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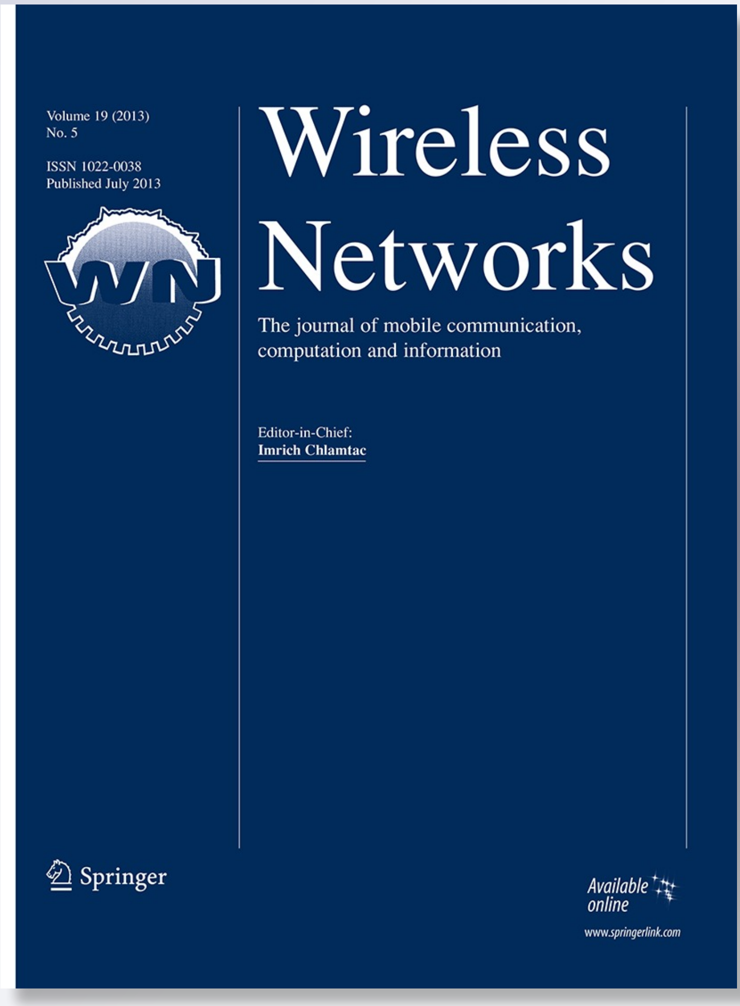

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Embracing RaptorQ FEC in 3GPP multicast services

Christos Bouras · Nikolaos Kanakis · Vasileios Kokkinos · Andreas Papazois

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Abstract Multimedia Broadcast/Multicast Services (MBMS) have been introduced by Third Generation Partnership Project (3GPP) aiming to efficiently deliver data to mobile users in a one-to-many way. In order to provide reliable multicast transmission, 3GPP recommends exclusively for MBMS the use of a Forward Error Correction (FEC) mechanism on the application layer. Raptor codes are standardized as the Application Layer FEC (AL-FEC) scheme over 3GPP MBMS. However, the 3GPP standardized systematic fountain Raptor code is nowadays considered obsolete, since a new variation of the Raptor codes has emerged. This enhanced AL-FEC scheme, named RaptorQ, promises higher protection efficiency and superior flexibility on the provision of demanding mobile multicast services. In this work, we provide an extensive performance evaluation presenting at first a theoretical performance comparison of the newly introduced RaptorQ FEC scheme with its predecessor Raptor code, examining the enhancements that RaptorQ introduces on the AL-FEC protection robustness. Thereafter, to verify the enhanced performance of RaptorQ, we present several simulation results considering the modeling of the AL-FEC protection over multicast services for next generation mobile networks, utilizing the ns-3 simulation environment. Investigating several mobile system parameters in conjunction with FEC encoding parameters, we provide valuable results regarding the impacts of the examined AL-FEC schemes application on the multicast services performance.

Keywords Forward error correction · Raptor · RaptorQ · Broadcast and multicast · Mobile networks · NS-3

1 Introduction

Nowadays there is a significant focus on the efficient deployment of mobile multicast standards to fulfill the objective of the target applications that require multiple users to receive the same data at the same time. The efficiency of multicast and broadcast services stands on the ability to sent the data only once in the network regardless the number of users that wish to receive them, allowing to share radio and core network resources and therefore achieving resource utilization both within the core as well as within the radio access network. Third Generation Partnership Project (3GPP) named its standard Multimedia Broadcast/Multicast Services (MBMS) [1]. MBMS aims to provide efficient delivery of data from a single source to several destinations in a point-to-multipoint (ptm) way. 3GPP defines two modes of operation for MBMS, the broadcast and the multicast mode. In order to deliver MBMS content to multiple receivers, 3GPP defines two delivery methods, namely download and streaming. MBMS download delivery method aims to deliver discrete objects (e.g. files) by means of a MBMS download session, while the purpose of MBMS streaming is the delivery of continuous media (i.e. speech, audio, video) through a

C. Bouras (✉) · N. Kanakis · V. Kokkinos · A. Papazois
Computer Engineering and Informatics Department, University of Patras and Computer Technology Institute and Press "Diophantus", N. Kazantzaki Street, Patras 26504, Greece
e-mail: bouras@cti.gr

N. Kanakis
e-mail: kanakisn@ceid.upatras.gr

V. Kokkinos
e-mail: kokkinos@cti.gr

A. Papazois
e-mail: papazois@ceid.upatras.gr

MBMS streaming session. 3GPP focuses on the provision of reliability control over the MBMS delivery. A crucial point in achieving this objective is the introduction of a Forward Error Correction (FEC) mechanism on the application layer for both MBMS delivery methods.

FEC is a method used for "forward" error control in data transmission over unreliable channels, such as radio transmission channels. The "forward" concept of FEC is justified by the redundant data transmission in advance with the source information, unlike the common methods for error control (i.e. ARQ, Carousel) that are based on lost or corrupted packets retransmission to obtain the recipients the ability to overcome packet losses. The application of FEC on ptm reliability protocols, such as the MBMS environment, provides particular advantages since the redundancy introduced in the multicast transmission can overcome the common methods limitations [2]. The most important property of FEC codes is the ability to use the same FEC packets to simultaneously repair different independent packet losses at multiple receivers. However, FEC comes with its own cost since FEC protection must be carefully applied with respect to the current network conditions so as to avoid channel bandwidth wastage and achieve an efficient and reliable multicast delivery.

3GPP recommends the use of the systematic, fountain Raptor code as an Application Layer FEC (AL-FEC) protection mechanism exclusively for MBMS [1]. Raptor FEC [3] was selected due to the higher performance compared with existing AL-FEC codes. However, in the meantime a new very promising variation of Raptor codes has emerged, named RaptorQ [4]. RaptorQ is the most recent member of Raptor codes family, providing exceptional protection performance and enhanced encoding parameters. Furthermore, a general FEC framework is introduced in [5] describing the concept of FEC to arbitrary packet flows. The FEC framework defines the application of Raptor and RaptorQ FEC schemes in order to provide a FEC protection mechanism that is independent of the type of the source data.

In this work we provide a performance analysis and comparison of the newly introduced RaptorQ code with the 3GPP standardized Raptor FEC scheme. We analyze the differentiation points of the two Raptor codes family members and we highlight the enhanced performance promised by the new RaptorQ code. Through a 3GPP LTE MBMS simulation environment we investigate the enhanced capabilities offered by RaptorQ on the AL-FEC protection efficiency evaluating the application of both the examined AL-FEC codes over download and streaming delivery scenarios. For the conduction of this evaluation we consider several system and FEC encoding parameters.

The rest of this manuscript is organized as follows: in Sect. 2 we provide an overview of the most important related works. Section 3 presents the 3GPP AL-FEC MBMS framework outlining the integration of the AL-FEC protection mechanism on the MBMS download and streaming delivery methods. In Sect. 4 we present a detailed description of the examined AL-FEC schemes. Furthermore, we provide a comparison between them concerning both functional and performance aspects. In Sect. 5 we present the MBMS environment we utilized to simulate AL-FEC protected download and streaming delivery sessions and we further present the conducted experimental results. Finally, in Sect. 6 we provide our conclusions and in Sect. 7 we highlight some possible steps that can follow this work.

2 Related work

Since the emergence and the 3GPP standardization of Raptor codes, several works have covered extensively the analysis and the evaluation of the systematic, fountain Raptor code as an AL-FEC protection scheme over mobile multicast environments. The authors of [6] provide an analytical investigation of the Raptor FEC performance, evaluating the tradeoffs between AL-FEC and physical layer FEC over MBMS download delivery for UMTS systems. The work presented in [7] studies the Raptor FEC application both for download and streaming MBMS services over 3G mobile cellular networks considering the impacts of AL-FEC on the telecommunication cost. In [8], the authors provide a novel proposal of the Raptor FEC application considering the exclusive use of AL-FEC, instead of applying a post-repair phase for the evolved MBMS (eMBMS) download delivery. The authors evaluate the performance of the proposed scheme providing a transmission cost analysis and considering different Multimedia Broadcast over a Single Frequency Network (MBSFN) topologies. The work in [9] provide a performance evaluation of the Raptor FEC scheme for streaming services over Long Term Evolution (LTE) single-cell MBMS environments, examining the impacts of the AL-FEC application on the network performance. Moreover, the same authors in [10] provide a comprehensive analysis of the impacts of several FEC encoding parameters in conjuction with network parameters on the overall MBMS system performance.

The authors of this manuscript provide in [11] an early investigation of the RaptorQ performance compared to that of Raptor code presenting some preliminary results on MBMS download delivery that consist the basis for the present full study. Furthermore, a comprehensive analysis of the processes behind the design and the performance of Raptor and RaptorQ FEC codes is provided in [12]. The work in [13] focuses on the specific constraints of Raptor codes application on mobile embedded systems. The authors evaluate the application of RaptorQ compared to the existing Raptor FEC code considering decoding complexity as well as energy consumption aspects. A comparative analysis of the performance of Raptor FEC code against Reed Solomon (RS) FEC codes is presented in [14]. The authors of this work provide a detailed comparison between the two FEC schemes considering several performance parameters over MBMS services.

Furthermore, during the standardization process of Raptor code, 3GPP released several evaluation documents comparing candidates AL-FEC schemes. Indicatively, we refer [15] which presents simulation results comparing the performance of Raptor with that of RS codes when used as AL-FEC for MBMS download and streaming services. The works [16, 17] contribute valuable simulation results, comparing the performance of Raptor FEC to that of RS FEC and furthermore to that of an ideal FEC code over MBMS streaming environments. Finally, 3GPP recently released in [18] an in progress evaluation of RaptorQ against Supercharged codes and a combinatorial FEC scheme based on RS and LDPC staircase codes to verify the qualification criteria of the FEC standardization candidates.

It is obvious that the majority of the related work refers to the evaluation of the Raptor FEC scheme against older FEC schemes with only a few studies dedicated to the newly introduced RaptorQ FEC code. However, the RaptorQ related works focus on a theoretical investigation or the evaluation of RaptorQ under very specific constraints of mobile networks. Our work comes to fill the gap of a comprehensive performance evaluation of RaptorQ FEC against its predecessor, Raptor code, providing an overall investigation of the enhanced RaptorQ capabilities introducing user-centric performance metrics.

3 AL-FEC MBMS delivery

In order to meet the increasing use of high bandwidth multicast services, 3GPP initially standardized MBMS in third generation mobile systems. MBMS is a unidirectional ptm service in which data are transmitted from a single source to a group of multiple mobile endpoints in a specific service area. MBMS allow for multiple mobile subscribers to share radio and core network resources and as such offer many advantages regarding system resource utilization. The MBMS provide two modes of operation, the broadcast and the multicast mode. 3GPP defines three distinct functional layers for the delivery of MBMS services: the user service, the delivery method and the bearers. MBMS user services are built on top of the MBMS bearer service. 3GPP defines a set of media codecs, formats and transport/application protocols to enable the deployment of several MBMS user services with different requirements. Furthermore, 3GPP defines two delivery methods for the MBMS user services, namely download and streaming. The delivery of software upgrades is an example of application using the download delivery method, while the delivery of real-time video is an example of the streaming delivery. MBMS delivery methods make use of the MBMS bearer service in order to distribute an application to multiple subscribers. Finally, bearers provide the mechanism by which IP data is transported. A MBMS bearer is an IP-multicast packet flow between a multicast gateway and the mobile MBMS subscribers. The MBMS user plane protocol stack of both delivery methods is illustrated in Fig. 1 [1]. As mentioned previously, a key aspect in the context of providing reliability control and enhanced transmission robustness is the use of a FEC technique in the application layer. More precisely, 3GPP has standardized an AL-FEC scheme exclusively for MBMS, that is based on the systematic fountain Raptor code.

3.1 Download delivery

MBMS download delivery method aims to distribute discrete objects (e.g. files) by means of a MBMS download session. Download delivery uses the FLUTE protocol when delivering content over MBMS bearers. FLUTE is built on top of the Asynchronous Layered Coding (ALC) protocol instantiation. ALC combines the Layered Coding Transport (LCT) building block and the FEC building block to provide reliable asynchronous delivery of content to an unlimited number of concurrent receivers from a single sender. Thereafter, FLUTE is carried over UDP/IP, and is independent of the IP version and the underlying link layers used. Further details on the FLUTE building block structure can be found in [1].

In order to apply AL-FEC protection on the MBMS download delivery, the transmitted file is partitioned in one or several source blocks. Each source block consists of

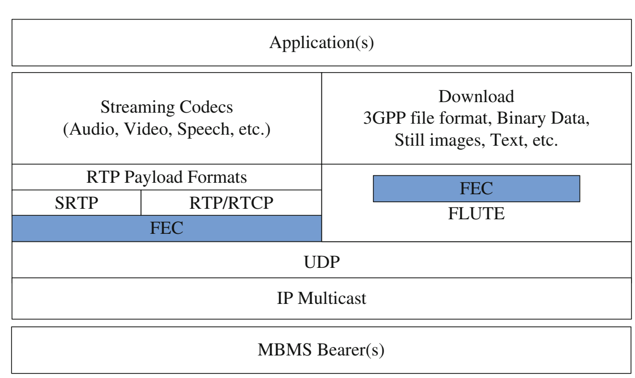

Fig. 1 3GPP MBMS protocol stack

k source symbols, each of length T except for the last source symbol, which can be smaller. Through the Raptor encoding, for each source block, redundant repair symbols are generated according to the desired amount of protection. 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 ID. Subsequently, one or more FEC encoding symbols are placed in each FLUTE packet payload and the resulting packets are encapsulated in UDP and distributed over the IP multicast MBMS bearer.

Furthermore, 3GPP defines a post-delivery procedure to provide file repair features for the MBMS download delivery. The purpose of the file repair procedure is to repair lost or corrupted file fragments from the MBMS download data transmission. A MBMS client is able to determine, for each source block of each file, which source symbols should have been received but have not and is also able to determine the number of symbols it has received. Therefore, each MBMS client is able to determine the number of further symbols required and send a file repair request message to a file repair server for unreceived symbols which will allow the MBMS FEC decoder to recover each protected block of the file. Thereafter, the MBMS client can receive the requested repair data through a point-to-point (ptp) or a ptm repair data delivery.

3.2 Streaming delivery

The purpose of the MBMS streaming delivery method is to deliver continuous multimedia data (i.e. speech, audio and video) over an MBMS bearer. MBMS makes use of the most advanced multimedia codecs (e.g. H.264 codec, enhanced aacPlus codec). Real-time Transport Protocol (RTP) is the application layer protocol for MBMS streaming delivery and provides means for sending real-time or streaming data over UDP transport layer. Furthermore RTP provides RTP Control Protocol (RTCP) for feedback about the transmission quality. As in the MBMS download method, 3GPP recommends the use of an AL-FEC mechanism by the sender before RTP flows are mapped onto UDP.

The MBMS AL-FEC streaming framework operates on RTP/UDP flows. A copy of the source packets is forwarded to the Raptor encoder and arranged in a source block with row width T bytes with each packet occupying a new empty row. The source block is filled up to k rows, where the value of k can be different for each source block and depends on the variable streaming services constraints. After forming a FEC source block from the packets to be protected together, the Raptor encoder generates the desired repair symbols. These generated Raptor repair symbols are then sent using the FEC repair packet format.

4 AL-FEC schemes

In general, AL-FEC codes can be considered as correcting codes for an erasure channel. In an erasure channel a transmitter sends a symbol i.e., a fragment of the source data, with the receiver either receiving or not the transmitted symbol. AL-FEC aims to cope with these symbol erasures by adding some redundancy in the transmitted data. Raptor codes were firstly introduced as a FEC erasure code in [19]. In this section we provide an analytical description of the two examined members of the Raptor codes family. We focus on the improvements that the newer member of Raptor codes, named RaptorQ, has emerged and we further provide a theoretical performance evaluation of the two examined schemes.

4.1 Standardized Raptor code

The use of Raptor codes in the application layer of MBMS has been introduced to 3GPP by Digital Fountain [20] aiming to provide service robustness against packet losses. Raptor codes are fountain codes, meaning that as many encoding symbols as desired can be generated by the encoder on-the-fly from the source symbols of a source block of data. Raptor codes are one of the first known classes of fountain codes with linear encoding and decoding time [19]. In preparation of the encoding, a certain amount of data is collected within a FEC source block. The data of a source block are further divided into k source symbols of a fixed symbol size. The decoder is able to recover the whole source block from any set of encoding symbols only slightly more in number than the source symbols. The Raptor code specified for MBMS is a systematic code producing n encoding symbols E from $k < n$ source symbols C, so as the original source symbols are within the stream of the transmitted symbols. This code can be viewed as the concatenation of several codes. The most-inner code is a non-systematic Luby-Transform (LT) code [21] with l input symbols F, which provides the fountain property of the Raptor codes. This non-systematic Raptor code is not constructed by encoding the source symbols with the LT code, but by encoding the intermediate symbols generated by some outer high-rate block code. This means that the outer high-rate block code generates the F intermediate symbols using k input symbols D. Finally, a systematic realization of the code is obtained by applying some pre-processing to the k source symbols C such that the input symbols D to the non-systematic Raptor code are obtained. The description of each step and the details on specific parameters can be found in [1].

Considering the performance of Raptor codes the most typical comparison is that to an ideal fountain code. An ideal fountain code can produce from any number k of source symbols any number m of repair symbols with the property that any combination of k of the $k + m$ encoding symbols is sufficient for the recovery of the k source symbols. This property, is the differentiation point between an ideal fountain code and the standardized Raptor code. More precisely, while an ideal code has zero reception overhead, i.e. the number of received symbols needed to decode the source symbols is exactly the number of source symbols, the Raptor code has a performance close to that property. Based on this, the performance of an AL-FEC code can be described by the decoding failure probability of the code, denoting the probability Raptor code to fail on successfully reconstructing the protected data as a function of the source block size and the received symbols. In fact, for $k > 200$ the inefficiency of the Raptor code can be accurately modeled by (1) as described in [22]:

$$p_{f_R}(n,k) = \begin{cases} 1, & if \quad n < k \\ 0.85 \times 0.567^{n-k}, & if \quad n \geq k \end{cases} \tag{1}$$

In (1), $p_{f_R}(n,k)$ denotes the decoding failure probability of the Raptor code if the source block size is k symbols and n encoding symbols have been received. It has been observed that for different k, the equation almost perfectly emulates the Raptor performance. While an ideal fountain code would decode the protected data with zero failure probability when $n = k$, the failure probability is still about 85 %. However, the failure probability decreases exponentially when the number of received encoding symbols increases. Moreover, a crucial point for the robustness of an AL-FEC protected delivery session is the transmission overhead. The transmission overhead is defined as the amount of redundant information divided by the amount of source data and is equal to the fraction $(N - K)/K$ in terms of percentage. In this fraction, N denotes the number of transmitted encoding packets and K denotes the number of the source packets.

4.2 New RaptorQ code

Since the systematic fountain Raptor code was adopted from 3GPP as the standardized AL-FEC scheme for MBMS, there has been significant progress in the design of erasure codes. The outcome of this progress is the emergence of an enhanced Raptor code at Internet Engineering Task Force (IETF) [4] in order to address the drawbacks of the standardized Raptor code on the recovery properties described in Subsect. 4.1. This newer member in Raptor codes family is known as RaptorQ code. RaptorQ is also a fountain and systematic FEC code. RaptorQ is a significantly more efficient AL-FEC code than the older Raptor code, in terms of superior flexibility and higher protection and coding efficiency. The encoding process of RaptorQ code is mostly identical with that of Raptor code described in the previous subsection. However, RaptorQ code introduces certain design selections, analyzed below, that ensure superior performance compared with that of Raptor code. A key differentiation between the two schemes is that the standardized Raptor code operates over Galois field GF(2) [3], while the enhanced RaptorQ code uses symbol operations over GF(256) [4] instead of over GF(2). Operating over larger finite fields allows RaptorQ to overcome the performance limitations of Raptor code since utilizing larger finite fields offers the potential of achieving recovery with lower reception overhead than the existing Raptor code. Moreover, additional important aspects of the enhanced properties of RaptorQ code are the increased number of possible source symbols and the increased number of generated encoding symbols. More precisely, RaptorQ can encode up to 56,403 source symbols into a source block in contrast to 8,192 of the Raptor code and furthermore can generate up to 16,777,216 encoding symbols, 256 times more than the older Raptor code. The expanded range of these two parameters simplifies the application of the AL-FEC protection and offers higher flexibility to RaptorQ. Based on the properties of RaptorQ code, it is obvious that can perform better and more flexible both for file delivery and streaming services. Since RaptorQ can deliver files up to 3.4 GB as a single source block maximizes the decoding efficiency and protection due to the spreading of protection across the whole file, particularly for very large files. On the delay-sensitive real-time applications, the flexible range of the block size parameter allows to determine a QoS trade-off between protection and latency considering the delay constraints of the transmitted application. At the same time RaptorQ achieves lower computational complexity [23] than the older Raptor code.

Concerning the performance of RaptorQ, as already mentioned, the key property of a Raptor codes member is the probability of a successful decode as a function of the received symbols similar to that of the standardized Raptor code described above. The decoding failure probability of RaptorQ code can be modeled by (2) [23]:

$$p_{f_{RQ}}(n,k) = \begin{cases} 1, & if \quad n < k \\ 0.01 \times 0.01^{n-k}, & if \quad n \geq k \end{cases} \tag{2}$$

In (2), $p_{f_{RQ}}(n,k)$ denotes the probability of a failed decode of a RaptorQ protected block with k source symbols if n encoding symbols have been received. Comparing (2) with (1), the performance superiority of RaptorQ code is unambiguous.

Seeking into the design aspects of the newly introduced RaptorQ code we thereafter analyze the origins of its superior performance. Although the majority of the basic encoding steps of RaptorQ are identical to those of Raptor code, there are several improvements and additions to the encoding and decoding operations:

1. On RaptorQ before the intermediate symbol generation, for a given source block of k source symbols, for encoding and decoding purposes, the source block is augmented with additional padding symbols. The reason for padding out a source block is to enable faster encoding and decoding and to minimize the amount of information that needs to be stored. The following step is the generation of the intermediate symbols from the source symbols where enhanced generator and pre-coding relationships (i.e., a two-stage pre-coding algorithm using LDPC and HDPC codes) are used, compared to the older Raptor code. Finally, in the second encoding step of RaptorQ, a modified, more efficient encoding process, than this of Raptor code, is applied in order to generate the encoding symbols.
2. For the encoding process, Raptor code uses simple exclusive-or operations over the symbols, i.e. operations over GF(2). This selection limits the recovery properties of Raptor code, since the best recovery probability such a code can achieve is $1 - \frac{1}{2^{m+1}}$ if $k + m$ encoding symbols have been received. RaptorQ code introduces the use of arithmetic operations on octets. Mathematically, octets can be thought of as elements of a finite field, i.e., the finite field GF(256). Using symbol operations over GF(256) achieves recovery from the reception of $k + m$ encoding symbols with probability $1 - \frac{1}{256^{m+1}}$. In order to avoid increasing the computational complexity, RaptorQ uses a clever combination of GF(256) and the low-complexity GF(2) operations, so that the vast minority of the symbol operations are over GF(2) and only a small minority are over GF(256).
3. Except from the use of symbols over larger alphabets, another new technique improving the decoding performance of RaptorQ is the use of the permanent inactivation [12], which is an interesting extension of the LT code and of inactivation decoding. In brief, a limited number of the intermediate symbols are declared to be permanently inactive while the remaining majority of symbols are LT symbols. In the encoding and decoding procedure the permanent inactive symbols are treated differently from the LT symbols utilizing an innovative technique which enhances the recovery properties of the RaptorQ code.

4.3 Protection efficiency in theory

In this subsection we provide a theoretical comparative evaluation of the two examined FEC schemes. It is clear that the key points featuring the performance of an AL-FEC scheme are the decoding failure performance with respect to the number of additional symbols received and further, as a direct consequence of this aspect, the amount of the transmission redundancy required to confront different packet losses patterns.

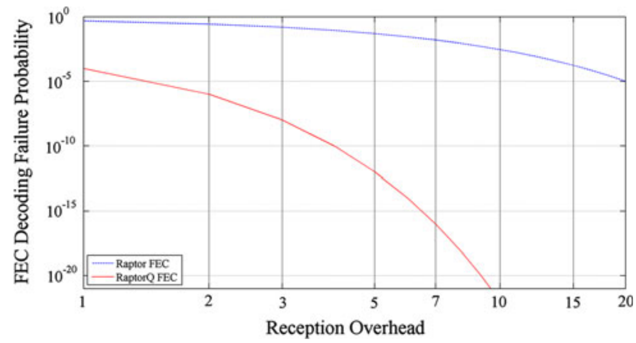

Fig. 2 FEC decoding failure probability versus reception overhead

To this direction, firstly we investigate the decoding performance compared to the reception overhead such a FEC code requires to successfully recover the protected data. Figure 2 presents the probability the FEC decoding process to fail in function to the number of additional symbols received, i.e., the reception overhead, comparing the performance of the standardized Raptor FEC code with that of RaptorQ.

Comparing the two plotted curves behavior, we can immediately remark that although Raptor failure probability decreases exponentially with the growth of the number of additional FEC symbols, the RaptorQ decoding performance supremacy almost eliminates this behavior of Raptor code. Indicatively, while RaptorQ requires only two additional symbols to succeed a practically zero failure probability, Raptor code requires to receive more than 20 additional symbols as indicated in Fig. 2. Based on this, we can say that RaptorQ almost perfectly emulates an ideal fountain FEC code.

The minimum requirements of RaptorQ code over the number of additional symbols have a direct impact on some extremely important aspects of an AL-FEC scheme efficiency. Reception overhead directly characterizes the robustness of a FEC code against packet losses, meaning that a FEC scheme requiring lower number of additional symbols can successfully decode the FEC protected data confronting packet losses patterns where a FEC code, with significant higher requirements on reception overhead, will fail. Consequently, RaptorQ FEC can operate successfully under poorer reception conditions than Raptor code, since, on condition that more symbols than the number of source symbols have been received, RaptorQ can tolerate higher packet losses than Raptor code can.

A direct result of this property is that the RaptorQ protection scheme can be successfully applied requiring significantly lower amount of redundancy. This fact implies that RaptorQ can provide enhanced protection while achieving high reduction on the required transmission overhead and the encoding process overhead. In order to verify this claim in the following part of the theoretical evaluation we illustrate how the transmission overhead of each AL-FEC scheme varies, compared to the packet loss rate on the application layer of a data reception session. For this evaluation, we examine the protection performance of the Raptor and RaptorQ FEC code against the performance of an ideal fountain code. For the conduction of this comparison we assume that each transmitted packet contains only one FEC symbol with the symbol size fixed, considering different values of the transmitted FEC source symbols number. Figure 3 presents the required AL-FEC transmission overhead, that a sender should introduce to the transmission in order to achieve succesfull decoding of the protected data assuming that a sufficient decoding failure probability threshold is 10^{-4}, in relation to the packet loss rate considering 8,192 and 32,768 transmitted FEC source symbols on Fig. 3a, b, respectively.

The first trivial observation from both plots is the proportional increment of the required AL-FEC transmission overhead with the packet loss rate. This is reasonable since as the number of lost packets of a reception session increases, the sender should introduce ever more redundancy to the transmitted data in order to confront the growing packet losses ratio. Furthermore, another remark from both figures is that RaptorQ FEC operates extremely close to an ideal fountain code in contrast to Raptor code. This performance directly implies from the significantly lower reception overhead of RaptorQ code that almost perfectly emulates an ideal code operation.

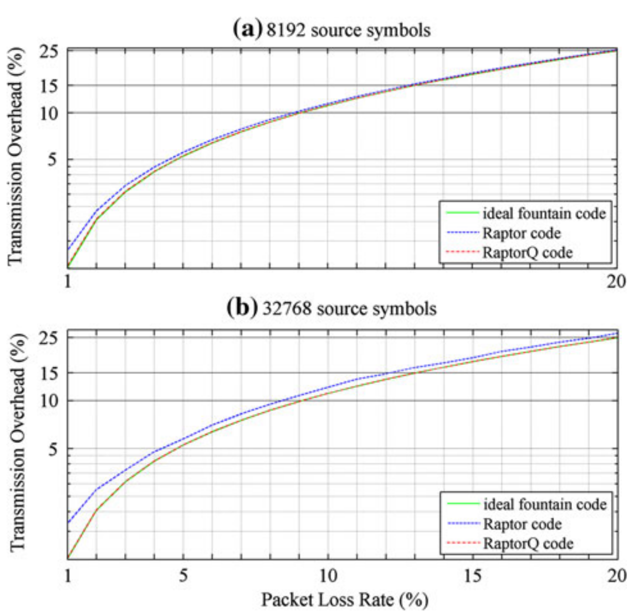

Fig. 3 AL-FEC transmission overhead versus packet loss rate for **a** 8,192 and **b** 32,768 source symbols

Moreover, observing more carefully the Raptor curve in contrast to the RaptorQ curve we can note that as the packet loss rate increase, the performance of Raptor FEC becomes ever more close to that of RaptorQ. This behavior is due to the fact that as the number of lost packets increase and consequently more redundant symbols are required from the FEC encoder, this growth constantly diminishes the reception overhead superiority of RaptorQ code since the difference in the additional received symbols between the two FEC schemes remains fixed regardless of the current reception conditions. Finally, examining the two figures in a comparative way, we can observe that in the case of 32,768 source symbols the differences on the required transmission overhead between the Raptor and RaptorQ code are higher than the case of the smaller transmitted object. This is reasonable, considering the encoding properties of the two FEC codes. As described above Raptor can encode up to 8,192 symbols within a source block, so in the second case the transmitted object is divided into multiple FEC source blocks, while using the RaptorQ encoder allows to send the whole object as a single source block. This property of RaptorQ maximizes the protection efficiency, since allows spreading the protection across the whole file in a FEC source block.

Finally, regarding the complexity of the presented FEC codes, in general both of them require linear encoding and decoding time i.e., the computation complexity of the FEC encoding or decoding process is proportional to the size of the source data. However, as illustrated in [13], RaptorQ code requires significantly higher decoding times than the existing Raptor code considering several block and symbol sizes. This is reasonable, since the tremendous improvement the GF(256) operation introduces on the decoding failure probability has a price, i.e., the higher decoding complexity of RaptorQ.

5 3GPP MBMS simulation results

In this section, we describe at first the selected simulation environment we utilize to conduct our investigation and thereafter we analyze the obtained simulation results considering the application of the two examined AL-FEC schemes compared to that of an ideal FEC code over download and streaming delivery scenarios.

5.1 Simulation environment

In order to simulate the application of the two examined AL-FEC schemes over 3GPP LTE MBMS environments, we utilize the ns-3 network simulator [24]. Our simulation model is composed of a source entity which is responsible to introduce the modeled applications into the multicast gateway

Table 1 Simulation settings

Parameter	Units	Value
Cell layout		Hexagonal grid
Cell radius	m	1,000
Carrier frequency	MHz	2,000
System bandwidth	MHz	5
Transmission time interval (TTI)	ms	80
Modulation scheme		16QAM
Channel model		3GPP typical urban (TU)
Path loss	dB	$L = 128.1 + 37.6log_{10}(d)^*$
Multipath		Jakes model
Penetration loss	dB	10
Shadowing		log-normal distribution
BS transmit power	dBm	43
BS antenna gain	dBi	14
BS antenna height	m	30
# UEs		100
UE's mobility model		Random walk

* *d*, distance between eNB and UE in km

(GW) and furthermore to apply the AL-FEC protection concept on the transmitted data. Thereafter, the multicast GW undertakes to forward the IP multicast flow to the simulated 3GPP radio access network, named evolved UMTS terrestrial Radio Access Network (eUTRAN). Finally, within eUTRAN, the base station, named evolved Node B (eNB), transmits the multicast traffic to multiple User Equipments (UE)s dropped in a specific cell area. The simulated network topology is illustrated in Fig. 4 and Table 1 presents further simulation settings we adopted during the conduction of the simulation experiments.

The modeled physical (PHY) channel covers the 3GPP LTE requirements. On the utilized propagation loss model, the LTE module of ns-3 [25] provides a proper LTE eUTRAN propagation loss model. The ns-3 LTE propagation model includes shadowing, multipath, penetration loss and path loss models allowing us to accurately model the losses due to propagation on the PHY layer. Moreover on the PHY layer, regarding the simulated channel coding scheme, PHY-FEC is applied to the data streams before the transport over the radio link. The applied coding scheme on the multicast channel is based on convolutional coding with fixed rate 1/3. Moreover, a 24-bit CRC protection is attached to the transmitted bitstream. On the modeled PHY layer, the successful reception of each PHY-FEC block is calculated according to a Signal to Noise Ratio (SNR) estimation based on OFDM simulation traces. Finally, the blocks are concatenated in order to determine if the source burst can be reconstructed and forwarded to the upper layers.

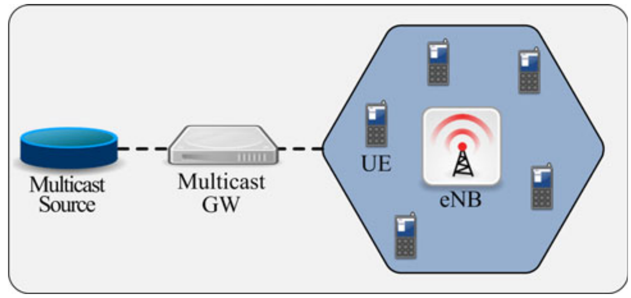

Fig. 4 Single-cell MBMS simulation topology

The most important part of the simulation model, the AL-FEC protection is modeled on the application source before the transmitted data being forwarded to the multicast GW. According to the specified Source Block Length (SBL) the transmitted packets are organized in AL-FEC source blocks and thereafter the redundant AL-FEC symbols are produced for each source block. The number of the generated additional AL-FEC symbols is determined by the transmission overhead a multicast sender introduces to the transmission. Thereafter, the generated source and repair symbols, with the assumption of one FEC symbol per packet, are transmitted through an IP multicast flow to multiple recipients. At the receiver side, we examine the AL-FEC decoding performance utilizing the mathematical modeling of the failure probability for each evaluated AL-FEC code according to a sufficient probability threshold. Subsequently, the probability of successful recovering each AL-FEC protected block derives from (1) and (2) when Raptor and RaptorQ code application is evaluated respectively. More specifically, we require each multicast user achieving FEC decoding failure probability 10^{-4} or less in order to consider a successfully reception of the transmitted block. It is worth mentioning that this assumption does not imply that a user with decoding failure probability higher than this value will surely fail to reconstruct the encoded block, but it is a sufficient practical threshold. Our contribution on modeling AL-FEC protection over the ns-3 simulation environment is available in [26].

5.2 Simulation results

In the following parts of the provided simulation results we evaluate the application of the Raptor and RaptorQ AL-FEC codes over a MBMS download delivery environment with respect to an ideal FEC decoder performance. More precisely, at first we examine the impacts of the two examined AL-FEC schemes on the amount of supported users, i.e. the service coverage, considering the exclusive use of the AL-FEC protection. Thereafter, we provide simulation results considering the total number of retransmitted packets during the MBMS download session utilizing the AL-FEC protection in conjunction with a post-delivery file repair phase as described in Sect. 3.1. Finally, we provide a performance evaluation of the two examined AL-FEC schemes over MBMS streaming scenarios, considering the application of the Raptor and RaptorQ FEC over a multicast video streaming transmission examining specific constraints of a streaming delivery.

5.2.1 *Service coverage versus AL-FEC transmission overhead on MBMS download*

The conducted simulations of this paragraph examine how the amount of the introduced AL-FEC transmission overhead affects the fraction of multicast users that can successfully receive the transmitted object i.e., the MBMS service coverage. For this evaluation we examine the exclusive use of AL-FEC without utilizing a ptp or a ptm post-delivery repair procedure. Regarding the conducted results, we simulate 100 mobile multicast User Equipments (UEs) participating in an AL-FEC protected download session, randomly dropped in the MBMS service. We provide simulation results over two different instances of mobility models with the UEs moving at 3 and 30 km/h, corresponding to urban pedestrian and vehicular mobility scenarios respectively. As already mentioned, the presented results refers to the 3GPP standardized Raptor FEC scheme and the new RaptorQ FEC code, with Figs. 5 and 6 presenting the impacts of the AL-FEC transmission overhead increase on the MBMS service coverage for the pedestrian and vehicular UEs case respectively. The transmitted object consists of 2,048 packets with each size fixed at 512 B and the SBL fixed at 1,024 symbols according to the recommended settings of [1].

Observing the plotted curves of Fig. 5 we can immediately remark the extremely close to ideal performance of the RaptorQ, since an ideal FEC code achieves less than 1 % better service coverage than RaptorQ. On the other hand, Raptor code presents performance quite far from the ideal FEC code and only achieves a little closer performance to that of RaptorQ for high values of transmission overhead where AL-FEC has to confront pedestrian UEs with high packet loss rates. This behavior is expected considering that RaptorQ requires only 2 additional symbols to meet the ideal FEC code performance according to the failure probability threshold, while Raptor code requires reception overhead equal to 24 additional symbols per source block. Moreover, we can observe that RaptorQ can operate almost ideal from the very first additional symbol, while the standardized Raptor code requires significantly more symbols to provide the possibility of successful recovering the protected data.

Regarding the vehicular model results presented in Fig. 6 we can immediately remark that the required transmission overhead is clearly higher than the pedestrian

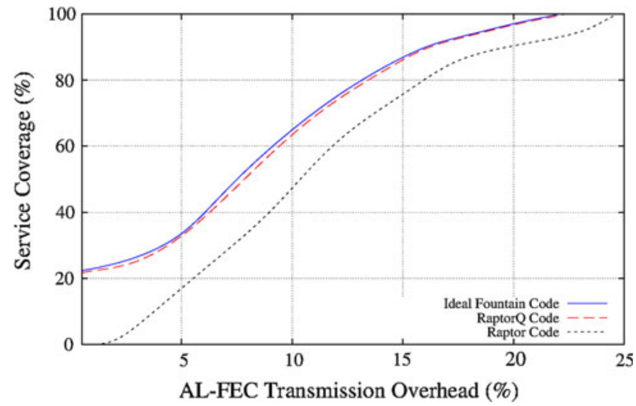

Fig. 5 Service coverage versus AL-FEC transmission overhead over pedestrian UEs

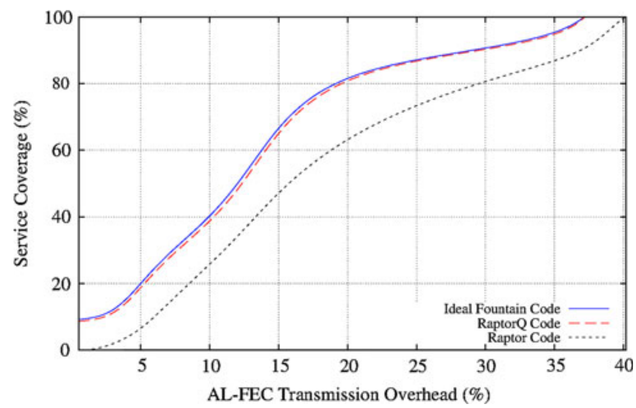

Fig. 6 Service coverage versus AL-FEC transmission overhead over vehicular UEs

UEs case due to the expected higher packet loss rate beacause of the higher evaluated velocity of the UEs. Indicatively, we can mention that the required transmission overhead to achieve the RaptorQ scheme 90 % of service coverage is about 30 % for the vehicular model in contrast to the 15 % of required overhead for the pedestrian case. Comparing the two evaluated AL-FEC codes, we can observe that RaptorQ code can achieve 80 % service coverage requiring about 18 % of introduced overhead, while the older Raptor scheme requires 30 % overhead revealing the supremacy of RaptorQ as also depicted in Fig. 5. Moreover, we can remark that the coverage curves of both AL-FEC codes for the vehicular model are less smooth than the curves corresponding to the pedestrian model since, despite the higher average packet loss rate, the higher velocity model offers the possibility of fewer UEs experiencing permanent very poor reception conditions.

Furthermore, regarding the curves behavior of both figures, we can observe that exists an efficient interval of transmission overhead selection for each mobility scenario. This efficient range can be defined between 5 % and 15 % for the pedestrian scenario and between 10 % and 20 % for

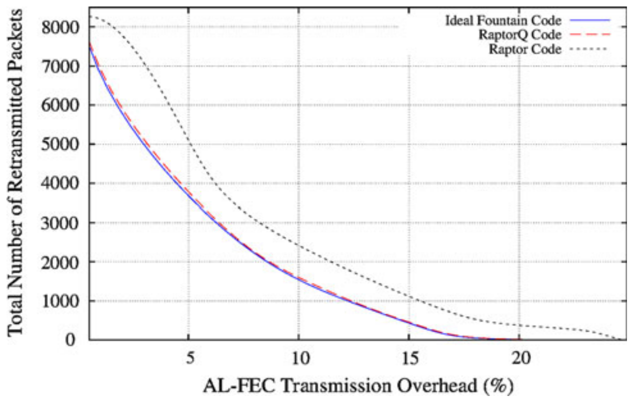

Fig. 7 Retransmitted packets versus AL-FEC transmission overhead

the vehicular scenario. Clarifying the latter, we can observe that increasing the transmission overhead in the specific intervals results in a proportional increase on the amount of UEs successfully recovering the protected data, while beyond this transmission overhead zone the gains on the system coverage are minimized.

5.2.2 *Retransmitted packets versus AL-FEC transmission overhead on MBMS download*

Under this part of the presented MBMS download simulation results, Fig. 7 presents how the total number of retransmitted packets during the MBMS download session period varies considering the application of the evaluated AL-FEC schemes in conjunction with a ptp file repair procedure over pedestrian UEs. The post-delivery ptp file repair phase is applied, as described in Sect. 3.1, until all UEs can successfully recover the transmitted object. For this evaluation we simulate 1,024 symbols protected together within an AL-FEC source block transmitting in total 2,048 packets each one of size 512 B.

As in the previous part of presented results, the plotted curves immediately reveal the primacy of RaptorQ since achieves significantly lower number of retransmitted packets compared to Raptor FEC. We can observe that RaptorQ performance is just a "step" behind the ideal fountain FEC code. At this point, we have to clarify that the total number of retransmitted packets is independent from each code reception overhead itself and only depends on the service coverage, because if a UE fails to decode the FEC protected block requests the retransmission of the exact number of lost source packets only. Furthermore, we can observe that Raptor curve presents an initial delay until it can reach the ideal curve form. This is a direct result of the conduct described previously in Fig. 5, since Raptor FEC inefficiency is more pronounced for low values of transmission overhead.

5.2.3 *Tune-in delay versus service coverage on MBMS streaming*

For this evaluation we examine the impacts of the AL-FEC protection on the tune-in delay with respect to the MBMS service coverage defined in the previous subsection. 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 $tune - in\,delay = protection\,period + \varepsilon$ [27]. It is obvious that tune-in delay strongly depends on the FEC encoding parameters and more specifically on the selected length of the FEC source block and the introduced AL-FEC transmission overhead. Based on this, on Fig. 8 we provide simulation results considering the application of the two examined members of Raptor codes family with respect to an ideal FEC code. The presented results refers to the simulation of the pedestrian mobility model utilizing a RTP flow of H.264 stream with 128 kbps video source rate considering the non-interleaved packetization mode [1] on the multicast clients. The AL-FEC SBL is fixed at 512 symbols and the size of transmitted packets varies between 672 B and 845 B.

Once again, RaptorQ almost perfectly emulates the performance of an ideal FEC fountain code. Examining the conducted curves, we can remark that RaptorQ requires consistently significant lower time for the tune-in process in comparison with Raptor until the service coverage reaches the value of about 95 %. For higher values of service coverage we observe that the achieved reduction of RaptorQ on the tune-in delay is gradually reduced. This behavior, which is also denoted in the previous subsection results, is due to the fact that the AL-FEC transmission overhead has an optimal zone of efficient operation with respect to the current packet loss conditions. Therefore, for high values of service coverage, where both Raptor schemes have to confront a small fraction of UEs with extremely bad reception conditions, the close behavior of the two examined AL-FEC codes is expected, since the tune-in delay performance strongly depends on the transmission overhead given that the examined SBL is fixed.

5.2.4 *Time utilization versus SBL on MBMS streaming*

At this last part of the presented simulation results we draw the impacts of different FEC encoding parameters selection on the

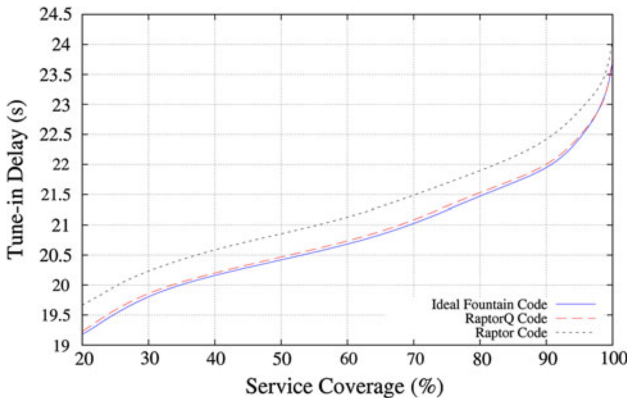

Fig. 8 Tune-in delay versus service coverage

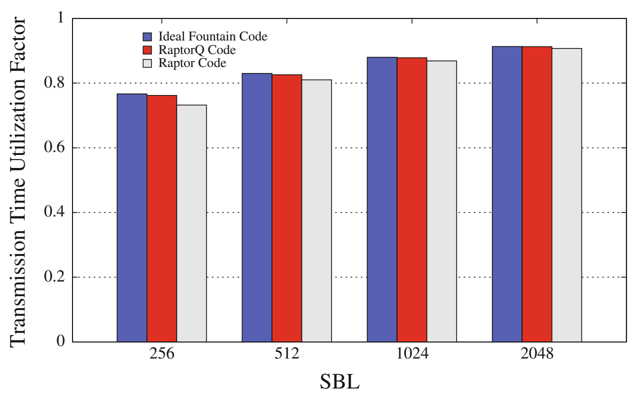

Fig. 9 Time utilization factor versus SBL

delivery procedure over pedestrian UEs, utilizing a factor, named Time Utilization. Time utilization factor ranges between 0 and 1 and defines the wasted transmission time due to the introduction of AL-FEC protection, considering the time the multicast source transmits redundant data compared to the time transmitting source data. Figure 9 presents how the transmission time utilization factor varies under the selection of different SBL for the AL-FEC encoding process targeting 85 % of service coverage on a MBMS streaming delivery. The conducted simulation results evaluate 4 different values, i.e. {256, 512, 1024, 2048}, of SBL considering the application of the presented AL-FEC schemes on the same RTP H.264 flow at 128 kbps with the size of transmitted packets varying between 672 B and 845 B as in the previous subsection evaluation.

Observing the plotted bars on Fig. 9 we can extract some very interesting remarks on the impacts of the selected SBL on the transmission efficiency and consequently on the protection efficiency of each examined AL-FEC scheme. We can immediately remark that increasing the selected SBL at the encoding process results in remarkable gains on the transmission efficiency, since the utilization factor constantly grows with the SBL. In more details, we can observe that the gain of collecting the transmitted symbols in SBL of size 2,048 yields in about 20 % higher time utilization compared to the case of transmitting the stream segmented into smaller and subsequently more FEC blocks i.e., the 256 SBL case. The observed increase in the time utilization factor with the expansion of the simulated SBL size in higher values is directly implied from the AL-FEC recovery properties, as mathematically described from the failure probability of each code, since increasing the SBL and consequently reducing the segmentation of the transmitted data into several blocks results in more efficient spreading of the protection redundancy in the transmitted object and thereafter in lower recovery failure probability.

Further studying the simulated AL-FEC codes performance for each individual SBL size, we can observe that as the SBL increase the differences between the time utilization achieved by each examined AL-FEC scheme are constantly reduced. Clarifying the latter, the increased number of symbols protected together within an AL-FEC source can eliminate the impacts of the Raptor's code higher reception overhead on its protection performance compared to RaptorQ, as similarly observed in the case of the RaptorQ and the ideal fountain code comparison.

6 Conclusions

In this work we have provided an extensive performance evaluation of the new, very promising variation of the Raptor codes family over 3GPP mobile multicast services. We have drawn the main functional improvements that the newest member of Raptor codes, named RaptorQ, has emerged compared to the 3GPP standardized Raptor code. Improvements that enables the enhanced efficiency of the newly introduced FEC code regarding the achieved protection performance and the required transmission redundancy. To verify the superiority of RaptorQ against Raptor code we have provided a theoretical evaluation of the two examined AL-FEC schemes application through which we were able to detect the enhanced features RaptorQ can provide on the field of reliable multicasting. Apart from the conclusions extracted from the early theoretical evaluation, we have further introduced a MBMS simulation environment considering the application of the examined AL-FEC schemes on both download and streaming delivery scenarios over evolved 3GPP systems. We have realized an investigation including several perspectives of the AL-FEC protection impacts over the 3GPP multicast services performance and further examining several FEC encoding parameters.

From the conducted simulation results we have verified the enhanced efficiency of the new RaptorQ FEC scheme evaluating the newly introduced AL-FEC code over various FEC encoding settings and we have examined how the mathematically expressed superiority of RaptorQ is reflected in the performance of mobile multicast services. The almost ideal behavior of RaptorQ requirements concerning the required additional data allows operating with significantly lower transmission overhead compared to the standardized Raptor FEC with respect to the evaluated AL-FEC encoding parameters. This property is beneficial for the mobile system efficiency since RaptorQ can effectively operate under poorer reception conditions while achieving significant reduction in the required redundancy and hence offering enhanced resource utilization. Indicatively, we have verified that the enhanced RaptorQ achieves in average about 15 % reduction on the required transmission overhead compared to Raptor code. In fact, for small values of introduced overhead RaptorQ FEC achieves a performance that exceeds the 20 % reduction with respect to the current network's conditions and the AL-FEC encoding parameters. Furthermore, we were able to examine the reflection of the enhanced RaptorQ properties on some specific constraints of both the MBMS delivery methods, providing over 10 % higher resources utilization and verifying once again the universal supremacy against the existing Raptor FEC scheme.

7 Future work

On possible future steps we could design a cross-layer scheme, which could adapt the AL-FEC encoding parameters based on an interoperability scheme between the AL-FEC layer with other protection mechanisms deployed in lower layers, optimizing the costly error protection framework in total. Moreover, in order to avoid the individual constraints of a feedback based mechanism, we could introduce a probabilistic approach on the AL-FEC parameters selection. Finally, as the newly introduced RaptorQ FEC scheme greatly addresses the shortcomings of the existing Raptor code, we could examine the possibility of utilizing AL-FEC protection over ptp environments where previously its utilization was considered inefficient.

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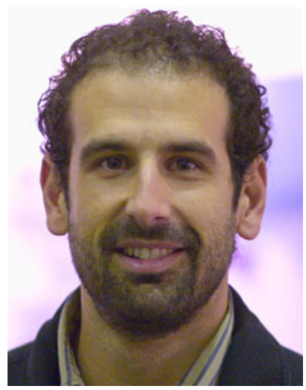
Author Biographies

Christos Bouras Christos Bouras is Professor in the University of Patras, Department of Computer Engineering and Informatics. Also he is a scientific advisor of Research Unit 6 in Computer Technology Institute and Press - Diophantus, Patras, Greece. His research interests include Analysis of Performance of Networking and Computer Systems, Computer Networks and Protocols, Mobile and Wireless Communications, Telematics and New Services, QoS and Pricing for Networks and Services, e-learning, Networked Virtual Environments and WWW Issues. He has extended professional experience in Design and Analysis of Networks, Protocols, Telematics and New Services. He has published more than 400 papers in various well-known refereed books, conferences and journals. He is a co-author of 9 books in Greek and editor of 1 in English. He has been member of editorial board for international journals and PC member and referee in various international journals and conferences. He has participated in R&D projects. He is member of experts in the Greek Research and Technology Network (GRNET), member of Scientific Committee of GRNET, member of Strategic Committee of Digital Greece 2020, also he is member of BoD of GFOSS, member of Central Committee of TEE and BoD of e - TEE (Vice President).

Nikolaos Kanakis obtained his Diploma from the Computer Engineering and Informatics Department of Patras University (Greece). Moreover, he received his Master Degree in 'Computer Science and Technology' from the same department. Currently, he continues his studies in order to obtain his Ph.D. His research interests include next generation mobile telecommunications networks, multicast protocols and reliable multicasting. He has published 4 research papers in well-known refereed conferences and scientific journals.

Vasileios Kokkinos obtained his diploma from the Physics Department of the University of Patras on October 2003. Next, he was accepted in the postgraduate program "Electronics and Information Processing" in the same department and on March 2006 he obtained his Master Degree. In 2010 he received his Ph.D. on Power Control in Mobile Telecommunication Networks from the Computer Engineering and Informatics Department (CEID). He is currently an R&D engineer at the Telematics and Distributed Systems Laboratory, CEID, and at the Computer Technology Institute and Press "Diophantus", working on data networks, next generation mobile telecommunications networks including LTE and LTE-Advanced networks, multicast routing and group management and radio resource management. He has published more than 40 research papers in various well-known refereed conferences, books and scientific journals.



Andreas Papazois obtained his diploma, M.Sc. and Ph.D. from Computer Engineering and Informatics Department, University of Patras, Greece. He is currently an R&D engineer at Research Unit 6: Networks Telematics and New Services, Computer Technology Institute & Press "Diophantus" (CTI). He worked as telecommunication systems engineer in Intracom Telecom S.A.. His research interests include Web Services, Future Mobile Networks, Error Control, Quality of Service and Multicast Transmission. He has published several research papers in various well-known refereed scientific conferences, books and journals. He has been technical commitee member for several scientific conferences and he is a reviewer for various international journals.