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RAPTOR CODE-AWARE LINK PROCESS FOR SPECTRALLY EFFICIENT UNICAST VIDEO STREAMING OVER MOBILE BROADBAND NETWORK.

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Abstract: - This paper proposes novel Raptor-aware link adaptation (LA) when application layer Forward Error Correction (AL-FEC) with Raptor codes is used for live, high quality, video unicast over mobile broadband networks. The use of Raptor code AL-FEC is taken into account for the adaptation of the modulation and coding scheme (MCS) used in the physical layer. A cross-layer optimization approach is used to select the Raptor code parameters and the MCS mode jointly, in order to maximize transmission efficiency. The proposed methodology takes into consideration the channel resources required to accommodate the Raptor overheads. Simulation results show that packet loss is eliminated and the amount of radio resource required is reduced significantly. **Automatic repeat request** (ARQ) **based unicast systems** require **up to 115.6 percent more channel resources, by** comparison **to the proposed Raptor- aware LA system without** retransmissions. **Furthermore, the Raptor-aware LA system can enhance the link budget** by **up to 4 dB, increasing coverage in LoS locations, and** can improve total good put by 46.7 percent compared to an ARQ-based system.

INTRODUCTION

MOBILE video traffic is rising significantly [1], mainly due to a significant rise in smart phone video applications. Thus supporting high quality video on mobile devices is very important. The efficiency of future wireless networks must be optimized to meet the convergence of video and data while strict quality of service (QoS) is guaranteed for each of the competing user streams. It is well-known that high quality video transmission over wireless networks is challenging because of the time-varying channel quality, the high data rates required and the stringent QoS demands of video. Mobile WiMAX [2] and 3GPP LTE [3] represent mobile broadband standards that offer high user data rates and QoS support for video applications.

Both technologies use similar Downlink (DL) PHY layers and have strong similarities in their MAC layers, while radio resource efficiency is pivotal in supporting QoS for multimedia services [4]. Thus this work is also applicable to LTE broadband networks. The use of Raptor code FEC at the application layer, applying cross-packet FEC, has been adopted for robust video broadcasting, by the 3GPP Multimedia Broadcast and Multicast Services (MBMS) standard [5] and DVB-H [6].

The error correcting capability of Raptor codes, even in severe channel conditions, has been well established. Raptor codes have been studied for wireless video broadcasting and multimedia download, for example over 3GPP MBMS networks in [7], [8], over WiMAX in [9], over DVB-H in [10]. Unicast video transmission is generally provided as a value-added service on top of video multicasting but it permits individualized error protection based on receiver feedback and channel quality indicators (CQIs) generated by the MAC/PHY layers.

In unicast transmission LA is performed and, typically, the ARQ mechanism is enabled to allow for retransmissions if packets are received in error at the MAC layer. The use of Raptor code AL-FEC for unicast video trans-mission has not been thoroughly investigated in the literature, however prior work has focused on unequal error protection for video and/or scalable video coding, e.g., [9]. Adaptive AL-FEC for unicast video transmission has been proposed in [11], [12], identifying the need to carefully select the FEC code overhead suitable for the level of packet loss experienced.

AL-FEC codes introduce additional over-heads that place high demands on valuable radio resources, in particular when high overhead codes are used. If the packet loss rate is overestimated, then wireless bandwidth will be wasted and if it is underestimated the received video quality will suffer due to errors and/or missing packets. In this work we propose a novel Raptor-aware LA method, where Raptor code AL-FEC is used as a cross-packet erasure code to protect unicast live H.264/AVC video streaming, without ARQ. The MCS mode is adapted jointly with the Raptor code rate used, according to the specific channel conditions and the channel feedback received.

In unicast transmission it is common for the PHY to receive feedback on the channel quality in order to adapt the MCS on a per user basis. We focus on minimizing the bandwidth required by Raptor code AL-FEC while maintaining quasi-error free reception, by selecting the Raptor code parameters jointly with the MCS mode, using a novel cross-layer design. It has been shown**, e**.g. [13], that cross-layer designs are necessary since they enable intelligent resource allocation to optimize spectrum efficiency, while providing high QoS.

Related Work and Our Contribution

The first point of differentiation with related work is that the selection of the MCS mode is usually not considered when using AL-FEC based on rateless codes. Typically more robust MCS modes are selected at the expense of through-put. However, MCS selection should take into account the use of AL-FEC to protect the video data stream and the additional robustness that this provides. Thus more efficient MCS modes could be used. For example, in [11] adaptive unicast video streaming with rateless codes is investigated with no consideration of the MCS used. Fez et al. [12] studies the use of adaptive LDPC AL-FEC for delivery of files in a carousel system over FLUTE [14] based on user feedback.

The analysis there does not account for the MCS selected and its impact on channel resources and file delivery does not impose the strict latency constraints of live video trans-mission. In [15] adaptive rateless coding is studied for unicast video streaming over mobile WiMAX, for 16QAM 1/2 only, without considering link adaptation. In [16], considering SVC video, the MCS mode is selected according to the channel SNR and the SVC video layer, while the RS-type AL-FEC is adjusted for each SVC video layer. In [9] the authors identify the need to predict the amount of redundant data according to the channel loss in order to reduce FEC data overheads for IPTV broadcasting, but the selection of MCS mode is not considered. In [8] the joint selection of the AL-FEC Raptor code rate and the code rate at the PHY layer FEC was investigated in order to minimize energy for downloads over FLUTE. However, this work also does not adjust the modulation scheme, since link adaptation for unicast transmission is beyond its scope. Failing to take into account the MCS mode and how this can be adjusted when adaptive AL-FEC codes are used, results in wasting valuable channel bandwidth.

A solution to this problem has not been reported in the literature. Here we select the MCS mode and the Raptor AL-FEC code rate jointly, so that the bandwidth required is minimized and transmission effi-ciency is maximized, while observing a given QoS at the application layer. Our work shows the benefits that Raptor-aware LA offers. When rateless codes are used for unicasting they can be based on two types of feedback, either feedback from the higher layers (transport or application layer) or feedback from the MAC/PHY layers. The former can provide a statistical average of Raptor decoding failure for a number of source blocks, which could be used to adjust the FEC code overhead [11], [12]. The time interval for the Raptor decoder feedback depends on the source block size and introduces latency through the round trip time, as shown in [11]. Nevertheless, such feedback is not able to follow the rapidly changing nature of a wireless channel, because the duration of a source block (containing a large number of symbols) commonly exceeds the channel coherence time.

The second type of feedback, generated from the PHY, is based on the channel state estimation used for LA at the MAC, such as the channel quality indicator. The CQI feedback frequency in WiMAX/LTE is every 1 to 3 OFDMA frames (5 ms each), according to [2], [17], depending on the rate of channel change. Our work here does not consider feedback from the Raptor decoder at the higher layers, as [11]. Unlike [11], where redundant symbols are sent until a source block is correctly acknowledged, our proposed system does not expect a higher layer feedback, thus no latency is introduced.

Since no acknowledgment is assumed in our work, our results are not directly comparable with [11]. Moreover, unlike this work, [11] does not consider wireless transmission, a wireless protocol and the bursty error nature of wire-less channels. Our work is based on the channel state information already available for the LA mechanism by the MAC/PHY, as in [15], but we propose an enhancement of the LA mechanism to take into account the use of Raptor code AL-FEC. The work in [15] is based on the channel estimation measurement to adjust the amount of Raptor redundant data. However, in [15] a byte-based Raptor FEC is used at the PHY layer as inter packet FEC channel coding, whereas our approach is applying cross-packet FEC at the application layer according to the standard [5]. When the source block duration is greater than the channel coherence time, the time diversity is exploited to the benefit of an era-sure code.

Thus the byte-based Raptor FEC scheme used in [15] can reduce the packet loss rate only to over 7 percent, for a 1 Mbps DL video transmission. Al Jobouri et al. [15] relies on the ARQ mechanism, as additional redundant data are piggybacked on a single ARQ retransmission, to attain a minimum of 1 percent packet loss introducing a small latency. In our work, however, we show that no ARQ is necessary if the Raptor AL- FEC redundancy is carefully selected jointly with the MCS mode. Moreover, in [15] the MCS adaptation by the LA mechanism is not taken into account. The assumed channel estimation feedback from the PHY does not cause the transmitter to pause since neither ARQ retransmission nor incremental redundancy are used. Instead, the Raptor encoded video is streamed with-out formal guaranty of error free delivery; however we use a theoretical LA approach to optimally select the MCS mode jointly with the Raptor AL-FEC code rate, as described in Section 4. This approach is shown to achieve quasi-error free reception. The LA algorithms in commercial products typically rely on channel feedback (e.g., CQI) along with vendor specific error statistics. **Further work is required to design** a practical LA implementation. Since our work uses the existing channel feedback at the PHY layer and the literature on live unicast video streaming over wire-less networks has primarily focused on ARQ or Hybrid-ARQ at the MAC, e.g., [15], [18], [19], we will compare the performance of our proposed Raptor-aware LA approach with the ARQ performance. This is in order to show the significant benefits offered by our approach in terms of channel resources required and PER attained at the receiver.

Hybrid schemes, combining ARQ with various types of inter-packet FEC have been proposed, e.g., [20]. The main problems commonly identified with the use of ARQ schemes for real-time video are latency, jitter and the residual packet errors [18], [21]. These are particularly accentuated in harsh channel conditions, when the channel coherence time is long [21]. A third point of differentiation with other related studies is that our work is based on the use of an accurate, time-correlated channel model, the 3GPP spatial channel model (SCM) [22], which models appropriately the packet loss process and the effects of Doppler spread.

In order to study the performance of Raptor code AL-FEC it is SGARDONI AND NIX: RAPTOR CODE-AWARE LINK ADAPTATION FOR SPECTRALLY EFFICIENT UNICAST VIDEO STREAMING OVER 403 important to take into account the well-known bursty nature of packet errors in a wireless channel [23]. The importance of the time-correlated nature of packet loss is also highlighted in [8], however related literature often ignores this fact. For example, in [11] the performance analysis of adaptive FEC for unicast video is based on a probabilistic packet loss rate. Similarly, in [15] the channel error model has a uniform distribution. In [7], [24] the performance of Raptor code AL-FEC is studied for MBMS UMTS assuming independent, random packet losses, while work in [16] is based on PER look-up tables that cannot model the instantaneous variations (deep fading) of the wireless channel and the time- correlated errors. In our work, the use of the Effective SINR Mapping (ESM) PHY layer abstraction technique [25] frees us from the need of PER look-up tables and allows the use of the time-varying fad-ing 3GPP SCM channel model.

Often in the related literature packet loss patterns from the PHY layer are applied, in order to assess the video performance of upper layers, as for example in [9], [16], [26]. However, this approach ignores the MAC fragmentation/ reassembly process and the relation between lost data packets at the PHY layer, at the MAC and then the effect at the application layer, as also discussed in [8], [27]. In this work we have developed a detailed cross-layer simulator of mobile WIMAX that takes into account the data encapsulation process across the application, IP, MAC and PHY layers, including the MAC fragmentation/reassembly process and MAC scheduling, in order to calculate accurately the PER at the application layer. Thus our work offers a detailed, holistic approach about how Raptor code AL-FEC is applied across all layers of mobile WiMAX, which has not been studied in related literature, including packet queuing and the scheduling mechanism in mobile WiMAX with respect to the Raptor repair symbols. A Raptor-aware scheduler is proposed.

This work addresses the QoS requirements of live, high bitrate, at 1.03 Mbps, H.264/AVC video transmission. The work is focused on a pedestrian scenario with a mobile station (MS) speed of 1 km/h, in a dense urban environment. At low MS speeds the channel coherence time is long and the channel may remain in deep fades for longer periods. This results in long packet error bursts and it has been shown, e.g., [21], [23], that in such channel conditions the ARQ retransmission mechanism is not very effective. Here only direct transmissions between the base station and a mobile terminal are considered.

In summary, this paper studies the performance of a novel Raptor-aware LA methodology when live, high quality H.264/AVC video is sent over a unicast mobile WiMAX link. Our novel cross-layer optimization approach maximizes the data good put while maintaining a near zero packet loss at the application layer.

The remainder of this paper is organized as follows. Section 2 outlines the principles of Raptor code AL-FEC and summaries the IEEE 802.16e protocol. Section 3 describes the simulator developed and the proposed cross-layer design. In Section 4 the cross-layer optimization methodology is explained, while in Section 5 the Raptor-aware LA performance is analyzed. Conclusions are presented in Section 6.

BACKGROUND

Raptor Codes:

The use of cross-packet FEC at the application layer, based on erasure codes to protect multimedia data from packet loss, is well established [28]. Raptor codes are a class of rate-less or fountain codes [29] first introduced in [30] that have been widely selected because of their unique properties. Their flexibility, in terms of the number of source symbols, K, and encoded symbols they generate, N, overcomes the limitations of other well-known erasure codes, such as Reed-Solomon (RS) codes, that can only support a limited number of input and encoded symbols (typically K <_ N _ 255) [28].

A rateless code can generate as many repair symbols as desired from the source symbols. Also Raptor codes have low decoding complexity, linear in K, enabling software-based implementation, whereas RS decoding is prohibitively complex, non-linear in K [8]. Finally, Raptor codes operate close to ideal erasure codes, offering overhead efficiency [28]. The Raptor decoder will recover the source data with high probability, if any of K(1+ð) symbols (source or repair) are successfully received, where d is a small real and ð > 0 [29]. The Raptor encoder partitions incoming data packets into several source blocks.

Each source block consists of a number of source symbols, K, each of length T bytes. For each source block a number of repair symbols, R, also of length T bytes are generated. Raptor codes, as specified in 3GPP MBMS [5], are systematic codes. The encoding and decoding algorithms are described in [5]. For the systematic Raptor codes, K encoded symbols are identical to the original K source symbols while R repair symbols are generated. In total N = K + R Raptor encoded symbols are transmitted for each source block. The Raptor code rate c is defined here as c = K/N.

IEEE 802.16e

Medium access control (MAC) layer—The 802.16e MAC layer [2] includes a number of adjustable features, such as adaptive MCS, ARQ, packet fragmentation and aggregation, variable size MAC Protocol Data Units (PDU), application specific service flows and PDU scheduling based on QoS. Packets from the higher layers arrive at the convergence sub layer (CS) of the MAC as MAC service data units (SDUs). Based on their QoS requirements, MAC SDUs are classified into service flows. There is the option for SDU fragmentation into MAC Protocol Data Units and this feature is assumed here, because small PDU sizes (less than 200 Bytes) were shown to improve the error rate in [31]. SDUs are also partitioned into ARQ blocks of fixed size.

The MAC PDU is the data unit exchanged between the BS and MS MAC layers. Once a PDU has been constructed, it is placed in the appropriate service flow queue and managed by the scheduler, which determines the PHY resource allocation (i.e., bandwidth and OFDMA symbol allocation) on a frame-by-frame basis. Each transmitted PDU is either received correctly or in error. The standard specifies a number of ARQ feedback mechanisms, such as cumulative ACK and selective ACK (S-ACK) [2]. Physical layer (PHY)—The mobile WiMAX standard has adopted Scalable-OFDMA (S-OFDMA)[2].

Table 1 shows 404 IEEE TRANSACTIONS ON MOBILE COMPUTING

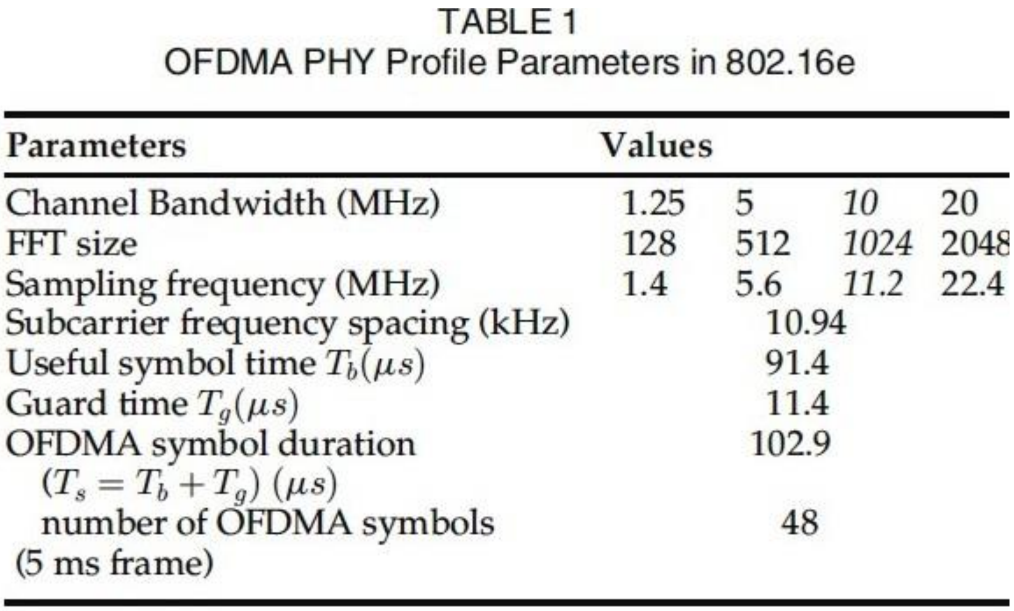
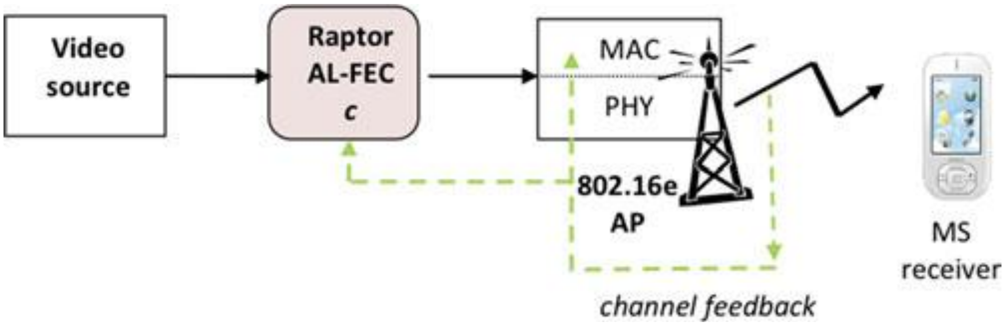


TABLE 1
OFDMA PHY Profile Parameters in 802.16e

Parameters	Values			
Channel Bandwidth (MHz)	1.25	5	*10*	20
FFT size	128	512	*1024*	2048
Sampling frequency (MHz)	1.4	5.6	*11.2*	22.4
Subcarrier frequency spacing (kHz)	10.94			
Useful symbol time $T_b (\mu s)$	91.4			
Guard time $T_g (\mu s)$	11.4			
OFDMA symbol duration ($T_s = T_b + T_g$) (μs)	102.9			
number of OFDMA symbols (5 ms frame)	48			

the relevant parameters for the S-OFDMA PHY. Simulations were performed assuming a 10MHz channel profile (highlighted in italics in Table 1). Our mobile WiMAX PHY layer simulator is described in [32]. The payload data is modulated using the full range of MCS modes as defined in [2] and shown in Table 2. Assuming a Partial Usage of Sub-Channels (PUSC) DL, as the only mandatory sub-channelization method in [2], the modulation symbols allocated to a sequence of slots in each DL OFDMA frame are assigned to a number of logical sub channels. According to [2] a slot is the minimum PHY resource allocation unit and for PUSC DL it is defined as one sub channel by two OFDMA symbols. For the 10 MHz profile, an OFDMA symbol consists of 30 sub channels for PUSC DL, each containing 24 data subcarriers [33]. Hence a slot contains 48 data subcarriers. Based on this, the slot payload capacity Psl for each MCS mode is calculated as shown in Table 2, where m represents the MCS modulation order and r the coding rate. The channel resources (in terms of slots) required for data transmission over a mobile WiMAX network are evaluated based on the slot payload capacity for each MCS mode. In our simulator a typical DL/UL ratio of 22:15 data symbols is assumed [33]. Our analysis methodology, however, can be used for any allowed channel bandwidth or DL/UL ratio.



2.3 GHz and the FFT size is 1,024. The MS speed is set at 1 km/h to simulate a typical pedestrian user. Each radio channel is made up of a large number of channel realizations, corresponding to the duration of the simulated trans-mission of 2,000 UDP packets at 1.03 Mbps. ESM PHY abstraction—To simplify the interface between the PHY link level and the MAC simulator, while modeling dynamic system behavior, a technique known as Effective SINR Mapping is used [25], [34].

This method compresses the SINR (per subcarrier) vector into a single Effective SINR (ESINR). The method is based on the computation of the mutual information (MI) per coded bit, which is derived from the received symbol-level MI, also known as the Received Bit mutual Information Rate (RBIR).

The first stage of the RBIR process is to find the symbol mutual information (SI), which is given per SINRns for each subcarrier ns, from a total of Ns subcarriers. The SIs within one coding block are then collected and normalized by the total number of coded bits to create the RBIR. Any error pattern in the block has equal influence on the decoded information bits [34], so the normalized mutual information per coded bit is a uniform metric of the decoding performance for that whole block. The technique is described in [25].

The effective SINR technique enables the instantaneous packet error rate to be computed for each channel realization, based on the instantaneous fading channel for a given packet length. This approach has been successfully used for example in [21], [35].A similar PHY abstraction technique was also used in [8].

CROSS-LAYER SYSTEM SIMULATION

This paper focuses on the simulation of a DL unicast trans-mission of live H.264/AVC video over a mobile WiMAX network. Raptor code AL-FEC is used with the proposed novel Raptor-aware LA. The live video is Raptor encoded at the server and then transmitted over a single hop link to a user's MS, as depicted in the system architecture of Fig. 1. The channel feedback is shown with the green dashed line. It is assumed that the existing channel estimation (i.e., CQI) obtained by the transmitter for LA, as in [15], is used at the MAC by the Raptor-aware LA to adjust the MCS mode. The MAC layer at the transmitter is aware that a particular service flow is Raptor encoded with a Raptor code rate c at present time.

The Raptor-aware LA algorithm will select the MCS mode in accordance with the Raptor code rate c and the channel SNR. The channel feedback can be also used by the Raptor encoder to adjust the Raptor code rate c jointly with the MCS mode. In our proposed system the Raptor code AL- FEC is not rateless (in the sense that an indefinite amount of repair symbols are generated until the source block is received correctly), but a specific Raptor code rate, c, is used at each link adaptation instance.

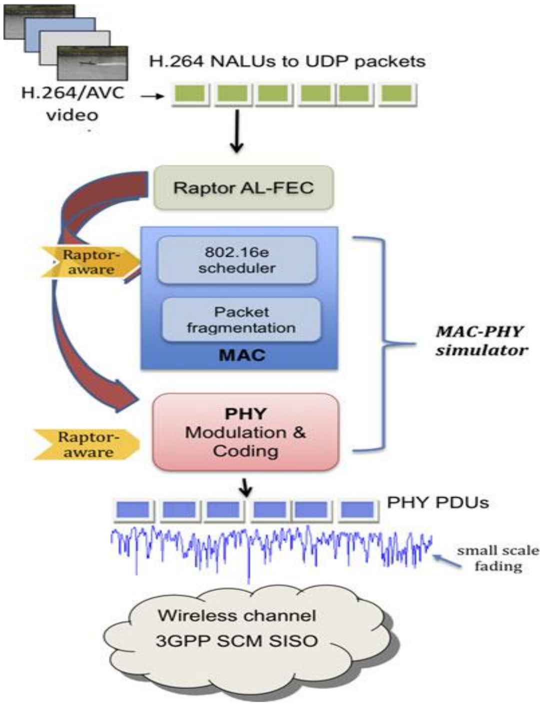
The SGARDONI AND NIX: RAPTOR CODE-AWARE LINK ADAPTATION FOR SPECTRALLY EFFICIENT UNICAST VIDEO STREAMING OVER 405 Fig. 2. Cross-layer system simulator. rateless property of Raptor codes is exploited so that the Raptor encoder obtaining channel information from the MAC, may change the code rate c, on- the-fly (e.g., if more redundancy is required), while generating repair symbols for the block currently encoded and for the following source blocks. This will not entail any latency because the system does not expect any ARQ feedback (at the MAC), as in [15], or Raptor decoder feedback from the higher layers, as in [11].

As this work deals with live video streaming and not file transfer, the Raptor code rate and MCS mode are chosen such as to reduce the probability of error at the receiver to an arbitrarily small value (as explained in Section 4.2) and cannot guarantee error free delivery. The performance assessment of a Raptor code enabled mobile WiMAX system for video transmission is challenging due to the many different system parameters at the PHY, MAC and application layers. Therefore, we have developed a comprehensive cross-layer WiMAX system simulator, as shown in Fig. 2. The simulator consists of different modules that model different components of the entire system: i) the wireless channel model, ii) the PHY layer, iii) the MAC layer and iv) the upper layer protocol stack, including the generation of H.264/AVC video packets and the Raptor encoding and decoding process.

The wireless 3GPP SCM channel model [22] is used to generate a time-correlated fading channel of several thousand realizations for a SISO system, assuming a given MS speed. The WiMAX MAC-PHY simulator developed in [21] is used to model the MAC SDU and PHY PDU loss process. It is based on the WiMAX PHY layer simulator described in [32]. The MAC and PHY layers are implemented according to the 802.16e standard [2]. A Raptor encoder/decoder conform-ing with the standard defined in [5] has been implemented on top of the WiMAX MAC-PHY simulator. The use of a comprehensive cross-layer system simulator differentiates this work from other related works, which fail to use a time correlted channel model, or ignore the impact of packet fragmentation at the MAC and the mapping of AL- FEC data formats to data structures in the MAC and PHY layers.

The performance of a mobile WiMAX system is studied when the proposed Raptor-aware LA is used. It is then com-pared with an ARQ-enabled mobile WiMAX system [2] using S-ACK, following the recommendations in [36]. A detailed analysis of the ARQ-enabled mobile WiMAX sys-tem was given in [21]. In order to study the Raptor code AL-FEC performance over a mobile WiMAX network, the transmission of a flow of UDP packets is simulated through the MAC and PHY layers of 802.16e. Simulation is per-formed for a single MS user, however the 3GPP SCM channel model used generates a time- correlated fading link of several thousand realizations for a generic user, which means that the statistics of the simulation model apply to any user.

Thus results can extend trivially to multiple links. Simulation is run for different mean channel SNR values and results are averaged over the small scale fading statistics for each mean SNR, as depicted in Fig. 2



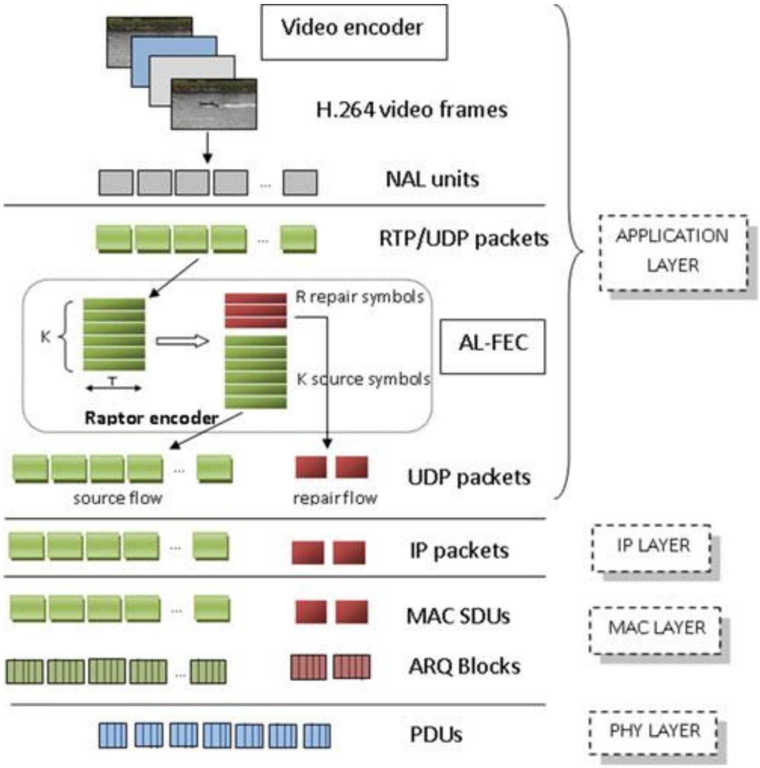
so our results are representative and extendable to multiple links. Multi-user interference is not studied in this work.

The simulation would include multiple links/users in order to study net-work congestion, but this is beyond the scope of this work. The unicast transmission of high bitrate live video certainly poses the problem of the bandwidth required and how many unicast users can be served, given the available net-work bandwidth. Thus, this study aims to minimize the bandwidth required per user (while maintaining a required level of QoS) so that more users may be served.

Application Layer

According to the H.264/AVC standard [37], video data are incorporated in network abstraction layer units (NALUs) with a maximum length of SP Bytes. It is assumed that each H.264 NALU is encapsulated in one RTP/UDP packet, as depicted in Fig. 3. UDP packets are of fixed size, SP Bytes, as also assumed in [7], [8], [38]. According to the standard [5], the Raptor encoder operates on a stream of incoming RTP/UDP packets at the application layer, to encode the UDP packets. In order to minimize jitter in the received video sequence due to the encoding process, as in [7], [28], [39] it is assumed that the video sequence is sent as a constant bit rate (CBR) flow. The Raptor encoder collects UDP packets to form blocks of source data. Each source block of size K _ T Bytes consists of K source symbols of length T Bytes.

In order to form a source block of size K _ T Bytes, it is assumed that n UDP packets are required. For each source block of K source symbols a number of repair symbols R, of length T Bytes are generated by the Raptor encoder. The systematic Raptor encoder specified in [5] is used here, with Raptor code rate c (c ¼ KKþR). The Raptor encoder generates l repair UDP packets per source block (containing the 406 IEEE TRANSACTIONS ON MOBILE COMPUTING, VOL. 14, NO. 2, FEBRUARY 2015 Fig. 3.



Cross-layer Raptor FEC simulation. Raptor repair symbols) [5], also of length SP Bytes. According to the 3GPP standard [5] the source and repair data form two separate UDP flows on the network. The process is depicted in Fig. 3. The receiver recovers the source symbols from the FEC encoded packets. 2. 802.16e MAC and PHY layers At the MAC layer each UDP packet is mapped to one MAC SDU and then transmit according to the 802.16e MAC layer protocol. Thus the MAC SDU error rate is equal to the UDP PER. SDUs are fragmented into PDUs. PDU packing is not enabled here. It is assumed that each MAC SDU is partitioned into ARQ Blocks, of length T also, as will be discussed next. At the MAC a Raptor-aware scheduler is assumed for the DL video transmission, which takes both flows (source and repair packets) into account, according to the selected Rap-tor code rate c. Resource allocation is dependent on the selected data modulation MCS mode, according to Table 2. The slot payload capacity increases with higher MCS modes, decreasing the number of slots required for the same bit rate. The full range of MCS modes supported by 802.16e (Table 2) has been simulated, using the PUSC DL sub-channelization method for a 10 MHz channel profile (Table 1).

802.16e MAC and PHY layers

According to [2], at the receiver the MAC waits to acquire all the ARQ blocks forming a MAC SDU before reassembling the SDU. SDUs are delivered as UDP packets to the Raptor decoder at the application layer. An SDU will not be delivered to the higher layers if any of its ARQ blocks are lost or discarded [2]. This policy however, aggravates the SDU packet error rate seen at the receiver in comparison to the ARQ block error rate (BLER). **From our work in** [21] it is clear that for the same mean channel SNR and MCS mode, the UDP PER is significantly higher than the BLER. If the whole SDU is discarded then much larger overheads are required for the AL- FEC. Since the AL-FEC is in place, sys-tem performance and FEC overhead efficiency would greatly benefit if SDUs with missing ARQ blocks were delivered to the Raptor decoder. The traditional IP receiver policy ignores a significant amount of correctly received data.

The detrimental effect of this policy on wireless transmission for 3GPP MBMS has been also studied in [24], [27] in conjunction with Raptor AL-FEC, where a permeable layer receiver (PLR) was pro-posed to allow the forwarding of partly received packets to the higher layers. For similar reasons [40] introduced an enhanced transport sub layer into the existing protocol stack of iMAX in order to reduce the high video frame error rate.

Cho et al. [41] also discusses cross-layer-design (CLD) protocols that relay corrupted packets to higher layers to offer significant improvement in wireless video throughput. The PLR assumptions [27] are extended here for a mobile WiMAX network, so that SDUs with missing ARQ blocks can be delivered to the higher layers. Hence the BLER at the MAC layer corresponds to the received Raptor symbol error rate at the Raptor decoder.

In order to study the Raptor code FEC performance, in our simulator it is assumed that the Raptor symbol boundaries are known at the MAC layer. During the partitioning of each SDU into its separate ARQ blocks, Raptor symbol boundaries are aligned with the ARQ blocks. The ARQ block size is chosen to be equal to the symbol size T. The alignment of blocks to symbols ensures that block errors can be directly mapped to Raptor symbol errors. Thus the calculated BLER is directly analogous to the Raptor symbol error rate.

If the boundaries between blocks and Raptor symbols were not aligned, the Raptor symbol error rate would increase by comparison to the BLER and more symbols would be considered lost at the Raptor decoder than symbols actually in error. This would deteriorate the Raptor decoding performance, calling for more repair symbols. For a Raptor-aware system design it is essential to use tight coupling between the AL-FEC data format and the MAC/PHY layer data structures, to improve the overhead efficiency. At the receiver, the MAC layer waits to receive all the PDUs forming a MAC SDU and then reassembles the SDU, with or without errors. Each SDU is delivered to the trans-port layer and then to the application layer as a UDP packet. The Raptor decoder collects the UDP packets corresponding to each encoded source block. When the Raptor decoder collects enough symbols, assume M, it will be able to correct the missing symbols and deliver the UDP packets error free to the video decoder [5] if M is slightly higher than K [29]. If, however, Raptor decoding fails, then the Raptor decoder will deliver to the video decoder only the source UDP packets that were received error free.

RAPTOR CODE CROSS-LAYER OPTIMIZATION

Trade-off AL-FEC Redundancy Versus MCS Throughput

The performance of IEEE 802.16e when Raptor code AL-FEC is applied, is studied in terms of the received UDP PER and spectral efficiency. Fig. 4 shows the UDP PER with and without Raptor AL-FEC versus mean channel SNR, for MCS mode 2 (16QAM 1/2) and Raptor code rates in the range 0.5-0.9. The source block length K is 1820. It can be seen that when MCS mode 2 is used, at SNR ¼ 12 dB only Raptor code rate c ¼ 0:5 deliver quasi error-free data (with PER_10_2). MCS mode 2 can deliver quasi-error free data with a higher Raptor code rate, c ¼ 0:7, only for SNR _ 14 dB. These results show that data can be delivered quasi-error free even at low mean channel SNR values, e.g., 12 dB, with a higher throughput MCS mode, such as 16QAM 1/2, when a low Raptor code rate is applied, such as c ¼ 0:5. The error correcting capability of Raptor codes depends on the symbol error rate encountered when a source block is decoded. Therefore if the symbol error rate was known, the amount of overhead and hence the associated code rate c could be determined accordingly. In order to understand how much redundancy is sufficient for Raptor codes to decode success-fully, we first focus on the performance over a range of mean channel SNR values when each of the MCS modes are used.

Optimization Problem:

The aim of our cross-layer optimization is to select jointly the MCS mode m and Raptor code rate c, such that the delivered good put is maximized, while the channel resources required are minimized at each mean channel SNR, under a given UDP PER constraint. In order to formulate the optimization problem we first need to define some terms. The average good put delivered per OFDMA frame for a flow of data, G flow ðs; c; m; K; T Þ, is defined as the total correct source bits received, SRX, at the application layer, divided by the number of OFDMA frames, FT ,required for the total number of UDP packets transmitted, including repair data. It is a function of the mean channel SNR s, the Raptor code rate c, the MCS mode m, the source block length K and the symbol length T.

Optimization Algorithm:

The heuristic cross-layer optimization algorithm proposed here identifies the pair of MCS, m and Raptor code rate, c, ðmi; ciÞ that maximizes good put- per-frame at each mean channel SNR value si, for a source block length K and a given target EUDP . The symbol length T remains constant. This methodology jointly controls the AL-FEC redundancy and the MCS mode according to the specific channel conditions and the system attains the highest good put for the least amount of PHY layer resource, offering the required level of QoS. The cross-layer optimization process is summarized by Algorithm 1.

Algorithm 1.

Cross-Layer Optimization for Selection of Optimum Raptor Code c and MCS Mode For each mean channel SNR and for each source block length K:

1) Select the suitable MCS modes mi that with Raptor AL-FEC delivers UDP PER _ EUDP. The candidate modes constitute a setMs.

2) 8 mode mi _ Ms locate the Raptor code rates c that attain PER _ EUDP and form a set of appropriate code rates, Ci ¼ fc1; c2; . . . ; clg. If no code rates achieve the target EUDP then mode i is excluded from the setMs and Ci ¼ ? f g.

3) 8 mode mi _ Ms form the candidate pairs of code rates for the candidate mode i as ðmi; c1Þ, ðmi; c2Þ; . . . ; ðmi; clÞ.

4) Form the set P of all suitable pairs for all modes i in Ms, and their appropriate code rates Ci. Within the set P of all candidate pairs, find the pair ps ¼ ðmk; cyÞ for which the goodput-per-frame is maximized. This is the recommended pair for the specific mean channel SNR and aptor parameter K.

RAPTOR-AWARE LA PERFORMANCE ANALYSIS

The performance of the Raptor-aware LA is studied in terms of PER, channel resources required and total system good-put. The optimized Raptor unicast system performs Raptor-aware LA using the optimum pairs ðm; cÞ shown in Table 4, selected by the cross-layer optimization algorithm. Table 5 reports the performance results for K ¼ 1;820 , showing the PER attained and the average percentage of slots required per DL-subframe, for mean channel SNR values in the range of 8 to 22 dB. It is observed that zero PER is attained at all SNR values of interest. It should be noted that the minimum observable PER in these simulation results is limited to 5 _ 10_4; given the number of simulated UDP packets (2,000). The results in Table 5 also show that the DL channel resources required decrease for higher throughput MCS modes and higher code rates, as expected. The optimized Raptor unicast system is compared with an ARQ-enabled mobile WiMAX system [2], with block lifetimes of 65 and 90ms. Based on the WiMAX Forum recommendations [17], [36], a maximum of four ARQ retransmissions are allowed for a block lifetime of 90 ms, and up to three retransmissions for a block lifetime of 65 ms. The ARQ-enabled mobile WiMAX system was analyzed in [21] and the ARQ performance results here are taken from that work.

For a given ARQ block lifetime at each mean channel SNR value, the MCS mode delivering the highest good-put with UDP packet error rate PER _ EUDP is selected, based on the good put-per-frame metric [21]. The constraint PERUDP _ EUDP is applied for a target value EUDP ¼ 10_2 and if that is not achieved it is then assumed that the ← The optimized Raptor system with Raptor-aware LA, uses higher throughput MCS modes at low channel SNR values, whereas for both ARQ block lifetimes only MCS mode 0 can be used, for SNR values up to 14 dB, in order to achieve PER _ 10_2. ← The optimized Raptor system offers a quasi-error free video service for mean channel SNR values as low as 8 dB. By comparison, the ARQ-enabled sys-tem cannot deliver PER _ 10_2 below 12 dB, when the ARQ block lifetime is 65 ms, and it is assumed that the video service would not be available. For a block lifetime of 90 ms the service would not be available below 10 dB. Thus the optimized Raptor system offers an extension of service range. ← The optimized Raptor system requires less DL channel resources than the ARQ-enabled system, for most of the channel SNR range studied. The highest reduction occurs at 14dB, where the ARQ-enabled mobile WiMAX system (for both block lifetimes) uses MCS mode 0 and requires 33.4 per- cent of slots per DL sub frame. The optimized Rap-tor system at the same SNR value requires only 9. Percent of the available DL resources, with the optimum pair [mode ¼ 2, c ¼ 0.7]. In this case the ARQ-enabled mobile WiMAX system requires 8. Percent more channel resources than the optimized Raptor system. ← the optimized Raptor system offers zero PER, whereas the ARQ-enabled system has a residual PER _ 0:01 at all SNR values (which may affect the video quality for some decoders). The ARQ block lifetime of 65 ms has a slightly higher residual PER than when the block lifetime is 90 ms.

CONCLUSIONS:

Our results have shown the benefits of a joint selection of MCS mode with the Raptor code rate, through Raptor-aware Link Adaptation and a cross- layer optimization approach. Results show that this approach increases the transmission efficiency for unicast streaming of high quality live video, while the video is delivered error-free. The ARQ-enabled WiMAX system (with a block lifetime of 65 ms) requires up to 115.6 percent more channel resources at an SNR value of 18 dB, than the optimized Raptor-aware LA system, when the maximum residual UDP PER is set 10_3. The proposed Raptor- aware LA also offers an increase in the total good put by 46.7 percent, in the SNR range 14-16 dB, and an extension of the service range by 4 dB, compared to an ARQ-enabled WiMAX system, with a block lifetime of 90 ms.

The trade-off between MCS mode throughput and Raptor code overhead was investigated for a range of mean channel SNR values, Raptor code rates and source block lengths K, for different UDP PER targets. Results showed that the larger source block length, K ¼ 1;820, is more efficient than K ¼ 1;040. These encouraging results open a discussion for practical issues regarding possible implementation in mobile broad-band systems. This work does not attempt to offer a full practical solution to the problem, as the parameter set can be extended (e.g., packet sizes, PER target values) and practical, system-specific issues should be considered. Further work is required to design a practical implementation of a Raptor-aware LA algorithm. **The methodology discussed in this paper is applicable** to other mobile broadband networks apart from mobile WiMAX.

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