice that those packet error rates π_j are computed only once (by simulation). The packet error rate at the IP level, denoted by Π, is defined as the ratio between the number of erroneously received IP packets and the number of transmitted IP packets.

In [2], it is proven that the packet error rate for XO strategy, denoted by Π^{XO}, takes the following form

$$\Pi^{\mathrm{XO}} = 1 - \sum_{k=N}^{C} p_N^{\mathrm{XO}}(k). \tag{1}$$

where $p_N^{\mathrm{XO}}(k)$ is defined as the probability that N successive MAC packets (belonging to the same IP packet) are successfully received in exactly k PHY packet transmissions when XO strategy is considered.

Then the $p_N^{\mathrm{XO}}(k)$ can be expressed as a function of $p_1(k)$ which is the probability that one MAC packet is received correctly after exactly k PHY packet transmissions and which is independent of the cross-layer strategy. In [2], it is written that

$$p_N^{\mathrm{XO}}(k) = \sum_{\vec{\mathbf{q}} \in Q_{k,N}} p_1(q_1)p_1(q_2)\cdots p_1(q_n) \tag{2}$$

where $\vec{\mathbf{q}} := (q_1, q_2, \cdots, q_N)$ and where the summation set $Q_{k,N} = \{(q_1, q_2, \cdots, q_N) | \sum_{i=1}^{N} q_i = k, 0 < q_i\}$ takes into account the fact that the N packets are received in exactly k transmissions. Actually Eq. (2) is useless in practice due to the high complexity for the determination of the set $Q_{k,N}$. To overcome this drawback, as remarked in [1], [2], Eq. (2) can be calculated recursively as follows

$$p_N^{\mathrm{XO}}(k) = \sum_{k'=1}^{k-N+1} p_1(k') p_{N-1}^{\mathrm{XO}}(k-k'). \quad (3)$$

Lastly, whatever the retransmission scheme and the cross-layer strategy, $p_1(k)$ takes the following generic form

$$p_1(k) = \begin{cases} (1-\pi_0) & \text{for } k=1 \\ (1-\pi_{k-1}) \prod_{j=0}^{k-2} \pi_j & \text{for } k>1 \end{cases}. \quad (4)$$

Remark 1: In [2], the packet error rate for the NO strategy, denoted by Π^{NO}, *is as follows*

$$\Pi^{\mathrm{NO}} = 1 - \left(\sum_{k=1}^{P_{\max}} p_1(k) \right)^N. \quad (5)$$

Notice that the MAC packet error rate at the MAC layer, denoted by $\Pi^{\mathrm{NO}}_{\mathrm{MAC}}$, *is obtained by putting* $N=1$ *in Eq. (5) and is equal to* $\Pi^{\mathrm{NO}}_{\mathrm{MAC}} = 1 - \sum_{k=1}^{P_{\max}} p_1(k)$ *which is independent of the MAC packet. Thus, the NO strategy does not yield unequal packet protection.*

III. Error Probability for each MAC packet

In this section, we will show that the XO strategy provides by construction an unequal packet loss protection for the different MAC packets.

Before deriving the probability to successfully receive the i-th MAC packet, we roughly justify that XO scheme is appropriate for doing unequal data protection. The first MAC packet can be transmitted as many times as needed, as long as the global transmission credit C is not reached. Once the first MAC packet is received without error, the second MAC packet is then sent and can be only retransmitted as long as the global transmission credit C minus the credit used by the first MAC packet is not reached. Therefore, by noting k_1 the number of transmissions used by the first MAC packet, there are $C - k_1$ possible transmissions for the second one. By assuming that the second MAC packet is successfully received after k_2 transmissions (thus $k_1 + k_2$ transmissions have been already used by the two first MAC packets), the third MAC packet can be sent $C-(k_1+k_2)$ times at most. And so on until either the N MAC packets (belonging to the same IP packet) are successfully received or the global transmission credit C is reached. Thus the first MAC packet seems to have the highest probability to be received without errors. More generally, we argue that the probability to successfully receive the i-th MAC packet is more important than the one to successfully receive the $(i+1)$-th MAC packet. Hence, the cross-layer approach seems to allow an unequal protection of the data and thus, is a judicious choice for applications presented in Section I.

Let us move now on to the derivations. Let $R_N^{\mathrm{XO}}(i)$ be the probability to receive erroneously i-th MAC packet belonging to the same IP packet consisting of N MAC packets in XO context. The probability to successfully receive the i-th MAC packet, knowing that the global transmission credit is C, is equivalent to the probability to successfully receive the i first MAC packets of the same IP packet in C transmissions at most. Indeed, if the $(i-1)$ previous MAC packets are received with error, the i-th MAC packet would not be transmitted and would be considered as erroneous. We then obtain

$$R_N^{\mathrm{XO}}(i) = 1 - \sum_{k=i}^{C} p_i(k), \quad \forall 1 \le i \le N. \quad (6)$$

In the next proposition, we prove that the probability to successfully receive the i-th MAC packet is more important than the one to successfully receive the $(i+1)$-th MAC packet in the XO context.

Proposition 1: Whatever the kind of HARQ scheme, we have

$$R_N^{\mathrm{XO}}(i) < R_N^{\mathrm{XO}}(i+1)$$

Proof: Thanks to Eq. (3), we have

$$p_{i+1}^{\mathrm{XO}}(k) = \sum_{j=1}^{k-i} p_1(j) p_i^{\mathrm{XO}}(k-j).$$

By considering the following variable change, $j' = k - j$, we obtain that

$$p_{i+1}^{\mathrm{XO}}(k) = \sum_{j'=i}^{k-1} p_1(k-j') p_i^{\mathrm{XO}}(j').$$

Then

$$R_N^{\mathrm{XO}}(i+1) = 1 - \sum_{k=i+1}^{C} \sum_{j=i}^{k-1} p_1(k-j) p_i^{\mathrm{XO}}(j)$$

By permuting the two sums, we have

$$R_N^{\mathrm{XO}}(i+1) = 1 - \sum_{j=i}^{C-1} \left(\sum_{k=j+1}^{C} p_1(k-j) \right) p_i^{\mathrm{XO}}(j)$$

As

$$\sum_{k=j+1}^{C} p_1(k-j) = \sum_{k=1}^{C-j} p_1(k),$$

the term $\sum_{k=j+1}^{C} p_1(k-j)$ corresponds to the packet error rate at the MAC layer when the transmission credit is $C-j$ (cf. Eq. (5)), and thus this term is less than 1. Consequently

$$R_N^{\mathrm{XO}}(i+1) > 1 - \sum_{j=i}^{C-1} p_i^{\mathrm{XO}}(j).$$

Moreover $1 - \sum_{j=i}^{C-1} p_i^{\mathrm{XO}}(j) = R_N^{\mathrm{XO}}(i) + p_i^{\mathrm{XO}}(C)$ and the term $p_i^{\mathrm{XO}}(C)$ is positive which concludes the proof. ■

In order to operate these unequal packet loss protection schemes, we need to let the MAC layer send the IP datagrams even with corrupted MAC packets to the IP layer. The receiver has to be modified accordingly and has to know the maximum number of corrupted MAC packets that it can allow within one IP packet as suggested in [13].

IV. Error Probability for a set of MAC packets

In this section, we will derive the probability to receive an IP packet in which at least i MAC packets are not correctly received. This probability is denoted by $T_N^{\rm s}(i)$ (with $\rm s \in \{XO, NO\}$) and one can easily check that

$$T_N^{\rm s}(i) = \sum_{j=i}^{N} S_N^{\rm s}(j)$$

where $S_N^{\rm s}(i)$ is the probability to have i erroneous MAC packets among N MAC packets belonging to the same IP packet. By "erroneous MAC packet", we mean that the MAC packet is received with error or is never transmitted.

As $S_N^{\rm s}(i)$ is positive, we have $T_N^{\rm s}(i+1) < T_N^{\rm s}(i)$. Moreover, by construction, we get $T_N^{\rm s}(1) = \Pi^{\rm s}$.

Let us start with the XO strategy. Thus, the i erroneous MAC packets are necessarily the last ones. Indeed, while a MAC packet is not successfully received, the remainding MAC packets are not sent. Then, the probability to have i erroneous MAC packets is equivalent to the probability to receive only $(N-i)$ MAC packets in exactly C transmissions and to receive only $(N-i)$ MAC packets in less than C transmissions when the $(N-i+1)$-th MAC packet is transmitted but always received with error. In other words, we get, for $i \in \{1, \cdots, N-1\}$,

$$S_N^{\rm XO}(i) = \sum_{k=N-i}^{C-1} p_{N-i}^{\rm XO}(k)\left(1 - \sum_{k'=1}^{C-k} p_1(k')\right) + p_{N-i}^{\rm XO}(C). \quad (7)$$

When $i \in \{0, N\}$, we also can prove in a similar way that

$$S_N^{\rm XO}(N) = 1 - \sum_{k=1}^{C} p_1(k) \text{ and } S_N^{\rm XO}(0) = \sum_{k=N}^{C} p_N^{\rm XO}(k). \quad (8)$$

The right hand side equation in Eq. (8) is obviously equal to $1 - \Pi^{\rm XO}$ since the probability to have no erroneous MAC packet among N is equivalent to the probability to have successfully received all the N MAC packets.

Let us move on to the NO strategy. In the NO strategy, having i erroneous MAC packets among N is equivalent to assert that $N-i$ MAC packets are received without error and that i MAC packets are received with error even after having used all their transmission credits. Receiving a MAC packet without error occurs with probability $\sum_{k=1}^{P_{\rm max}} p_1(k)$. Receiving a MAC with error occurs with probability $1 - \sum_{k=1}^{P_{\rm max}} p_1(k)$. Consequently the final expression is

$$S_N^{\rm NO}(i) = \binom{N}{N-i}\left(\sum_{k=1}^{P_{\rm max}} p_1(k)\right)^{N-i}\left(1 - \sum_{k=1}^{P_{\rm max}} p_1(k)\right)^{i}. \quad (9)$$

The binomial coefficient, $\binom{N}{N-i}$, is due to the fact that the indices of the i erroneous MAC packets can be taken among all the N MAC packets. After simple derivations, we have

$$T_N^{\rm NO}(i) = \binom{N}{N-i}\left(1 - \sum_{k=1}^{P_{\rm max}} p_1(k)\right)^{i}\left(\sum_{k=1}^{P_{\rm max}} p_1(k)\right)^{N-i} \times {}_2F_1\left(1, i-N; 1+i; 1 - \frac{1}{\sum_{k=1}^{P_{\rm max}} p_1(k)}\right)$$

where ${}_2F_1(\bullet)$ is the so-called hypergeometric function.

Thanks to these expressions, we prove the next proposition.

Proposition 2: For any IR-HARQ scheme such that $C = NP_{\rm max}$ and $P_{\rm max}$ proportional to t_0, we have

$$T_N^{\rm XO}(N) = T_N^{\rm NO}(N)$$

Proof: For any IR-HARQ scheme, we have $\pi_{mt_0+m'} = \pi_{m'}$. As it exists an integer a such that $P_{\rm max} = at_0$, we get $p_1(mt_0+m') = p_1(m')q^m$ with $q = \prod_{j=0}^{t_0-1}\pi_j$. By recalling Eq. (8) and by putting $i = N$ in Eq. (9), we obtain that

$$T_N^{\rm XO}(N) = 1 - \sum_{k=1}^{C} p_1(k), T_N^{\rm NO}(N) = \left(1 - \sum_{k=1}^{P_{\rm max}} p_1(k)\right)^{N}.$$

The expression of $T_N^{\rm XO}(N)$ can be modified as follows

$$T_N^{\rm XO}(N) = 1 - \sum_{k=1}^{Nat_0} p_1(k) = 1 - \sum_{m=0}^{Na-1}\sum_{m'=1}^{t_0} p_1(mt_0+m')$$

Moreover, one can prove that $q = 1 - \sum_{k=1}^{t_0} p_1(k)$. As a consequence, after straightforward algebraic manipulations, $T_N^{\rm XO}(N)$ can be simplified as follows

$$T_N^{\rm XO}(N) = \left(1 - \sum_{k=1}^{t_0} p_1(k)\right)^{Na}$$

Similar derivations for $T_N^{\rm NO}(N)$ leads to the same expression. ■

In contrast, as $T_N^{\rm s}(1) = \Pi^{\rm s}$, we already proved in [2] that $T_N^{\rm XO}(1) < T_N^{\rm NO}(1)$.

V. Numerical illustrations

In this simulation part, the theoretical and empirical evaluations of the different error rates are done under the following assumptions:

- IR-HARQ scheme is implemented by means of the Rate Compatible Punctured Convolutional (RCPC) codes with a mother code rate of $R_0 = 1/4$ [15]. The number of MAC packets per IP packet is $N = 3$. The number of bits per MAC packet is $L_{\rm MAC} = 120$. We use a QPSK modulation. The global transmission credit is $C = 24$ (for the XO strategy).
- We consider an Additive White Gaussian Noise channel.
- As done for the derivations, the ACK/NACK feedback is error-free. The CRC is also assumed to be ideal.

Theoretical expressions are obtained by inserting the estimated values of π_j (for $j \in \{0, \cdots, t_0-1\}$). Empirical packet error rates are obtained by sending thousand IP packets.

In Fig. 1, we represent the PER per MAC packet index versus the SNR in the XO strategy and the PER per MAC packet (independent of the index) for the NO strategy. We observe that theoretical and empirical results perfectly match. Furthermore, as previously proven, $R_N^{\mathrm{XO}}(i)$ is smaller than $R_N^{\mathrm{XO}}(i+1)$, i.e., the more protected MAC packets are the first ones. In the NO strategy, in order to be fair for comparing the relative performance of both contexts, we fix the following constraint: $C = NP_{\max}$. We remark that at medium and high SNR even the worst protected MAC packet in the XO strategy is more protected than any MAC packet in the NO strategy. Only at very low SNR, the last MAC packets within the IP packet for the XO strategy undergo a loss in performance compared to those of the NO strategy. Consequently, compared to the NO strategy, the XO strategy is very efficient relatively (since it enables us to do unequal packet protection which is an advantage for several real systems) and even absolutly (since each MAC packet is better protected than for the NO strategy at operating SNR).

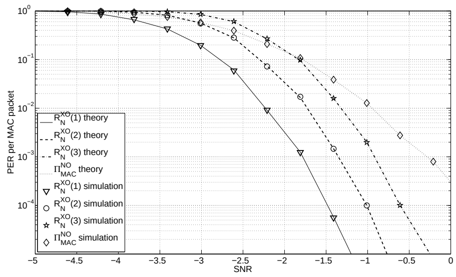

Fig. 1. Theoretical and empirical PER versus SNR for different MAC packet indices in the XO strategy and for any MAC packet in the NO strategy.

In Fig. 2, we respectively plot $T_N^{\mathrm{XO}}(i)$ and $T_N^{\mathrm{NO}}(i)$ versus SNR for different values of i. Theoretical results are identical to empirical ones, what shows that the closed-form expressions given by (7) and (9) are valid. Once again, the XO strategy offers better performance than the NO strategy except when $i = N$ as proven in Proposition 2. Furthermore, we remark that, if the constraint on the whole integrity of IP packet is relaxed (which is possible for some applications as soon as the IP layer is application-aware), then the gain in energy consumption can be significant.

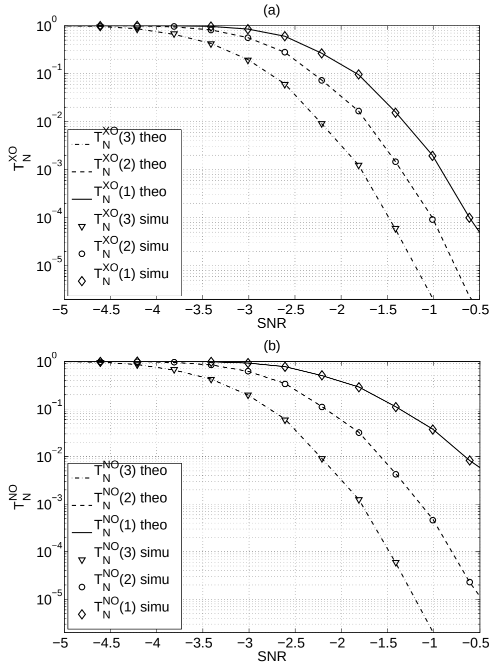

Fig. 2. Theoretical and empirical probability to have i erroneous MAC packets among N for (a) the XO strategy, and (b) the NO strategy.

VI. Conclusion

We have shown that the cross-layer strategy for HARQ scheme introduced in [1] induces an unequal packet loss protection. This can be a relevant approach for practical scheme such as multimedia application. Our claims are based on theoretical analysis and have been confirmed through numerical simulations.

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