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Application layer forward error correction for multicast streaming over LTE networks

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SUMMARY

The next step beyond third generation mobile networks is the Third Generation Partnership Project standard, named Long Term Evolution. A key feature of Long Term Evolution is the enhancement of multimedia broadcast and multicast services (MBMS), where the same content is transmitted to multiple users located in a specific service area. To support efficient download and streaming delivery, the Third Generation Partnership Project included an application layer forward error correction (AL-FEC) technique based on the systematic fountain Raptor code, in the MBMS standard. To achieve protection against packet losses, Raptor codes introduce redundant packets to the transmission, that is, the forward error correction overhead. In this work, we investigate the application of AL-FEC over MBMS streaming services. We consider the benefits of AL-FEC for a continuous multimedia stream transmission to multiple users and we examine how the amount of forward error correction redundancy can be adjusted under different packet loss conditions. For this purpose, we present a variety of realistic simulation scenarios for the application of AL-FEC and furthermore we provide an in-depth analysis of Raptor codes performance introducing valuable suggestions to achieve efficient use of Raptor codes. Copyright © 2012 John Wiley & Sons, Ltd.

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KEY WORDS: forward error correction; long term evolution; raptor codes; streaming delivery; multimedia broadcast and multicast

1. INTRODUCTION

The Third Generation Partnership Project (3GPP) multimedia broadcast and multicast service (MBMS) has been standardized as a feature in 3GPP systems to broadcast and multicast multimedia content to multiple mobile terminals via MBMS radio bearer. MBMS is a point-to-multipoint (PTM) standard, whose further evolvement and enrichment attracts nowadays widespread interest [1]. Transmitting the same data to multiple recipients allows network resources to be shared. MBMS extends the existing 3GPP architecture with the introduction of the MBMS bearer service and MBMS user services. MBMS user services are built on top of the MBMS bearer service. The MBMS bearer service offers two modes: the broadcast and the multicast mode. 3GPP specifies two delivery methods for the MBMS user services: the download method providing delivery of discrete objects and the streaming method providing delivery of continuous media. Long Term Evolution (LTE) provides both single-cell MBMS transmission mode, where the MBMS services are transmitted in a single cell, and multicell evolved MBMS transmission mode, providing synchronous MBMS transmission from multiple cells, also known as multicast/broadcast single frequency network transmission mode. Currently, there is significant focus on the need for optimizing streaming

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services in the context of delivering popular multimedia content, especially video services, to multiple mobile subscribers [2]. In the remainder of this work we focus on the streaming delivery method over single-cell MBMS environments.

Forward error correction (FEC) is a method for error control of data transmission that is used to augment or replace other reliability methods. Generally in FEC, the sender introduces redundant information in the data transmitted, providing the ability to overcome losses and corruptions at multiple receivers, without the retransmission of lost data. In multicast protocols the use of FEC has very strong motivations. The encoding eliminates the effect of independent losses at different receivers, while achieving a reduction in the rate of packet loss, according to the introduced redundancy by the FEC encoder, results in large mitigation to the need of sending feedback to the sender for lost packets retransmission. Especially in MBMS, application layer FEC (AL-FEC) can address the problems not dealt with by physical layer FEC or by other error protection mechanisms in upper layers, to provide reliability and scalability against different packet loss rates. Raptor AL-FEC, unlike FEC in lower layers, provides erasure coding capabilities, meaning that Raptor aims to provide protection against data losses and not against data corruptions. These data losses correspond to packets that are lost or rejected as corrupted by the lower protocol layers. Consequently, 3GPP recommends the use of AL-FEC for MBMS, and more specifically, Raptor codes [3] have been selected because of their high performance in comparison with other AL-FEC schemes.

Streaming services are suitable for real-time content delivery, where data reception is tightly time-constrained. Therefore, the use of retransmission-based methods to confront packet losses is not appropriate for streaming delivery. For multicast streaming, an efficient method to obtain reliability [4] to the transmission is to introduce enough redundancy (i.e., the FEC overhead) so that each packet is transmitted only once. The sender should decide the most suitable amount of overhead it will transmit to cope with different receiver's packet loss rates.

To this direction, in this work, we study the application of AL-FEC for the streaming delivery method over LTE networks. Because the redundancy of FEC aims to overcome packet losses, we first investigate how the packet loss rate varies at multiple receivers and how the amount of AL-FEC protection that a multicast sender should introduce to the transmission alters for different system parameters using realistic simulation scenarios. Furthermore, we investigate which is the optimal AL-FEC overhead considering different cell deployments, user mobility models and AL-FEC encoding parameters, to satisfy as many users as possible. We provide an extensive examination of the benefits that a, AL-FEC reliability scheme can provide in multicast streaming environments. We investigate the interaction of the AL-FEC application with the network performance and we explore the impact of the Raptor FEC parameters on the AL-FEC system robustness.

The remainder of the manuscript is structured as follows: in Section 2 we provide the related work in AL-FEC for download and streaming delivery methods over mobile networks. Section 3 provides an overview of the MBMS streaming framework and the application of AL-FEC over it. We describe the MBMS protocol stack, the streaming delivery method, and we provide a detailed description of Raptor codes. Section 4 describes the simulation framework we use for the evaluation of AL-FEC over MBMS streaming services and in Section 5 we present the simulation results. Finally, in Section 6 we provide our conclusions and we present some possible future steps over the field. For the reader's convenience, Appendix A presents an alphabetical list of the acronyms used in the manuscript.

2. RELATED WORK

The authors of this manuscript provide a preliminary study on the application of AL-FEC for LTE multicast streaming services in [5]. Apart from this initial investigation that consists the basis for the present full study, to the best of our knowledge, other related works presented cover research on AL-FEC for MBMS download delivery method over the LTE mobile networks or for MBMS streaming services over prior to LTE systems.

In [6], a file recovery scheme for the LTE MBMS download delivery method was presented. The authors proposed the exclusive sending of redundant packets, using AL-FEC, that is, Raptor codes, instead of using the retransmission-based error recovery scheme, until all the receivers recover the

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file. The authors in [7] presented an evaluation of MBMS download services in universal mobile telecommunications system (UMTS) mobile networks. This work investigated the optimal dimensioning of Raptor codes based on a probabilistic method that models the multicast user distribution. It should be noted that both Refs. [6] and [7] have been performed from the telecommunication cost perspective. The work presented in [8] evaluated the trade-off between AL-FEC and physical layer FEC over MBMS download delivery services in UMTS systems. The authors investigated the benefits of FEC on user experience and radio resource consumption through a system level simulator. The authors in [9] proposed the usage of FEC protection in combination with point-to-point (PTP) and the PTM file repair schemes for the MBMS download delivery method over UMTS systems. The goal of this study is the optimization of the network resource usage by balancing the FEC transmission overhead with file repair procedures after the MBMS transmission. The work in [10] proposed a novel scheme providing reliability for single-cell evolved MBMS download delivery method, considering the application of Raptor FEC at application layer and hybrid automatic repeat request at link layer. The goal of this analysis is to minimize the number of retransmissions in hybrid automatic repeat request considering the properties of Raptor codes and satisfy the QoS requirement as well.

The study in [11] included among others an investigation of Raptor codes as a method to provide application layer QoS in the MBMS streaming framework over third generation networks by adjusting the AL-FEC parameters to maximize the amount of satisfied users who participate in video stream reception. The work in [12] investigated different system design options for MBMS video streaming over mobile networks such as enhanced general packet radio service and UMTS. One of their main goals was to evaluate and to clarify the impact of AL-FEC application on the overall system performance. The authors in [13] introduced a method, where partly erased data can be utilized in the decoding process to enhance the performance of Raptor codes in multicast streaming applications over a predecessor of LTE mobile networks. In [14], the authors provided a power control analysis for streaming delivery over HSDPA systems, including the impacts of the AL-FEC application to the transmission. Finally, in [15] an adaptive scheme over 3GPP video broadcast streaming services was presented. The authors proposed a joint optimization framework of video coding, AL-FEC, and physical layer rate selection to enhance the end user experience.

It is obvious that the related works do not provide an in-depth analysis of the AL-FEC performance over multicast streaming services, but examine the application of AL-FEC in a limited context of the multicast transmission and consider a restricted range of aspects of mobile networks prior to LTE. Therefore, our persuasion is to fill the gap of the evaluation of AL-FEC over LTE multicast streaming services, providing a thorough performance analysis of the application of AL-FEC over MBMS streaming.

3. AL-FEC FOR MULTIMEDIA BROADCAST AND MULTICAST SERVICE STREAMING

In this section, we provide an overview of the streaming delivery method, focusing on the use of Raptor codes as AL-FEC for MBMS streaming services. Furthermore, we provide a description of the standardized systematic Raptor codes and their performance.

3.1. Multimedia broadcast and multicast service streaming delivery

The purpose of the MBMS streaming delivery method is to deliver continuous multimedia data (i.e. speech, audio, video) over an MBMS bearer. The protocol stack used by MBMS streaming delivery [3] is illustrated in Figure 1. MBMS makes use of the most advanced multimedia codecs such as H.264 for video applications and enhanced AAC for audio applications. Real-time transport protocol (RTP) is the transport protocol for MBMS streaming delivery. RTP provides means for sending real-time or streaming data over user datagram protocol (UDP). Furthermore, RTP control protocol provides the ability for feedback on the transmission quality. 3GPP recommends the use of FEC mechanism by the sender before RTP flows are mapped onto UDP. Thereafter, the resulting UDP flows are generally mapped on the MBMS Internet Protocol (IP) multicast bearers.

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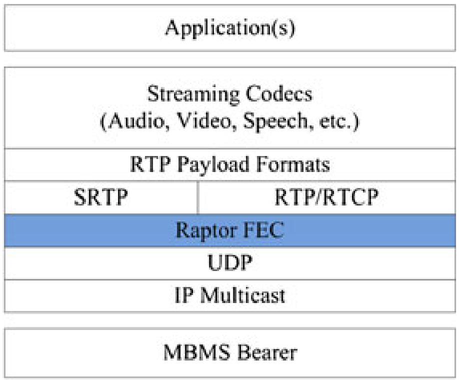

Figure 1. MBMS streaming services protocol stack.

A key functionality of the MBMS streaming delivery method is the provision of reliability control in the transmission by means of FEC for RTP flows. At the FEC layer the mechanism for applying protection to streaming media consists of three components: the construction of a FEC source block from the source media packets belong to one or several UDP packet flows, the modification of source packets to indicate the position of the source data from the source packet within the source block and the definition of repair packets, sent over UDP, which can be used by the FEC decoder to reconstruct missing portions of the source block. At the sender, the mechanism begins by processing original UDP packets to create a stored copy of the original packets in the form of a source block, and FEC source packets for transmission to the receiver. After constructing the source block from the original UDP payloads to be protected, the FEC encoder generates the desired amount of FEC protection data, that is, encoding symbols. These repair symbols are then sent using the FEC repair packet format. The receiver recovers the original packets directly from the FEC source packets. If any FEC source packets have been lost, but sufficient FEC source and FEC repair packets have been received, FEC decoding can be performed to recover the FEC source block. Consequently, if a user equipment (UE) that supports MBMS streaming services receives a mathematically sufficient set of encoding symbols, then the FEC decoder shall recover the entire source block of data.

3.2. Raptor codes for multimedia broadcast and multicast service AL-FEC

The 3GPP has standardized Turbo codes as the physical layer FEC codes and Raptor codes as the application layer FEC codes for MBMS aiming to improve service reliability [16]. Because Turbo FEC is applied both on unicast and multicast transmissions, Raptor FEC is the only method dedicated to the MBMS reliability enhancement. The use of Raptor codes in the application layer of MBMS has been introduced to 3GPP by Digital Fountain (San Diego, California USA) [17]. 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 code with linear time encoding and decoding [18]. In preparation for 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 FEC encoding symbols only slightly more in number than the source symbols. The Raptor code specified for MBMS is a systematic fountain code producing n encoding symbols E from $k < n$ source symbols C. This code can be viewed as the concatenation of several codes. The most-inner code is a nonsystematic Luby-Transform (LT) code with l input symbols F, which provides the fountain property of the Raptor codes. This nonsystematic 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 preprocessing to the k source symbols C such that the input symbols D to the nonsystematic Raptor code are obtained.

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The description of each step and the details on specific parameters can be found in [3]. The study presented in [19] shows that Raptor codes have a performance very close to ideal, that is, the failure probability of the code is such that in case that only slightly more than k encoding symbols are received, the code can recover the source block. In fact, for $k > 200$ the small inefficiency of the Raptor code can accurately be modeled by (1) [20]

$$p_f(m,k) = \begin{cases} 1 & \text{if } m < k, \\ 0.85 \times 0.567^{m-k} & \text{if } m \geqslant k. \end{cases} \tag{1}$$

In (1), $p_f(m,k)$ denotes the failure probability of the code with k source symbols if m symbols have been received. It has been observed that for different k, the equation almost perfectly emulates the code performance. Although an ideal fountain code would decode with zero failure probability when $m = k$, the failure for Raptor code is still about 85%. However, the failure probability decreases exponentially when the number of received encoding symbols increases.

4. SIMULATION FRAMEWORK

To evaluate the performance of Raptor codes for streaming services over MBMS environment, we utilize an open source simulation platform introduced in [21]. This framework of LTE networks simulates both the evolved Universal Terrestrial Radio Access Network and the evolved packet system. It is a fully functional simulator that provides several traffic flows at the application layer through the implemented LTE protocol stack. It supports, among others, multiuser scenarios in single-cell and multicell environments, simulating different user mobility models, handover procedures, different scheduling algorithms, and a variety of physical layer models. To run a simulation, we have to create a scenario that corresponds to the individual simulation requirements. After setting the network topology, creating cells, evolved Node Bs (eNBs) and the UEs, we have to set the simulated applications and finally the simulation duration. The simulator provides a tracing functionality, displaying directly the simulation results considering packets at the application layer.

To simulate single-cell MBMS mode of LTE networks, we extend the already provided functionalities of this framework. The network architecture of our simulation framework is illustrated in Figure 2. In the evolved Universal Terrestrial Radio Access Network, the eNBs are the collectors of the information that has to be transmitted to UE over the air interface. Within the evolved packet core, as specified in [16], an MBMS specific functional entity, the Broadcast Multicast Service Center (BM-SC) serves as an entry point for content provider used to initiate the modeled MBMS bearer service and deliver IP multicast traffic. Also, the BM-SC is responsible for

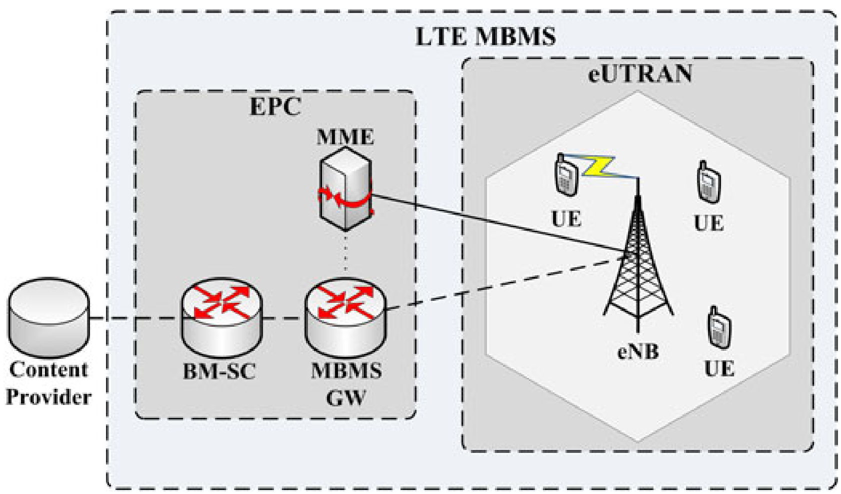

Figure 2. LTE MBMS network architecture.

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providing protection against errors to the transmitted data through AL-FEC. The content provider is the multimedia multicast source and provides discrete and continuous media to the BM-SC. Furthermore, the MBMS gateway has been modeled. This functional entity exists at the edge between eNBs and the BM-SC and its main functionalities are to forward the protected packets to each eNB transmitting the streaming service and to control the multicast session start/stop via the mobility management entity.

Our simulation scenarios provide real-time video traffic models at the application layer, which are encapsulated in RTP and forwarded to lower layers (Figure 1). The main concept of our simulation framework is the addition of a FEC protection mechanism on the application layer of the simulated multicast streaming services according to the 3GPP specifications. The application of FEC protection scheme to the multimedia stream is introduced at the BM-SC, using Raptor codes as described above. For our MBMS simulations we modify the provided H.264 flow, to distribute the RTP/UDP/IP packets in a PTM manner to the simulated UEs. Furthermore, we integrate the Raptor AL-FEC scheme, described above, to the H.264 flow, while we do not consider the examination of the Turbo FEC encoding at the physical layer. The modeled AL-FEC encoder, illustrated in Figure 3, generates the additional packets according to the desired protection. More precisely, the produced packets form the source block(s) according to the maximum number of symbols per source block, in line with the assumptions described in Section 5 below. After constructing the source block from the original packets to be protected, the modeled FEC encoder generates the desired amount of protection, that is, n encoding symbols are produced from k source symbols for each source block. Therefore, the overhead added from the Raptor encoding, that is, the number of FEC repair symbols divided by the number of FEC source symbols, is equal to the fraction $(n - k) / k$. This fraction, in terms of percentage, indicates the Raptor overhead that the FEC protection technique introduces to the transmission. After the applied FEC framework, the resulting UDP flows are mapped on the MBMS IP multicast bearers. Finally, the modeled multicast bearers require only a few modifications of the existing LTE user plane protocol stack of packet-switched services, to support MBMS mode.

The presented simulation framework allows us to evaluate a variety of streaming flows encoded at different source rates for different simulation duration. The modeled streaming flows are transmitted

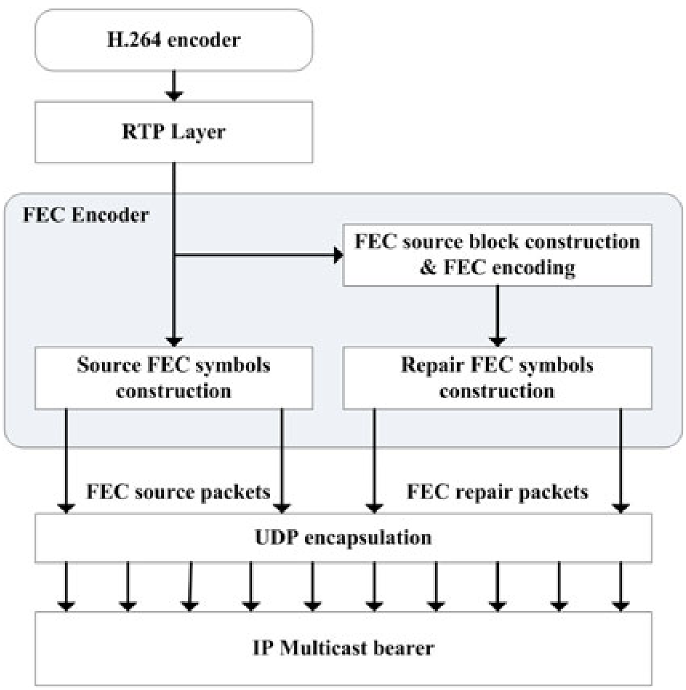

Figure 3. MBMS video streaming FEC framework.

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in realistic multicast environments with variable density of mobile users in the MBMS service area and different user mobility models. Furthermore, because our simulations concern the single-cell MBMS mode, we can simulate different deployments selecting the number of adjacent cells acting as intercell interference and the cell radius. On system parameters we can evaluate the performance for different values of the system bandwidth and a variety of channel models. At the modeled AL-FEC layer the parameters that can be selected are the Raptor overhead introduced to the protected data and the number of symbols protected in a FEC source block.

At the receiver side we examine the user satisfaction, in the sense of successfully decoding the FEC protected stream, depending on the amount of protection that Raptor encoding adds to the transmitted flow. The theoretical performance of the Raptor FEC code depends on the amount of data received by each user in the multicast area. If less data has been received than the size of the block to which FEC protection has been applied, recovery of the original block is obviously impossible. If an amount of encoding symbols has been received, which is not less of the number of source symbols, the probability of successful decoding the media stream can be directly extracted by (1).

5. PERFORMANCE EVALUATION

This section provides the experimental results of the evaluation that we conducted based on the simulation framework presented in the previous section.

5.1. Simulation setup

Our simulation setup is able to provide results for variable and realistic network conditions. The LTE system simulation parameters that are taken into account for the experiments are presented in Table I. The macrocell propagation model for urban area, proposed in [22], is selected for our simulation scenarios. The selected single-cell MBMS deployment, illustrated in Figure 4, simulates an MBMS center cell and an adjacent ring of six cells acting as intercell interference. For this experimental evaluation we use two transmission scenarios. In the first scenario we assume that a H.264 video flow, encoded at different source rates, is transmitted in a point to multipoint way to the multicast users through MBMS bearers, while in the second transmission scenario we assume that each user receives, simultaneously with the multicast video content, one best effort flow through unicast bearers. It is our belief that the second transmission setup provides simulation results for realistic, high load network conditions.

For the FEC encoding process we assume that the symbol size is fixed and each resulting packet contains one FEC symbol. The simulation experiments evaluate the performance of Raptor codes, according to the introduced overhead to the transmission for different parameters from the user satisfaction perspective. We assume that a user is satisfied if the amount of received encoding symbols is sufficient to decode successfully all the source blocks of the transmitted multimedia. More specifically, we demand that the probability of decoding failure for each source block of the stream is less

Table I. Simulation settings.

Parameter	Units	Value
Cell layout		Hexagonal Grid, 3 sectors per site
Simulation duration	s	120
Carrier frequency	MHz	2000
System bandwidth	MHz	5/10
Channel model		3GPP Typical Urban (TU)
Propagation model		3GPP Macro cell – Urban Area
Path loss	dB	$L = 128.1 + 37.6 \log_{10}(d)$, d = distance between eNB and UE in km
UE Rx Antennas		2
BS # Antennas		1
BS transmit power	dBm	43
BS antenna gain	dBi	14

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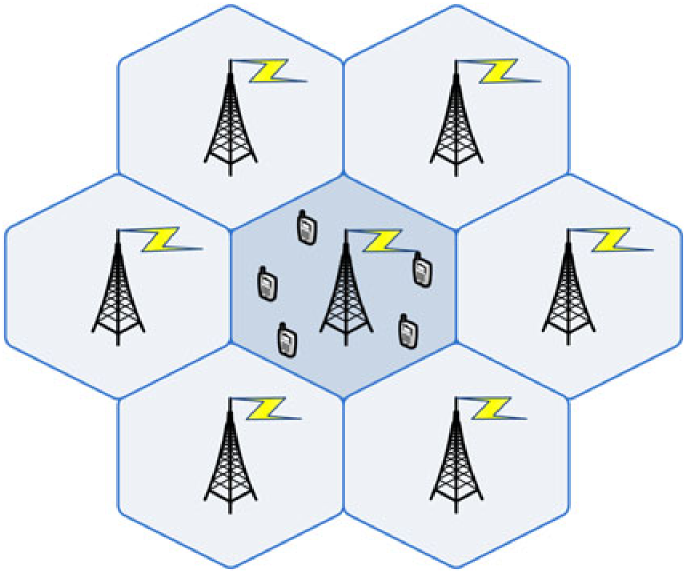

Figure 4. Selected network simulation deployment.

than 10^{-2} as proposed in [23] to consider a user satisfied. It is worth mentioning that this assumption does not imply that a user with decoding failure probability higher than this value will fail to reconstruct the encoded data, but it is a sufficient practical threshold.

5.2. Packet loss rate

In this subsection we present simulation results concerning the packet loss rate (PLR) of the network for the MBMS video streaming flow. It is clear that the main parameter that influences the amount of AL-FEC protection, a multicast sender should introduce to the transmission, is the PLR of the multicast receivers. On the basis of this, before proceeding to the evaluation of AL-FEC performance, we try to analyze the network's PLR performance. More specifically, Figure 5 provides the average PLR of the PTM multimedia service for different user's mobility, considering both pedestrian (3 km/h) and vehicular (30 and 120 km/h) users. Figure 5(a) presents PLR for the two transmission scenarios described above, simulating 5 MHz system's bandwidth, while Figure 5(b) refers to 10 MHz bandwidth. Furthermore, both figures present results for 200 mobile UEs dropped in the single-cell MBMS area, the cell range is set to 2000 m and the H.264 video flow is encoded at 128 kb/s.

By analyzing the two plots presented in Figure 5, we can directly observe the differences between the two transmission scenarios. The simultaneous transmission of PTP best effort flows with the PTM video flow results in a large increase of the MBMS PLR compared with the scenario that simulates only the MBMS transmission. This is anticipated because the presence of unicast bearers transmitted to each multicast user increases the network load both in the core network and the radio access network. Another immediate observation is the remarkable gain in the PLR performance with the increase of the system bandwidth from 5 to 10 MHz as indicated in Figure 5(b).

Furthermore, both figures indicate the increase of the PLR that multicast users present with the increase of the speed that UEs move. To clarify this, we notice that simulating pedestrian and vehicular (30 km/h) users results in fairly low values of the average video PLR, while considering the higher mobility model (i.e., UEs moving at 120 km/h), we notice high enough PLR, especially when the system bandwidth is set to 5 MHz. This is reasonable, considering the channel realization of the different simulated mobility models.

5.3. Applicatoin layer-forward error correction overhead

In this part of experiments we first examine the average AL-FEC overhead against the number of multicast users dropped in the MBMS area and then we present how the AL-FEC overhead varies in

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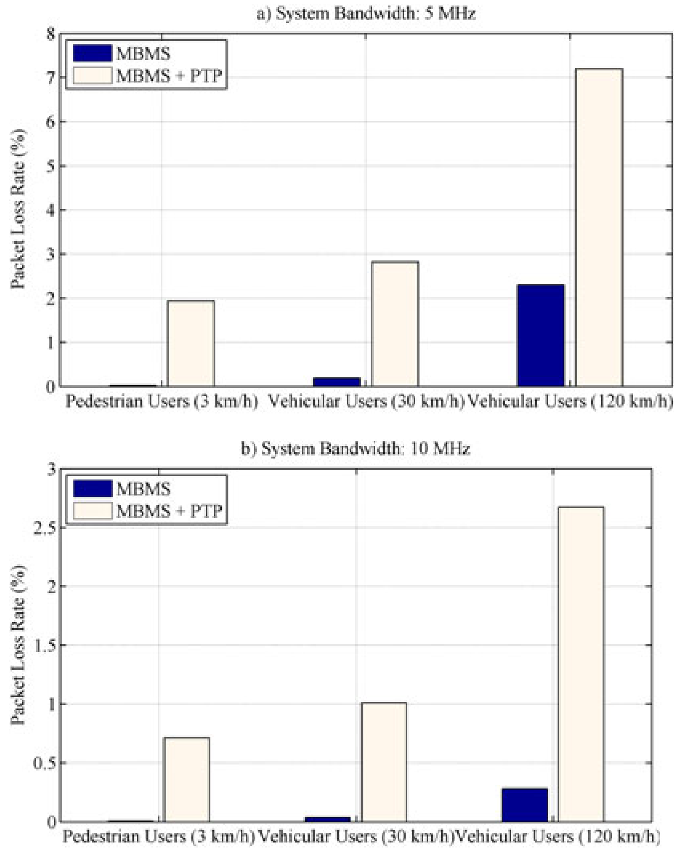

Figure 5. Packet loss rate versus different mobility models for system bandwidth (a) 5 MHz and (b) 10 MHz.

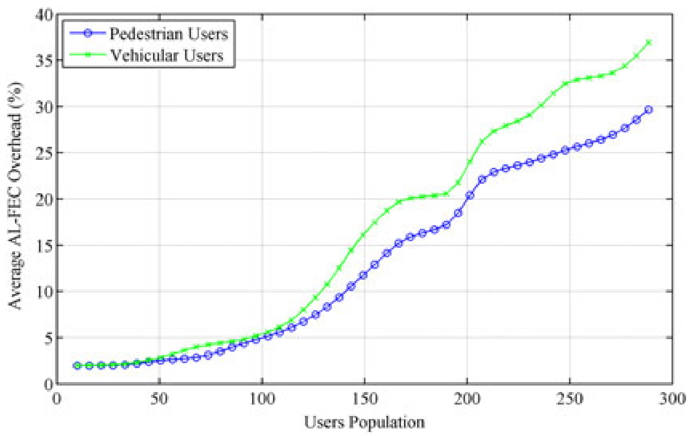

Figure 6. AL-FEC overhead versus multicast users population.

function of the cell range. For this evaluation we simulate the second scenario where, a PTM H.264 flow, encoded at 128 kb/s, is transmitted to mobile users moving at 3 and 30 km/h corresponding to pedestrian and vehicular mobility models, respectively, and a PTP best effort flow is transmitted in parallel to each multicast user. The system bandwidth is set to 5 MHz. As regards the AL-FEC configuration, the source block length is fixed at 400 symbols per FEC source block and the decoding failure probability target is set to 10^{-2}, based on the assumption described in the previous section.

Figure 6 depicts the average AL-FEC overhead required, a multicast sender should introduce to the video flow to achieve the failure probability target for the whole fraction of MBMS users, versus the multicast users population.

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As we can observe from Figure 6 the AL-FEC overhead increases as the number of MBMS users increases. This behavior is reasonable considering the transmission setup we simulate, with the simultaneous presence of the unicast bearers. Consequently, as the number of users increases the number of established unicast bearers increases too, resulting especially in the core network load growth. Furthermore, simulating the same cell deployment, the increase of the UEs number implies the increase of the users density in the specific MBMS service area. The increase of the multicast users density leads to even more users experiencing, sporadically or not, poor reception conditions because of the actual interference augmentation. Moreover, it is clear from the plotted curves of Figure 6 that vehicular users require larger amount of AL-FEC redundancy than the pedestrian users. This behavior is due to the higher packet losses that the vehicular users experience, because the increase in the simulated users velocity results in the increase in the wireless channel impairments. This is also illustrated in the PLR analysis provided in the previous subsection.

Another interesting remark is that when the population exceeds 100 users, the necessary AL-FEC overhead increases faster compared with the overhead's behavior below this threshold. In addition, above this threshold the differences between the two mobility models are enhanced.

Figure 7 illustrates the impact of the cell range growth on the required AL-FEC overhead, with the number of multicast users set to 200.

From the two plotted curves, we notice that the required average AL-FEC overhead increases as the cell range increases. For low values of cell range the necessary overhead is low for both pedestrian and vehicular users. When the cell range is less than 5000 m the difference between the average AL-FEC overhead of the two mobility models is around 5%. On the other hand, when the cell range exceeds the 5000 m limit, we notice that the necessary overhead of the vehicular mode is very close to that of the pedestrian mode. This happens because as the cell range increases, users moving at higher speed can better exploit the multiuser diversity gains that LTE provides. In general, the required average overhead increases as the cell range increases, leading to high values of AL-FEC overhead. This is reasonable in a multiuser environment, where different users experience variable packet loss rates because of different radio channel conditions and given that as the cell size increases, even more users experience poor reception conditions.

5.4. User satisfaction

In the present paragraph we try to investigate more in-depth the performance of Raptor codes considering the impact of the introduced AL-FEC overhead on the fraction of satisfied users. A user is considered satisfied based on the assumptions described in Section 5.1 for the FEC decoding failure probability target. The FEC encoding is applied on a H.264 video flow with source rate 128 kb/s and the source block length is fixed at 400 symbols per FEC source block. Our simulations include both of the previous described transmission scenarios, that is, the MBMS video streaming service with

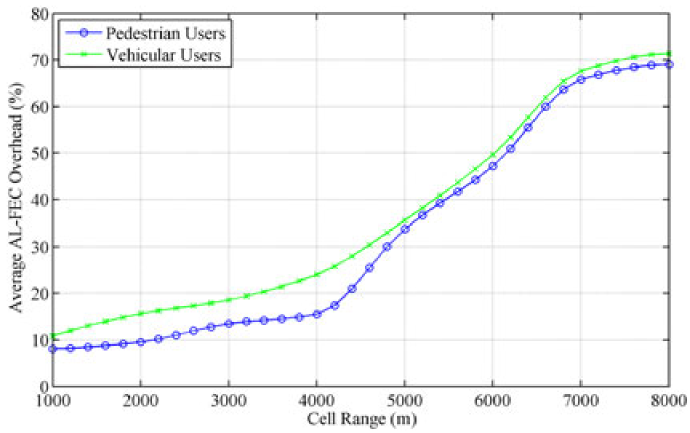

Figure 7. AL-FEC overhead versus cell range.

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and without the presence of parallel PTP best effort flows, simulating 200 pedestrian and vehicular users dropped in the MBMS service area and the cell range fixed at 2000 m. Figure 8 depicts the AL-FEC performance from the perspective of satisfied users percentage, as the Raptor overhead introduced in the transmitted stream increases. Figure 8(a) and (b) illustrate how the Raptor FEC performance varies, simulating 5 and 10 MHz system bandwidth, respectively.

By observing the two plots of Figure 8 in a comparative way, we can directly figure out the gains the increase of system bandwidth provides to the system performance. More precisely, simulating 200 vehicular users moving at 30 km/h for the second transmission scenario, where each UE receives simultaneously with the MBMS streaming flow a unicast flow and setting the system bandwidth at 5 MHz result in over 35% of AL-FEC overhead to satisfy the whole fraction of simulated users. Although for the same simulation setup, setting the system bandwidth at 10 MHz results in a dramatic reduction of the required protection, as of now the AL-FEC overhead is 15% for the same goal. This is reasonable because the amount of FEC protection that a multicast sender should introduce to the transmission depends on the packet losses of each UE. Therefore, according to the results presented in Section 5.2, the system bandwidth increment results in reducing the independent packet losses a UE deals with and this implies, also, the reduction of the necessary AL-FEC overhead.

Another very interesting issue from both plots is the existence of a point, beyond which a further increment in AL-FEC overhead is not efficient. This means that the additional gains in the decoding performance are minimized. Thus, by observing each plotted curve, we can determine a point of efficient selection of the Raptor overhead that a sender should introduce to the transmission, aiming

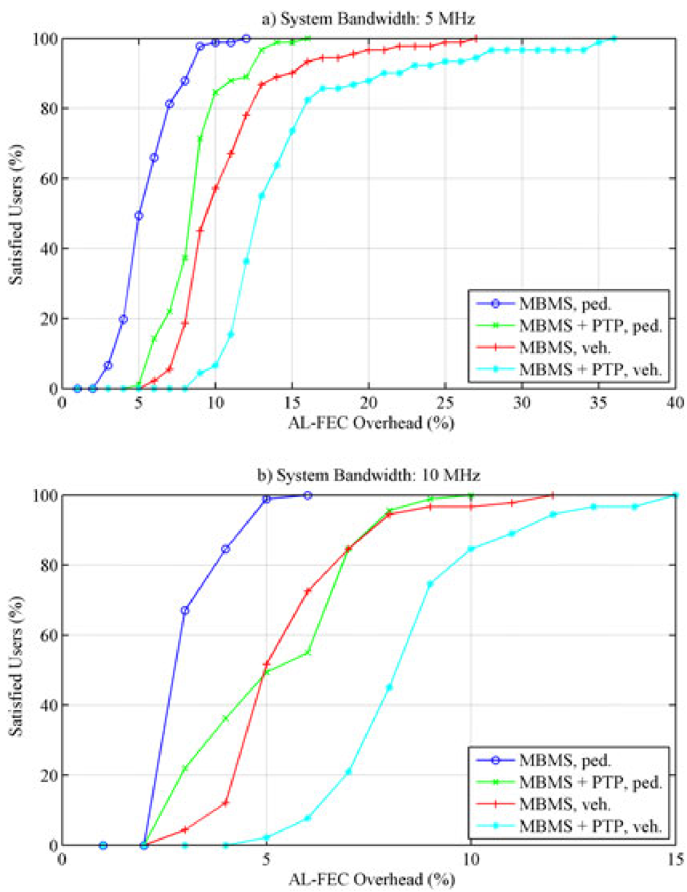

Figure 8. Percentage of satisfied users versus AL-FEC overhead for system bandwidth: (a) 5 MHz and (b) 10 MHz.

to satisfy a large proportion of users. Indicatively, when the multicast content is transmitted, considering the first scenario, to vehicular users and the system bandwidth is 5 MHz, assuming that the satisfactory performance is when 90% of terminals are satisfied, the required optimal overhead is 15%, because further increment to 25% succeeds about only 5% more satisfied users. On this basis, it is clear from the results that there is an optimal value of Raptor overhead in each curve, in terms of the trade-off between transmission redundancy and satisfied users.

5.5. Source block length

In this last part of experiments we evaluate the impact of the modeled FEC encoder parameters on the performance of the decoding of the protected stream. In more detail, we present results on how the percentage of satisfied users varies for different number of FEC symbols per source block concerning different fixed values of AL-FEC overhead. As in the previous subsection the user satisfaction is defined based on the assumptions described in Section 5.1. We simulate 200 pedestrian users dropped in the MBMS service area with cell range 2000 m and the system bandwidth fixed at 5 MHz. Figure 9(a) and (b) illustrate the simulation results conducted for a FEC protected PTM H.264 stream, encoded at 128 and 440 kb/s, respectively, considering the second, higher network load transmission scenario.

As we can observe from both plots, the increment of the number of protected symbols in a FEC source block is beneficial for the performance of the decoding procedure. This behavior directly results from the operation of the Raptor codes described previously. Especially for some certain values of source block length (SBL), the gains during the decoding procedure are remarkably high.

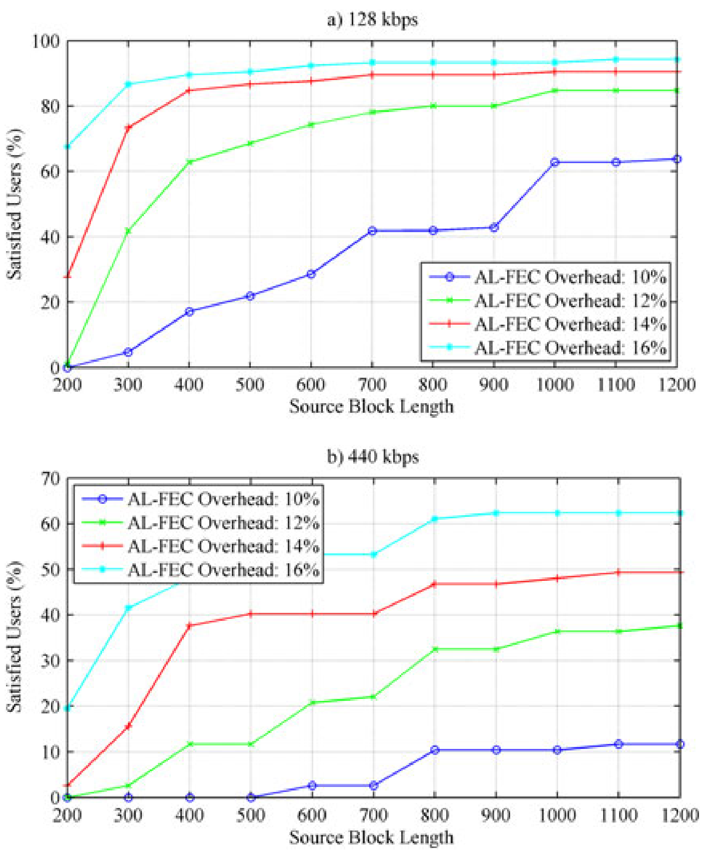

Figure 9. Percentage of satisfied users versus source block length for video source rate: (a) 128 kb/s and (b) 440 kb/s.

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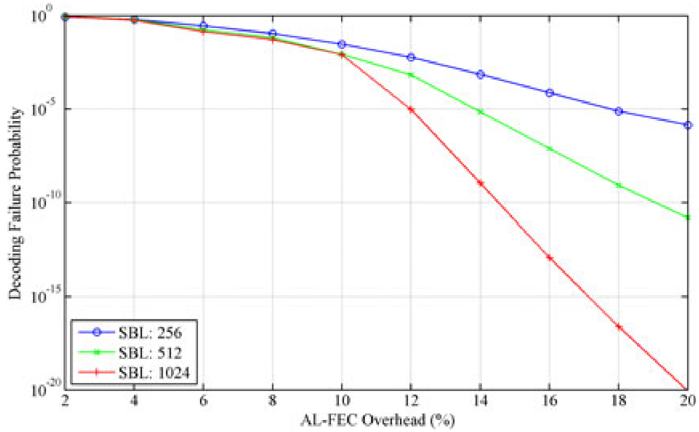

Figure 10. Raptor FEC decoding failure probability versus AL-FEC overhead.

It is obvious from the results that the increase of the AL-FEC overhead is not the only way to introduce further reliability in a Raptor FEC scheme. To make it clear, we can indicatively observe from Figure 9(a) that to achieve 80% of satisfied terminals, a multicast sender can introduce 16% of AL-FEC overhead setting the SBL at 300 symbols or can reduce the AL-FEC redundancy at 12% increasing the FEC SBL at 900.

Another notice is that in the case of 440 kb/s source video rate, the percentage of satisfied users is significantly lower than the case of 128 kb/s for the same setup of AL-FEC overhead and SBL. This is reasonable because the number of packets to be protected for the same transmission interval in the case of 440 kb/s is considerably higher than the case of 128 kb/s.

Moreover, to evaluate more thoroughly the effect of the number of FEC symbols protected together in a FEC source block, we relax the predefined assumption about the FEC decoding failure probability and in Figure 10 we illustrate how the decoding performance varies for different values of AL-FEC overhead, considering some typical values of SBL.

Observing the plotted curves of Figure 10 we can note the gains in the FEC decoding performance from the increment of the number of symbols protected together in a FEC source block. Especially as the AL-FEC overhead increases the Raptor FEC code performs consistently better for higher values of SBL. Characteristically, we notice that setting the SBL at 1024 and introducing 20% AL-FEC overhead to the protected stream results in remarkably low FEC decoding failure probability of about 10^{-20}. However, considering the same introduced overhead, but using SBL fixed at 256 results in about 10^{-6} failure probability. This behavior is implied directly from the Raptor's decoding performance properties, defined by Equation (1) in Section 3.

To conclude, the overhead and the SBL of the AL-FEC encoder should be carefully selected based on the amount of protection to apply and on different service constraints and parameters (e.g., delay) to achieve efficient use of AL-FEC.

6. CONCLUSIONS AND FUTURE WORK

In this work, we have evaluated the performance of AL-FEC based on the Raptor codes provided by Digital Fountain to provide reliability against packet losses in 3GPP LTE MBMS streaming services. We have examined how the Raptor overhead varies during different network conditions and which is the optimal overhead that a multicast sender should introduce to the transmission to achieve successful delivery of the multimedia content in a PTM manner. Our method for the evaluation of the benefits that FEC protection provides is based on a realistic MBMS simulation environment, where an AL-FEC protection scheme is modeled over video streaming services.

For our simulations we have used different transmission scenarios, which meet future user requirements of mobile networks. First, we have provided some experimental results for the network's performance considering the packet loss rate, the main parameter that affects the amount of

FEC protection a sender should introduce to a multicast transmission. Thereafter, we have extracted valuable conclusions on how the AL-FEC redundancy varies, based on different network deployments and parameters. Introducing the user satisfaction correlated with the decoding performance of each multicast user, we have provided simulation results that can enhance the application of AL-FEC considering the trade-off between the amount of the introduced redundancy and the fraction of satisfied users. Finally, except for the AL-FEC overhead, we have examined further FEC encoding parameters providing interesting conclusions for the impacts on the AL-FEC protection efficiency.

Before drawing the most important conclusions of this work, we should mention that the amount of the prefixed introduced FEC overhead is a matter of argument in the application of AL-FEC schemes. A small amount of redundant symbols can have almost no protection gain, while a large amount of FEC redundancy may substantially increase the transmission overhead without providing sufficient protection gains. To this direction, we have conducted a trade-off evaluation of the AL-FEC application considering the fraction of multicast users that can successfully reconstruct the FEC protected data against the introduced redundancy. These conclusions can provide a significant increase in the protection scheme efficiency. Moreover, by the in-depth analysis of the Raptor decoding process, we have drawn valuable conclusions about the encoding parameters of the MBMS AL-FEC framework. We have concluded that a careful selection of the FEC encoding parameters could be beneficial for the AL-FEC performance. Most notably, an increment in the length of the source block can enhance the protection performance without increasing the introduced redundancy and thus having further results on the spectral efficiency.

Some possible future steps that could follow this work may be the modeling of Turbo FEC on the physical layer of our simulation framework and the design of a cross-layer mechanism for FEC protection over multicast streaming delivery services. Through a cross layer analysis, we could further evaluate the AL-FEC benefits for streaming services concerning physical layer protection aspects, that is, Turbo FEC encoding rate, and advanced multimedia codecs (e.g., scalable video coding [24]). Another possible consideration is the design and the evaluation of an adaptive algorithm that computes the optimal FEC encoding process. This mechanism could be based on a feedback-reporting scheme about network conditions, as the one proposed in [25], and based on this reporting the AL-FEC encoding parameters could be adjusted. Finally, the recently appeared AL-FEC scheme, named RaptorQ [26], could further enhance the research field of reliable multicasting over mobile networks.

APPENDIX A: ACRONYMS

Acronym	Explanation
3GPP	3rd Generation Partnership Project
AL-FEC	Application layer FEC
BM-SC	Broadcast/multicast service center
eNB	evolved Node B
FEC	Forward error correction
LTE	Long Term Evolution
MBMS	Multimedia broadcast/multicast service
PLR	Packet loss rate
PTM	Point-to-multipoint
PTP	Point-to-point
QoS	Quality of service
RTP	Real-time transport protocol
SBL	Source block length
UDP	User datagram protocol
UE	User equipment
UMTS	Universal mobile telecommunications system

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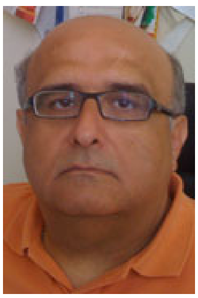

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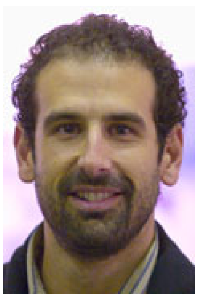

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