A Competitive AL-FEC Framework over Mobile Multicast Delivery

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***Abstract*—Reliability control is a key concern on the evolution of real-time mobile multicast services. To this direction the use of forward error correction (FEC) on the application layer is widely adopted in several mobile multicast standards. FEC is a feedback free error control method where the transmitter introduces in advance redundant information to enable receivers recovering data erasures. On multicast delivery and especially on the time constrained streaming delivery where retransmission-based error recovery methods are not feasible, the most suitable error control method is the use of application layer forward error correction (AL-FEC) codes. In this work, we introduce a novel AL-FEC deployment policy over mobile multicast standards utilizing online algorithms. We aim on the efficient application of AL-FEC protection with RaptorQ codes over multicast streaming delivery in the context of competitive analysis. We provide a competitiveness analysis model of AL-FEC application over mobile multicast real-time environments and we introduce an innovative online algorithm adjusting the introduced redundancy of AL-FEC protection according to the FEC encoding parameters in order to satisfy the individual constraints of a multicast streaming delivery.**

***Keywords*-forward error correction, RaptorQ codes, mobile multicast networks, real-time delivery, online algorithms, competitive analysis**

I. INTRODUCTION

Forward Error Correction (FEC) is a protection method against packet losses adopted in several multicast standards. FEC concept, unlike the common methods of error control (e.g. ARQ, Carousel), is based in its “forward” feature where redundant information is transmitted in advance with the source data in order to enable a receiver to overcome data erasures, making FEC a feedback-free mechanism. The feedback-free feature of FEC perfectly matches the individual constraints of a radio multicast transmission where feedback reports are costly or even impossible [1]. Based on this, several mobile multicast standards have introduced FEC protection on the application layer (AL-FEC) of its multicast services boosted by powerful AL-FEC codes, i.e. Raptor codes family [2], that have recently emerged.

However, FEC protection comes with its own cost since controlling the introduced redundancy is not a trivial issue. The multicast sender should introduce enough redundancy on the transmission so as to ensure that the recipients will be able to reconstruct the transmitted object recovering arbitrary data losses while, at the same time the redundant information should be adapted at the current reception conditions to avoid resources wastage. On real-time content delivery, where data reception is tightly time-constrained, the use of retransmission-based methods to confront packet losses is not appropriate. An efficient method to obtain reliability to the real-time service transmission is to introduce enough redundancy (i.e., the AL-FEC transmission overhead) so that each packet is transmitted only once. The multicast sender should decide on the most suitable amount of overhead will transmit, in order to cope with different receiver’s packet loss rates. Moreover, the transmitter has to decide on the amount of protection will introduce to each encoded AL-FEC source block upon its construction without prior knowledge on the packet loss conditions has to cope with. Based on this, the design of an algorithm adjusting the introduced AL-FEC transmission overhead can be reduced on the basis of an online problem. Online problems assume that complete knowledge of the entire input is not available to an algorithm and the input is revealed in parts, with an online algorithm responding to each new input upon arrival.

In general, online algorithms [3] are used to confront problems where the input of the algorithm is not available in advance. Subsequently, online algorithms have to generate output without knowledge of the entire input since input information arrives in the future and is not accessible at present. The effectiveness of online algorithms is evaluated using competitive analysis. The main concept of competitiveness is to compare the output generated by an online algorithm to the output produced by an optimal offline algorithm. The competitive ratio of an online algorithm A is defined with respect to an adversary. In general, the adversary generates a sequence σ and the online algorithm A has to serve σ. When constructing the sequence σ, the adversary always knows the description of the online algorithm A. The optimal offline algorithm knows the entire request sequence in advance and can serve it with minimum cost. Formally, given a sequence σ, $A(\sigma)$ denotes the cost of the online algorithm A and $OPT(\sigma)$ denotes the cost of the optimal offline algorithm. An online algorithm A is called c-competitive if there exists a constant α such that $A(\sigma) - c \cdot OPT(\sigma) \leq \alpha$ [4].

Online algorithms are widely utilized in many research fields of mobile networks over several perspectives. The work presented in [5] proposes a data selection policy where, in the concept of competitive analysis, the decision of transmitting

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source data, retransmitting a packet or transmitting a redundant codeword is investigated. The work presented in [6], examines the frequency assignment problem introducing distributed online algorithms. In the context of energy constraints and the design of routing algorithms, the authors of [7] propose an online algorithm on maximizing the throughput of multihop radio networks. Moreover, in [8] online algorithms are utilized on multicast routing problems over energy-constrained adhoc networks. Finally, the work presented in [9] introduces a competitive online algorithm in terms of energy efficiency and delay in scheduling problems over wireless multicast environments.

In this work we present an online algorithm on the efficient application of AL-FEC protection over mobile multicast environments. The proposed online AL-FEC protection scheme is able to provide reliable delivery requiring no knowledge on the network conditions. The presented online algorithm targets on real-time multicast services providing robust transmission with respect to the tight time constraints of a streaming delivery. Since RaptorQ AL-FEC codes can achieve enhanced performance as the number of AL-FEC symbols per source block increases, the presented online algorithm exploits this fact and adapts the amount of AL-FEC introduced redundancy according to the AL-FEC source block length reducing the number of transmitted AL-FEC repair symbols as the source block length increases. Thus, the online scheme introduces adaptation nature on the RaptorQ AL-FEC application achieving a trade-off between robustness and user experience over real-time services. To this direction, we introduce a competitive framework under which the proposed online algorithm is designed. Furthermore, in the context of competitive analysis our online scheme is evaluated against the optimal offline algorithm.

The rest of this paper is organized as follows: In Section II we present the competitive framework under which we form the problem of AL-FEC application introducing the optimal offline algorithm and the proposed online scheme. In Section III we present the performance evaluation of the proposed online algorithm against its optimal offline instance. Finally, in Section IV we conclude the proposed online algorithm and we draw some possible future steps that could follow the presented work.

II. COMPETITIVE FRAMEWORK

A. Problem Formulation

In this section we present the network model and the assumptions we utilize to introduce our proposed scheme on the AL-FEC application over mobile multicast environments.

The transmission environment we introduce refers to a typical mobile multicast streaming environment. The same data are transmitted to a fraction of users participating on the multicast delivery through a shared unreliable radio channel. The transmitted data considered to be a continuous object, as in a streaming delivery session, are encapsulated in a UDP/IP multicast flow, where a multicast source injects packets into the network.

On the AL-FEC protection mechanism, we consider the application of the newly introduced RaptorQ FEC scheme [10]. The multicast sender introduces redundant information within the source data in order to enable multicast receivers to overcome independent packet losses and successfully reconstruct the transmitted data. On the AL-FEC encoding, the transmitted object is partitioned in one or several source blocks. Each FEC source block consists of k source symbols with k depending on the selection of the encoding parameters. The size of a FEC source block is denoted as source block length (sbl). Through the RaptorQ encoding, for each FEC source block, a certain amount of redundant symbols, also called repair symbols, are generated according to the desired amount of protection introduced by the multicast source. A unique ID is assigned on each resulting encoding symbol, which can be a source or a repair symbol, in order to identify the type of the symbol according to the assigned value. At the receiver side, a multicast client is able to determine, for each FEC source block, which source symbols should have been received but have not and is also able to determine the number of encoding symbols it has received.

RaptorQ FEC is the newest member of Raptor codes family providing powerful capabilities on the AL-FEC protection application [11]. The performance of the RaptorQ AL-FEC code can be described by the decoding failure probability of the code, denoting the probability to fail on reconstructing the protected data as a function of the source block size and the number of received symbols. The decoding failure probability of RaptorQ code can be modeled by (1) [12]:

$$p_{f_{RQ}}(n,k) = \begin{cases} 1, & \text{if } n < k \\ 0.01 \times 0.01^{n-k}, & \text{if } n \geq k \end{cases} \tag{1}$$

In (1), $p_{f_{RQ}}(n,k)$ denotes the probability of a failed decode of a RaptorQ protected block with k source symbols if n encoding symbols have been received.

In this work, we assume the transmission of a packet sequence with independent packet loss masks applied to each multicast receiver according to an examined packet loss rate. On the utilized sequence of packets, each packet is denoted by the triple $\{uid, sbn, (i,l)\}$ where:

- uid: is an ID identifying each AL-FEC resulting packet in each source block
- sbn: is the number of the FEC source block the specified packet is organized to
- (i,l): denotes if the specified packet is lost in the receiver i with the boolean l set to 0 if packet is lost

The packet loss pattern applied to the sequence of transmitted packets is denoted p, corresponding to the average network packet loss rate and taking values in the range $[0,1]$. At each multicast receiver, a packet loss mask is applied independently based on the value of p. The packet erasures are randomly distributed at the multicast receivers as illustrated in Fig. 1, where an instance of the successful or not reception of 10 transmitted packets at 5 multicast receivers is presented with p set to 0.2 inline with the assumptions of the previously

User 1	(1,0)	(1,1)	(1,1)	(1,1)	(1,1)	(1,1)	(1,1)	(1,1)	(1,0)	(1,0)
User 2	(2,1)	(2,1)	(2,1)	(2,1)	(2,1)	(2,1)	(2,1)	(2,1)	(2,1)	(2,1)
User 3	(3,1)	(3,0)	(3,1)	(3,1)	(3,0)	(3,0)	(3,0)	(3,1)	(3,1)	(3,0)
User 4	(4,1)	(4,1)	(4,1)	(4,1)	(4,1)	(4,1)	(4,0)	(4,1)	(4,1)	(4,1)
User 5	(5,1)	(5,1)	(5,1)	(5,0)	(5,1)	(5,1)	(5,1)	(5,1)	(5,1)	(5,1)

Fig. 1. An Instance of Packet Erasures

described network model. Moreover, we assume that the packet loss mask is randomly distributed at the whole fraction of the transmitted object and each transmitted packet contains one AL-FEC symbol of fixed length.

At each multicast receiver the AL-FEC decoding process is modeled according to the decoding failure probability of (1) in order to denote the examined AL-FEC source block as successfully reconstructed or not. On the decoding process, we assume that a sufficient threshold for the failure probability of a recovered source block is 10^{-2} or less as proposed in [13].

B. Offline Optimal Algorithm

Regarding the cost of the optimal offline algorithm, we assume that a multicast transmitter, with a priori knowledge of the packet losses pattern of the system, will introduce a certain number of redundant symbols. Since the examined AL-FEC application problem is a cost minimization problem, the optimal policy from the transmission cost perspective on the selection of the AL-FEC overhead a multicast source should introduce to the transmission is not the introduction of a huge amount of overhead aiming to enable the higher packet loss user to successfully recover the transmitted object. Subsequently, the optimal algorithm will introduce the minimum number of required redundant symbols so as to cope with the average value of packet loss aiming to satisfy as many users as possible. The scheme that can ensure the optimal selection of the transmission overhead is described by a multicast source that selects the introduced redundancy to a value close to the average packet loss rate of the network as denoted in [14]. On the present analysis the multicast sender can exploit the practically zero reception overhead of RaptorQ since, as described in (1) can achieve the specified failure probability threshold requiring to receive no more additional symbols than the number of the transmitted symbols. Subsequently, the optimal AL-FEC selection policy can introduce as many repair symbols as the average number of lost symbols in the multicast users. Based on this, the number of repair symbols r the optimal offline algorithm will introduce in each source block can be computed as: $r \geq (sbl + r) \cdot p$.

Consequently, the cost of the optimal offline algorithm for each source block, defined as: $OPT = sbl{+}r$ can be described by (2):

$$OPT = \frac{sbl}{1-p} \tag{2}$$

C. Weighted Online AL-FEC Algorithm

In this paragraph we present an online algorithm on the selection of the introduced AL-FEC transmission overhead over mobile multicast streaming environments. The proposed algorithm is based on weights assignment in each processed AL-FEC packet. The algorithm takes as input each processed packet and assigns a weight to the packet according to its unique id i.e., the number of packets included in each FEC source block and the size of the source block each packet belongs to. Thereafter, the algorithm determines if the processed packet will be included in the introduced redundancy comparing the assigned packet's weight with a selected threshold t. The value of t determines the required robustness of the AL-FEC protection. Finally, the algorithm examines if the processed packet is the last packet of the current FEC source block in order to compute the transmission overhead will introduce to the multicast transmission.

Algorithm 1 Weighted AL-FEC Online Algorithm

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procedure $(pkt, sbl, t)$
    $pkt.w \leftarrow log_2(pkt.uid)/log_2(sbl)$    ▷ compute the weight of the processed packet
    if $pkt.w \leq t$ then    ▷ determine if the processed packet will be included in the overhead
        $count \leftarrow count + 1$
    end if
    if $pkt.id \bmod sbl = 0$ then    ▷ check if the processed packet is the last of the block
        transmission overhead $\leftarrow count/sbl$    ▷ compute the transmission overhead of the block
    end if
end procedure
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In the above algorithm pkt, sbl, t denote each processed packet, the size of the AL-FEC source block the current packet belongs to and the multicast sender selected threshold respectively. It is obvious that the sbl of the source block each packet is organized to can be extracted by the packet sbn attribute.

The presented online algorithm introduces adaptation features in AL-FEC application in the sense of the transmission overhead reduction as the length of the AL-FEC source block increases. Actually, the assigned weight of each packet reduces with the source block size increase resulting the algorithm to introduce fewer repair AL-FEC symbols as the source block grows for a given threshold.

On the cost analysis of the proposed online scheme, the number of redundant AL-FEC packets of each source block can be easily extracted as follows according to the weights assignment process with respect to the selected threshold t.

$$\frac{log_2(pkt.id)}{log_2(sbl)} \leq t \Rightarrow log_2(pkt.id) \leq t \cdot log_2(sbl) \Rightarrow$$

$$2^{log_2(pkt.id)} \leq 2^{t \cdot log_2(sbl)} \Rightarrow pkt.id \leq \left(2^{log_2(sbl)}\right)^t \Rightarrow$$

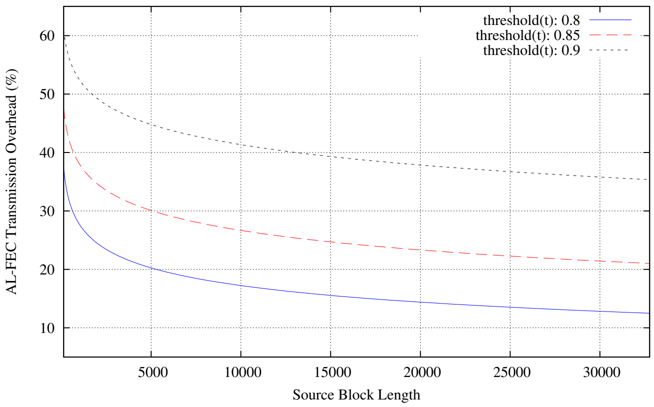

Fig. 2. Introduced AL-FEC Transmission Overhead vs. Source Block Length

$$pkt.id \leq sbl^t \tag{3}$$

Hence, since the number of introduced AL-FEC repair packets can be extracted by (3) computing the ID of the last packet passing the threshold, the cost of the proposed online algorithm in terms of the total number of transmitted packets per source block can be computed by (4):

$$ALG = sbl + \lfloor sbl^t \rfloor \tag{4}$$

Consequently, according to the definition of the competitive ratio of an online algorithm as described earlier and since the online algorithm addresses a cost minimization problem its competitive ratio can be computed as:

$$c = max \frac{ALG}{OPT}$$

Therefore, the competitive ratio of the proposed online algorithm can be computed by (4) and (2) as:

$$c = (1 + sbl^{t-1})(1 - p)$$

III. PERFORMANCE EVALUATION

In this section we present a performance evaluation of the proposed online AL-FEC algorithm providing extensive simulation results based on the previously described network model and utilizing the RaptorQ AL-FEC code.

A. Introduced AL-FEC Transmission Overhead

In this paragraph we illustrate the operation concept of the proposed weighted online algorithm on the AL-FEC redundancy will introduce in the multicast transmission. More precisely, Fig. 2 presents how our online scheme adapts the introduced AL-FEC transmission overhead for different values of source block length and threshold t. The provided results consider source block length between 128 and 32768 source symbols per block and the value of threshold t fixed at 0.8, 0.85 and 0.9.

The curves presented in Fig. 2 illustrate the AL-FEC overhead introduction policy of the presented online scheme. Analyzing the shape of the plotted curves we can immediately remark that the proposed online algorithm follows an exponential decay on the amount of AL-FEC transmission overhead will introduce in a real-time multicast service transmission. This fact is a direct consequence of the calculation formula for the last AL-FEC packet ID will be included in the process of determining the amount of redundant AL-FEC repair symbols. Furthermore, the value of the utilized threshold t determines the amount of robustness a multicast sender wishes to introduce in the transmission, since the value of t actually determines the initial maximum value of the introduced AL-FEC transmission overhead for the minimum size of sbl.

Outlining in more detail the online algorithm operation, we can observe that for low values of sbl, i.e., for sbl size up to 4096, the reduction on the introduced transmission overhead is higher than the reduction achieved for higher values of the number of AL-FEC symbols protected together within a source block. This choice was based on the fact that as the sbl size increase, the enhancement on the AL-FEC Raptor codes family protection efficiency between adjacent values of sbl is reduced, according to the works presented in [14], [15].

In the rest of this section we provide empirical simulation results, illustrating how the described reduction operation of the online algorithm acts on the robustness of the AL-FEC protection and further on a streaming delivery constraints.

B. Recovered AL-FEC Blocks

This part of the presented evaluation results demonstrates the protection efficiency the proposed online algorithm achieves compared to the optimal algorithm. Fig. 3 demonstrates how the total number of successfully recovered AL-FEC block varies against the number of AL-FEC source symbols protected together within an AL-FEC source block. For this evaluation we examine the source block length range between 128 and 32768, transmitting an object encoded to 4 source blocks to 100 multicast users with the average packet loss rate fixed to 8% and the online algorithm threshold t selected to 0.7.

Observing the results presented in Fig. 3 we can immediately remark that both plotted curves reflect the AL-FEC transmission overhead selection policy of both evaluated algorithms, i.e., the optimal offline algorithm and the proposed weighted online algorithm. On the optimal offline algorithm case, we can remark that as the sbl size increases the total number of successfully recovered AL-FEC blocks increases too. The observed increment on the number of successfully recovered blocks and consequently on the achieved protection efficiency is steeper for sbl values up to 4096 symbols. This fact does not imply from the transmission overhead the optimal offline algorithm introduces in each instance of simulation, since as already described in the theoretical analysis provided in Section II the optimal offline algorithm exploits its knowledge on the packet loss conditions has to confront with and introduces a fixed, in terms of percentage, transmission overhead according to the average packet loss rate and independently of the current sbl. Therefore, the remarked increase in the

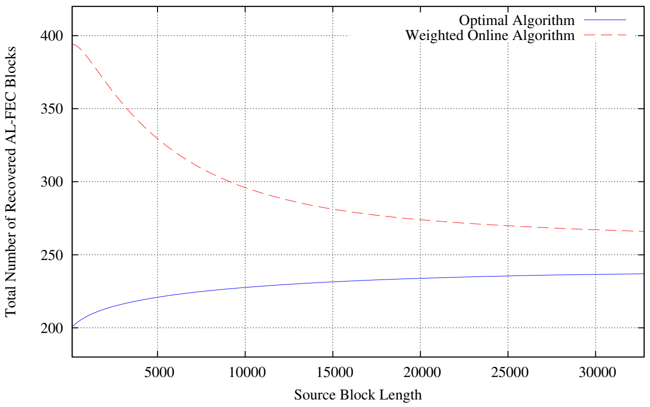

Fig. 3. Recovered AL-FEC Blocks vs. Source Block Length

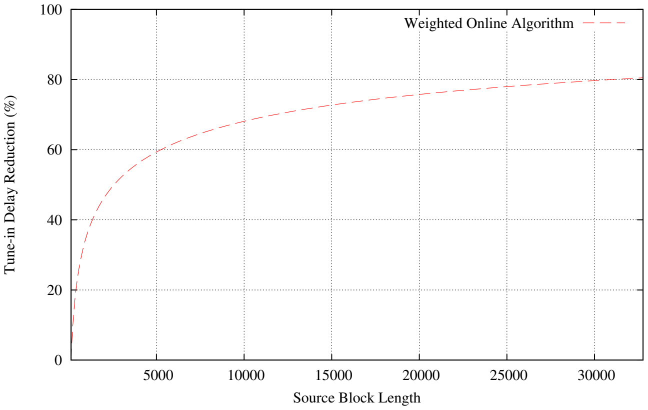

Fig. 4. Tune-in Delay Reduction vs. Source Block Length

number of successfully recovered AL-FEC source blocks is due to the protection efficiency properties described in the previous subsection, i.e., as the number of AL-FEC source symbols protected together within a source block increase, RaptorQ AL-FEC achieves enhanced decoding efficiency and protection.

On the other hand, analyzing the performance of the proposed online scheme we can immediately remark that the number of successfully received AL-FEC source symbols is proportional to the size sbl. This fact is anticipated since as depicted in the results presented in Fig. 2 the amount of introduced AL-FEC protection is reduced with the sbl increase. Moreover, the form of the online algorithm curve follows the form of the introduced transmission overhead since for low values of sbl, i.e., up to 4096 the number of successfully decoded AL-FEC source blocks is reduced steeper compared to higher sbl values where the reduction becomes ever more smooth. However, the outcome of the presented results is that even in the range of 128 to 4096 sbl size where the reduction on the introduced transmission overhead is steep the gain on the introduced redundancy is considerably higher than the losses on transmission robustness. Indicatively we can mention that the introduced AL-FEC redundancy is reduced about almost 25% while the number of successfully received source symbols is reduced about 12% when the sbl is increased from 128 to 4096 symbols. Moreover, comparing the minimum with the maximum value of sbl, the reduction on the introuded redundancy reaches the 43.5% while the reduction on the recovered source blocks is 27.5% achieving constantly a sufficient number of successfully received source blocks. Therefore, the online weighted algorithm can achieve significant reduction on the amount of AL-FEC redundancy providing at the same time adequate protection against packet losses.

C. *Tune-in Delay Reduction*

The objective of the proposed online scheme is to introduce reliability in multicast transmission, reducing at the same time the impacts of the AL-FEC introduced redundancy on the tight constraints of a real-time service. To this direction, in this subsection we examine the impacts of the proposed weighted online algorithm on a typical metric for the user experience of real-time services, called tune-in delay. Tune-in delay is defined as the time interval between the start of the packets reception until the start of correct decoding the received packets of each FEC source block. Tune-in delay is experienced by a user who joins the multicast streaming session and the first received packet is anywhere but at the very start of the FEC source block. On the tune-in process a receiver first synchronizes to the FEC block, waiting for the reception and successful processing of each FEC block, before attempting to decode the media. Subsequently, the tune-in delay is a function of the FEC protection period and the decoding delay, typically defined as $tune\text{-}in\ delay = protection\ period + \varepsilon$ [16].

In Fig. 4 we demonstrate the reduction, in terms of percentage, on the tune-in delay the online algorithm operation achieves, comparing the measured average tune-in delay value for each evaluated source block length with the tune-in delay for the case of the smallest evaluated source block length, i.e., 128 source symbols per AL-FEC source block. Subsequently, the curve of Fig. 4 illustrates how the weighted online algorithm operation reduces the tune-in delay as the source block length increase. As in the previous part of results, we simulate 100 multicast users, with the algorithm threshold t selected to 0.7 and the transmitted object divided to 4 source blocks.

Observing the presented results of Fig. 4, we can immediately remark that the application of the proposed weighted online algorithm on the AL-FEC protection provides remarkable gains in the tune-in delay of a multicast real-time service. In more detail, we can observe that for the case of 512 symbols of sbl size the online algorithm achieves already a reduction in the tune-in delay of about 20%, while for the case of the maximum evaluated sbl size, i.e., 32768 symbols the achieved reduction reaches the 80%. The form of the tune-in delay reduction curve directly implies from the online algorithm operation, analyzed in the earlier Fig. 2. It is anticipated the curve of the tune-in delay reduction to be the reverse of the introduced AL-FEC transmission overhead curve, since as the sbl size increase the online algorithm introduces decreased AL-FEC redundancy in a source block and subsequently the achieved reduction on the tune-in delay constantly increases.

Contrasting the results presented in Fig. 4 with that in Fig. 3, we have to mention that the gains that the proposed online alogrithm offers in the tune-in delay constraint of a real-time delivery is considerably higher compared to the losses on the AL-FEC protection strength as described in Fig. 3. This fact is particularly important, especially for streaming delivery where the tolerance on packet losses is higher compared to the download delivery, and the tight time constaints are essential for the overall quality of experience of a real-time service user.

IV. Conclusions & Future Work

In this work we have introduced a deterministic online scheme on the AL-FEC application. We have examined the impacts of a weighted online alogorithm on the deployment of AL-FEC protection over real-time mobile multicast services utilizing the newly introduced RaptorQ FEC code. The proposed online scheme adapts the introduced AL-FEC transmission overhead exploiting some performance properties of the Raptor family codes according to the AL-FEC encoding parameters. To analyze the performance of the proposed online algorithm in the basis of competitive analysis, we have introduced a realistic mobile multicast network model. We have demonstrated that the competitive ratio of the proposed deterministic online algorithm depends on the AL-FEC encoding parameters and more specifically on the number of AL-FEC source symbols protected together within an AL-FEC source block. Thereafter, we have presented an operation analysis of the online scheme and furthermore we have provided empirical simulation results on the performance of the proposed online algorithm examining the achieved protection efficiency and the impacts on the time constraints of a real-time service. From the extracted simulation results, we were able to verify that the the online scheme can provide robustness on a multicast real-time delivery while at the same time can reduce the introduced AL-FEC redundancy. We have demonstrated that the reduction on the transmission overhead as the size of sbl increase is beneffical for a real-time delivery multicast environment since the proposed online scheme exploits the extraordinary performance properties of the powerful RaptorQ AL-FEC code providing a trade-off between transmission robustness and user experience.

Some possible future steps that can follow this work are the extension of the proposed weighted online algorithm with an evolved weight assignment mechanism which will utilize several AL-FEC encoding parameters as well as network parameters. Another direction could be the design of a more sophisticated online algorithm which, utilizing a feedback report mechanism on the network conditions, could adapt the introduced AL-FEC transmission redundancy. Furthermore, it is our belief that an online crosslayer scheme adapting the AL-FEC encoding parameters on the application layer considering the amount of protection on lower layers could be beneficial for the protection efficiency of a multicast transmission. Finally, we could investigate the feasibility of utilizing online algorithms on the application of AL-FEC protection over unicast mobile environments.

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