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Cross-layer design of adaptive modulation and coding for multicast system with random network coding

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Abstract

This paper deals with a cross-layer design that combines link adaptation in the physical layer with random network coding for layered video multicasting in a cellular system. The objective is to design the optimum signal-to-noise ratio (SNR) threshold for adaptive modulation and coding (AMC) that can satisfy the target frame loss rate (FLS) under a delay constraint associated with real-time multicasting services. A common uplink feedback channel shared by all users is introduced to reduce the redundant transmission of the random network-coded packets, so that no unnecessarily redundant transmission can be made when the multicast packet is successful for all receivers, avoiding the overhead of the uplink wireless resource associated with each user for individual feedback. Based on our analytical results on spectral efficiency for the cellular system, we show that the aggressive AMC design approach with the common feedback channel in the multicast system outperforms all other approaches.

1 Introduction

Due to the rapid development of the electronics industry, low-cost and small-size computers have become a trend. This has enabled handheld devices to have stronger computation ability, and more and more applications can be implemented. As a result, many downloading and streaming services over mobile devices, such as live streaming, have become more popular. Multicasting or broadcasting is a method of delivering data to a group of users by a single transmission. The use of multicast is of particular interest for high data rate multimedia transmission because of its ability to save network resources.

In a wireless environment, data is usually lost during transmission due to packet loss or packet delay. Random network coding (RNC) has been considered as a useful means of improving the reliability as a forward error correction (FEC) scheme in the application layer for the multicast/broadcast transmission systems. As the redundant packets will be transmitted only until the multicast packet is successful for all receivers, each receiver can recover

the source message immediately after a sufficient number of the linearly independent random network-coded packets have been received for a set of packets. Therefore, the advantage of RNC in the multicast/broadcast network is that no unnecessarily redundant transmission can be made as long as a common uplink feedback channel is available to indicate if all users have successfully received the frame subject to RNC.

In previous studies, it has been shown that a signal-to-noise ratio (SNR) threshold for adaptive modulation and coding (AMC) can be further optimized to improve its bandwidth efficiency by taking the retransmission opportunities into account, e.g., truncated automatic repeat request (ARQ) [1,2]. A similar design principle can be applicable to multicast/broadcast networks, in which the maximum allowable number of redundant packets by random network coding can be considered in the design of a more aggressive AMC mode. In a multicast/broadcast network, a most robust AMC mode must be employed to cover all users in the different channel conditions, which reduces the bandwidth efficiency of the users under good channel conditions. The inefficiency associated with link adaptation can be handled by scalable video coding (SVC) for the multicast/broadcast service. SVC encodes a high-quality video stream that contains one or more subset

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bit streams, each formed by dropping packets from the original video to reduce the bandwidth [3]. SVC can be useful for adapting the video quality to varying channel conditions (data rate) of the individual user in the mobile system. An SVC stream has one base layer and one or more enhancement layers. As the base layer provides a minimum quality, frame rate, and resolution of the video, it must be protected by the most robust AMC mode so that all multicast/broadcast users can decode it. Since the enhancement layers represent the same video at gradually increasing quality, frame rate, or resolution, the quality of service coverage is scalable with the channel condition, depending on up to which enhancement layers can be correctly processed, while enhancing the overall system efficiency.

In this paper, we consider a cross-layer design approach that combines AMC in the physical layer with random network coding in the application layer for scalable video-coded multicast transmission. Our work deals with the effect of only the application layer FEC on the AMC design rather than the combined effects of all possible retransmission schemes in the different layers (e.g., hybrid ARQ in the physical layer). Our design objective is to optimize the SNR threshold of the given AMC mode in the physical layer, which determines the specific coverage area for the individual SVC layer in the multicast/broadcast network, while satisfying the given target frame loss rate (FLR) under the delay constraint of the real-time streaming services. In particular, when the maximum number of redundant packets is specified by the delay constraint, the quality of service (QoS) requirement in the application layer is governed by FLR. A target packet error rate (PER) of each RNC-encoded packet in the physical layer must be determined to meet the FLR constraint in the application layer. Subsequently, the SNR threshold of AMC mode is optimized to satisfy the target PER.

Furthermore, a more aggressive AMC design can be employed to maximize the bandwidth efficiency when the redundant packet transmissions are permitted within the given delay constraint. We design an AMC mode that maximizes the system bandwidth efficiency under the cross-layer performance requirements by taking the effect of RNC into account for the multicast and broadcast network. Accordingly, we provide an analysis of the average spectral efficiency for the proposed design schemes under the random user distribution with inhomogeneous channel conditions.

The organization of the paper is as follows: Section 2 presents the related works for retransmission and scalable video coding schemes for a multicast system, including a brief introduction to random network coding, which will be the fundamental parts of our baseline system model. In Section 3, we consider a downlink broadcast channel using an AMC scheme to serve a layered video stream

for mobile broadcast service and present a detailed model of our layered video transmission system with a common feedback channel associated with random network coding. In Section 4, the proposed design of AMC mode is described, and its average spectral efficiency is analyzed. The numerical results for our analysis are given in Section 5, which compares the performance of the AMC design schemes with and without the common feedback channel. Finally, concluding remarks are given in Section 6.

2 Related works

2.1 Retransmission and feedback schemes for a multicast system

As data rates are ever increasing in emerging broadband mobile systems, such as 3GPP LTE networks, retransmission schemes to improve reliability have been considered feasible even in broadcast/multicast transmissions for streaming services. A simple retransmission mechanism is to retransmit every corrupted or lost packet that each mobile terminal requests for retransmission. Retransmission protocols have been proposed for broadcast and multicast by exploiting an uplink feedback channel to indicate a lost packet [3,4]. Different types of retransmission schemes have been analyzed for error control in multicast protocols geared toward multimedia applications [5]. However, individual retransmission of the requested packets would consume more retransmission resources and result in lower retransmission efficiency. In other words, allocating an individual feedback channel for each receiver incurs huge overhead as a large number of receivers are active at the same time. These in turn lead to two design issues:

- Developing a reliability enhancement technology in a multicast retransmission protocol to reduce downlink inefficiency associated with redundant transmissions of the lost packets
- Designing an efficient feedback channel structure for multicast retransmission to reduce uplink overhead

For the first issue, network coding has been introduced in multicast retransmission to improve retransmission robustness and efficiency in a wireless network [6]. In the network coding-based retransmission, each receiver sends a NACK message through the feedback channel if it does not correctly receive a packet. When it receives a NACK, however, the sender does not immediately retransmit the lost packet. Instead, the sender maintains a list of the lost packets and their corresponding receivers. During the retransmission phase, the sender forms a new packet by XOR operation over a set of the lost packets. It has been revealed through intensive work that significant bandwidth efficiency improvements can be achieved by retransmission with XOR-based network coding [6].

In this particular scheme, however, the feedback channel overhead problem still remains, as the feedback information is required to keep track of the individual lost packet.

To solve the feedback overhead problem, RNC has been proposed for broadcast/multicast transmission [7]. In contrast to XOR-based network coding, RNC linearly encodes packets in a symbol-wise manner using random coefficients and operations in a selected finite field $GF(q)$, where $q = p_{\text{prime}}^m$ with a positive integer m and a prime number $q = p_{\text{prime}}$. RNC can generate a potentially limitless stream of encoding symbols, which is known as a rateless property. For example, using RNC over a source message, i.e., a set of packets $\{\mathbf{x}_m\}_{m=1}^M$, an encoded packet \mathbf{x}_{comb} is obtained as $\mathbf{x}_{\text{comb}} = \sum_{m=1}^M \alpha_m \mathbf{x}_m$ where $\{\alpha_m\}_{m=1}^M$ is a randomly selected element of $GF(q)$. By selecting a different set of $\{\alpha_m\}_{m=1}^M$, a new encoded packet is generated in a rateless fashion. At the receiver, immediately after a sufficient number of the linearly independent coded packets have been received for a set of packets, the receiver can recover the source message. The source message of M packets can be recovered if and only if the number of error-free encoded packets is larger than or equal to M . If the number of received packets is not enough to decode the set of packets, the receiver sends a NACK message back to the sender over a feedback channel until the set of packets is successfully decoded. The advantage of RNC is that the sender does not have to know which packet is lost at which receiver. In other words, detailed feedback may not need to be implemented, unlike the XOR-based network coding. This leads to the design of a common feedback channel, which can be shared among all receivers in the system. Due to its shared nature, the feedback overhead is independent of the number of receivers. In RNC-based multicast transmission, the sender keeps transmitting coded packets until no feedback signal is detected over the common feedback channel. Upon receiving no feedback from all receivers, the sender proceeds to process the next set of packets.

There have been various proposals for employing common feedback channels for broadcast/multicast channels [8-13]. The common feedback channel has been studied for the XOR-based network coding to estimate the number of users in error for a particular packet via a voice-vote mechanism [8]. For the redundant packet transmission of the Reed-Solomon codes, the common feedback channel also has been studied to reduce the uplink overhead [9]. The common feedback channel was considered for the retransmission of resource allocation information, such as with a MAP message in a WiMAX system [10]. The common feedback channel was used to obtain CQI information from the users

[11]. A concept of the common feedback channel and its structure have also been proposed for IEEE 802.16m systems [12,13].

2.2 Scalable transmission for a multicast system

Since the average SNR of each user varies according to path loss and fading (e.g., shadowing and/or small-scale fading) in a cellular system, the data rate of the multicast stream is mainly limited by the least reliable user. For unicast services, meanwhile, the sender can adaptively select a modulation and coding set (MCS) based on the channel quality and device capability at an individual receiver. Such an adaptive modulation and coding (AMC) plays a key role in improving the bandwidth efficiency, especially as the channel quality varies among the multiple users in the cellular systems. However, an issue with AMC in wireless multicast services is that when multiple receivers experience heterogeneous channel conditions, a transmitter must employ the most robust MCS that can be processed successfully by all wireless receivers in the multicast group, so as to accommodate all receivers. As a result, the multicast data rate and video quality are limited by the users with the worst channel conditions.

One approach of solving the channel heterogeneity among the users is to make use of hierarchy in data [14]. SVC divides a video stream into multiple sub-streams, called layers [15]. Layered forward error correction (FEC) was proposed as an error control mechanism in a layered multicast framework, in which receivers can obtain the different levels of protection commensurate with their respective channel conditions by organizing FEC into multiple layers [16]. Alternatively, to cope with heterogeneity, the non-uniform phase-shift keying (PSK) has been used [17]. The method uses a non-uniform constellation design in which the most important layer data is encoded to constellation points that are farther apart from each other than the points to which the less important layer data are encoded.

SVC combined with an AMC scheme provides an excellent solution to wireless multicast video streaming [18-23]. An SVC stream has one base layer and one or more enhancement layers. The base layer provides the minimum quality, frame rate, and resolution of the video, while the enhancement layers represent the same video with gradually increasing quality, frame rate, or resolution. To address the issue of the low data rate due to the users with the worst channel quality, we can apply the different modulation and coding sets to the different layers of the scalable video sequence, such that the users in good channel conditions receive more enhancement layers to obtain better video quality, while the users in bad channel conditions receive fewer enhancement layers on the top of the basic video quality.

3 System model

We consider a downlink broadcast channel that adopts the AMC scheme to serve a layered video stream for mobile broadcast service, as in a mobile WiMAX network. Furthermore, a common uplink feedback channel is considered to reduce the signaling overhead for requesting the redundant transmission, as discussed in Section 2.1. In this section, we present a detailed model for our layered video transmission system with a common feedback channel.

3.1 Layered transmission with SVC

In our proposed system, we can use any of the popular layered video coding schemes, which are implemented to encode a frame into multiple layers for scalable transmission, as discussed in Section 2.2. Layer 0 is intended to be the base layer, which contains the most important information. High-order layers belong to the enhancement layer, which provides incremental improvements to refine the video quality progressively. In each layer, a video frame is fragmented into M data packets, which are encoded into Q packets, which can be accomplished using a random network encoder. Since only finite delays and buffer sizes can be afforded in practice, the maximum number of redundant transmissions has to be bounded. This number can be specified by considering the maximum allowable delay of the video stream over the round trip delay required for each redundant transmission. In other words, a real-time requirement of video service is translated into the maximum number of redundant transmissions allowed per frame, L_{\max} . Assuming that the maximum number of redundant transmissions allowed per frame is limited to L_{\max} , then the random network encoder generates $Q = M + L_{\max}$ encoded packets per frame. Since only finite redundant transmissions are allowed, error-free delivery cannot be guaranteed. If a frame is not received correctly after transmitting Q -encoded packets, it will be dropped, and a frame loss will be declared. To maintain an acceptable video stream quality, we impose the performance constraint of P_{loss} , which is the maximum allowable FLR after L_{\max} redundant transmissions. P_{loss} and L_{\max} are the application layer QoS requirements that are closely associated with the AMC design, and mainly govern the overall bandwidth efficiency.

3.2 Common feedback channel

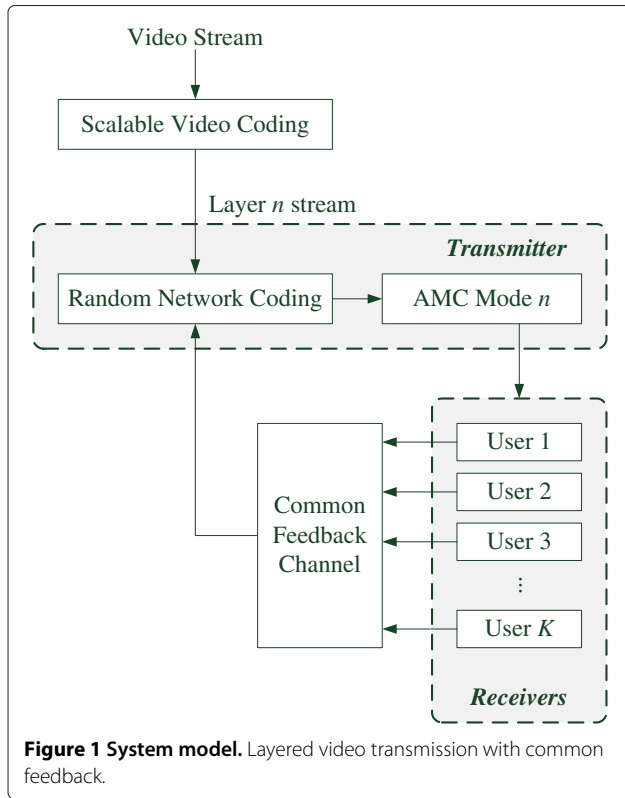
To reduce unnecessary redundant packet transmission, a feedback channel is introduced to the uplink channel. If a user does not receive a frame successfully, a request signal will be sent to the base station for transmitting the redundant packet. However, this would incur enormous signaling overhead in the uplink when a dedicated feedback channel resource is allocated to an

individual user. Instead, a common feedback channel can be employed for NACK feedback information from all users, as discussed in Section 2.1. In the common feedback channel, all users send an identical NACK signal through the common uplink channel resource without carrying the users' identifications. In the implementation, the base station may reserve a radio resource unit as a common feedback channel. The base station will keep transmitting the redundant packets until no signal is detected over the common feedback channel. Immediately after transmitting L_{\max} redundant packets, the base station is allowed to transmit the subsequent video frame.

3.3 Adaptive modulation and coding

Each encoded packet is further protected by FEC coding, such as turbo codes, and modulated using M -ary quadrature amplitude modulation (QAM). The packets of the layered streams are transmitted in their own AMC mode. The base layer that contains the most important information is transmitted by MCS with the lowest data rate for reliable delivery, while the higher layers are transmitted by MCS with higher rates for enhancing the bandwidth efficiency. In the current discussion, we assume N AMC modes are available, one for each layer. A specific AMC mode assignment to individual layer depends on the rate scheduling and service coverage design. A MCS for each user is subject to its channel condition, which is known by the channel quality indication (CQI). In order to maximize the bandwidth efficiency, a common MCS must be configured for serving the user with the worst channel, which subsequently determines the AMC mode for its base layer. In a typical multicast service, e.g., the enhanced multicast and broadcast service (E-MBS) in mobile WiMAX, there must be an effective means of planning the service coverage for the scalable video-coded multicast system that eventually determines the best AMC mode of each SVC layer for each user (for example, see [23]). The specific coverage design issue is beyond this paper. In this paper, we adopt a rather simple model, in which each stream of the different SVC layers is unequally protected by the different MCS, e.g., QPSK for a base layer and M -ary QAM for the higher layers (the larger M for the higher layer). Without loss of generality, we simply assume that video layer n is transmitted in AMC mode n with the spectral efficiency of R_n (bits per second per hertz). Figure 1 shows the end-to-end transmission system model for layered video transmission that employs a common feedback channel associated with random network coding for each SVC layer.

Let $\gamma_{\text{th}}^{(n)}$ and γ_k denote the SNR threshold of AMC mode n and the received SNR of user k , respectively. Assuming that $\gamma_{\text{th}}^{(1)} < \gamma_{\text{th}}^{(2)} < \dots < \gamma_{\text{th}}^{(N)}$ for N AMC modes available, if $\gamma_k \geq \gamma_{\text{th}}^{(n)}$, user k attempts to decode the



video streams up to layer n . In the following section, we will design an optimum set of SNR thresholds for AMC, $\{\gamma_{th}^{(n)}\}_{n=1}^N$, to meet the given QoS requirements for the application layer. In order to simplify the AMC design, we consider the following approximate PER expression for AMC mode n :

$$PER_n(\gamma) \approx \begin{cases} 1, & \text{for } 0 < \gamma < \hat{\gamma}_n \\ a_n \exp(-g_n \gamma), & \text{for } \gamma \geq \hat{\gamma}_n \end{cases} \quad (1)$$

where γ is the instantaneous SNR, along with the fitting parameters a_n , g_n , and $\hat{\gamma}_n$, which can be determined by fitting into the PERs obtained by simulation for M -ary QAM and convolutional code over a Rayleigh fading channel. Fitting parameters are illustrated for the different MCS in Table 1, which is obtained for the fixed packet length of 1,024 bits. Using (1), we can represent the FLR for each

Table 1 Parameters of approximate PER expressions

	a_n	g_n	$\hat{\gamma}_n$ (dB)	Modulation	Coding rate
Mode 1	36.86	31.724	0.651	QPSK	1/2
Mode 2	32.25	7.6037	6.275	16QAM	1/2
Mode 3	24.72	2.4391	10.05	16QAM	1/2
Mode 4	20.62	0.9556	13.34	16QAM	2/3
Mode 5	16.19	0.3571	16.56	16QAM	5/6

mode n after transmitting $L = 0, 1, \dots, L_{\max}$ redundant packets as follows:

$$FLR_n(\gamma, L) = 1 - \sum_{\ell=0}^L \binom{M+\ell-1}{\ell} \{PER_n(\gamma)\}^\ell \{1 - PER_n(\gamma)\}^M. \quad (2)$$

There are two types of AMC design approaches to determine the optimal set of SNR thresholds: aggressive AMC and conservative AMC threshold designs [1,2]. The idea of aggressive AMC design is to employ a higher level of modulation and coding by allowing for a looser constraint in FLR at earlier transmission opportunities. As multiple redundant transmissions are permitted within the given delay constraint, a more robust MCS can be employed for the later transmission when the earlier aggressive transmission fails, possibly taking advantage of the diversity of the diversity gain accrued over additional transmission opportunities. The aggressive AMC design will determine the optimal SNR thresholds so that the QoS requirement may be satisfied over the given overall delay constraint. Meanwhile, the conservative AMC design is intended to meet the QoS requirement strictly in each transmission without taking advantage of the additional transmission opportunities within the delay constraint. It has been demonstrated previously that a significant gain in bandwidth efficiency can be achieved by the aggressive AMC design over the conventional AMC design [1,2]. As all previous works on the aggressive AMC design are dealing with a unicast system, either combined with or without a FEC scheme, our current problem has focused on the multicast system with the application layer FEC scheme.

Meanwhile, a feedback channel (as modeled in Figure 1) is essential to improving the bandwidth efficiency of RNC, especially when a real-time delay constraint is imposed. In case that no feedback channel is available, the additional retransmissions will be always limited to the maximum number of allowable retransmissions, hurting the bandwidth efficiency. In the application layer FEC scheme with random network coding, however, indication of successful reception by all receivers through the feedback channel can immediately eliminate unnecessary retransmissions, improving the bandwidth efficiency. Note that the efficiency by the different AMC design approaches (aggressive or conservative ones) depends on whether a feedback channel exists or not. One of our main contributions in this paper is to analyze the effect of common feedback channel on our cross-layer optimization in the multicast system.

3.4 SNR distribution

We assume that K users are uniformly distributed over a single cell, e.g., around a base station (BS) in a circular cell of radius D_{edge} . This particular assumption allows

for dealing with the heterogeneous case in which the average SNRs of all users are different as they are randomly located throughout the coverage area. The PDF of the distance between the k -th user, and the BS is given by [24] as follows:

$$f_{D_k}(d) = \frac{2d}{D_{\text{edge}}^2}, \quad 0 < d \leq D_{\text{edge}}. \quad (3)$$

We model the effect of path loss between the BS and the k -th user as $L_p(D_k) = \epsilon \cdot D_k^\beta$, where ϵ and β represent the path loss constant and exponent, respectively. By taking into account the path loss, the average SNR experienced by the k -th user, $\bar{\gamma}_k$, can be expressed as

$$\bar{\gamma}_k = \frac{\bar{\gamma}_0}{\epsilon \cdot D_k^\beta} \quad (4)$$

where $\bar{\gamma}_0$ is defined as the average SNR at a reference distance, i.e., $L_p(D_k) = 1$. Let h_k denote the instantaneous channel coefficient between the BS and the k -th users. We assume that $\{h_k\}$ are independent and identically distributed over K users, each modeled as a complex Gaussian random variable with $E\{|h_k(n)|^2\} = 1$, i.e., $h_k(n) \sim \mathcal{CN}(0, 1)$. Then, the SNR of the k -th user takes the following form:

$$\gamma_k = \bar{\gamma}_k |h_k|^2 \quad (5)$$

4 AMC design and performance analysis

4.1 AMC design

In the current AMC design associated with SVC, unequal error protection (UEP) can be supported using the different AMC mode for the different video layer. For each AMC mode, SNR threshold can be determined so as to meet the pre-specified performance, e.g., a target block error rate in the physical layer or a target FLR in the application layer. In the current RNC-based application layer, FLR is considered as an appropriate performance criterion that takes the additional error correction capability subject to the given delay requirement into account. By imposing the FLR requirement on the AMC design, a typical physical layer block error rate requirement has been now translated into the application layer performance requirement as a cross-design approach. In general, each AMC mode can set its own target FLR, which can support another level of UEP. In this paper, however, we assume that all AMC modes set to the same target FLR, without loss of generality, which allows for focusing on the AMC design issue only. Therefore, UEP is supported only by employing the different AMC mode for the different SVC layer.

Meanwhile, our proposed scheme relies on aggressive AMC design, which allows for increasing the target PER

in the earlier transmission opportunities. This is to find the minimum AMC threshold value for satisfying the QoS requirement of FLR at P_{loss} only over the given overall delay constraint, not just in every transmission. In other words, AMC threshold must be minimized such that $\text{FLR}_n(\gamma, L_{\text{max}}) \leq P_{\text{loss}}$ can be achieved over the given overall delay constraint governed by the maximum number of L_{max} transmissions, i.e.,

$$\gamma_{\text{th}}^{(n)} = \min_{\text{FLR}_n(\gamma, L_{\text{max}}) \leq P_{\text{loss}}} \gamma, \quad (6)$$

where $\gamma_{\text{th}}^{(n)}$ is the optimal AMC threshold value for a stream of the SVC layer that employs the AMC mode n for our aggressive AMC design approach. Its throughput gain would be compared to that of a conservative AMC design approach, in which $\gamma_{\text{th}}^{(n)}$ is set to satisfy the target FLR performance in every transmission.

Since the $\text{PER}_n(\gamma)$ is monotonically decreasing with γ while $\text{FLR}_n(\gamma, L_{\text{max}})$ is monotonically increasing with $\text{PER}_n(\gamma)$, (6) can be solved immediately as

$$\gamma_{\text{th}}^{(n)} = \text{PER}_n^{-1}(p^*) = \left(\frac{-1}{g_n}\right) \ln\left(\frac{p^*}{a_n}\right) \quad (7)$$

where p^* is a target PER corresponding to the optimal threshold such that

$$P_{\text{loss}} = 1 - \sum_{\ell=0}^{L_{\text{max}}} \binom{M+\ell-1}{\ell} (p^*)^\ell (1-p^*)^M. \quad (8)$$

Note that there is no closed-form solution for p^* in (8). Instead, we can numerically calculate it offline using Newton's method or any other algorithm, since M , L_{max} , and P_{loss} do not vary dynamically. Therefore, a look-up table for p^* can be constructed as illustrated in Table 2. It is clear from Table 2 that the PER requirement becomes looser when more redundant packets are allowed for retransmissions, e.g., $p^* = 0.0624$ with $L_{\text{max}} = 10$ and $p^* = 0.0139$ with $L_{\text{max}} = 5$, both satisfying an FLR of $P_{\text{loss}} = 10^{-6}$ for $M = 20$. The similar characteristics are observed for the different system parameters and QoS requirements.

Table 2 The target PERs for some QoS parameters

M	L_{max}	P_{loss}	p^*
20	5	10^{-6}	0.0139
20	10	10^{-6}	0.0624
20	10	10^{-4}	0.1013
10	1	10^{-4}	0.0014
10	0	10^{-4}	0.0000101

4.2 Spectral efficiency analysis

In this section, we present the expression for the average spectral efficiency of the aggressive AMC design in the scalable video streaming scenario. For the current analysis, overhead associated with the packet header of the random network coding is not considered while assuming no error is incurred over the uplink feedback channel.

First, we analyze a distribution of the SNR γ_k in the given service zone. Since we consider the Rayleigh fading channel, the SNR γ_k is exponentially distributed with a mean of $\epsilon \cdot (D_k)^\beta / \bar{\gamma}_0$ by (5), i.e., for any given distance D_k from the base station, its CDF is given as

$$F_{\gamma_k|D_k}(\gamma) = \Pr \left\{ \gamma_k = \frac{\bar{\gamma}_0 |h_k|^2}{\epsilon \cdot D_k^\beta} \leq \gamma \mid D_k \right\} \quad (9)$$

$$= 1 - \exp \left\{ -\epsilon \cdot D_k^\beta \gamma / \bar{\gamma}_0 \right\}.$$

Subsequently, by assuming that the locations of users are i.i.d., the CDF of the SNR γ_k is now averaged over the random location of the users:

$$F_{\gamma_k}(\gamma) = \int_0^{D_{\text{edge}}} F_{\gamma_k|D_k=u}(\gamma) f_{D_k}(u) du \quad (10)$$

$$= 1 - \frac{1}{D_{\text{edge}}^2} \int_0^{D_{\text{edge}}} \exp \left(-\frac{\epsilon z^{\beta/2} \gamma}{\bar{\gamma}_0} \right) dz.$$

Using the Taylor series expansion of the exponential function, (10) can be rewritten as

$$F_{\gamma_k}(\gamma) = 1 - \frac{1}{D_{\text{edge}}^2} \int_0^{D_{\text{edge}}} \left(1 + \sum_{m=1}^{\infty} \left(-\frac{\epsilon \gamma}{\bar{\gamma}_0} \right)^m \frac{z^{m\beta/2}}{m!} \right) dz \quad (11)$$

$$= 1 - \frac{1}{D_{\text{edge}}^2} \sum_{m=0}^{\infty} \left(-\frac{\epsilon \gamma}{\bar{\gamma}_0} \right)^m \frac{1}{m!} \int_0^{D_{\text{edge}}} z^{m\beta/2} dz$$

$$= 1 - \sum_{m=0}^{\infty} \left(-\frac{\gamma}{\bar{\gamma}_{\text{edge}}} \right)^m \frac{1}{m! (m\beta/2 + 1)}.$$

For a special case of $\beta = 2$, (11) is reduced to

$$F_{\gamma_k}(\gamma) = 1 - \sum_{m=0}^{\infty} (-\gamma/\bar{\gamma}_{\text{edge}})^m \frac{1}{(m+1)!} \quad (12)$$

$$= 1 + \frac{\bar{\gamma}_{\text{edge}}}{\gamma} \{ \exp(-\gamma/\bar{\gamma}_{\text{edge}}) - 1 \}$$

which can be differentiated to find the PDF of γ_k as follows:

$$f_{\gamma_k}(\gamma) = \frac{\bar{\gamma}_{\text{edge}}}{\gamma^2} - \left(\frac{\bar{\gamma}_{\text{edge}}}{\gamma^2} + \frac{1}{\gamma} \right) \exp \left(-\frac{\gamma}{\bar{\gamma}_{\text{edge}}} \right). \quad (13)$$

The accuracy of (12) can be checked with the distribution by simulation under the same assumptions as in the analysis. In fact, Figure 2 demonstrates that analytical and simulation results coincide with each other, which validates the accuracy of our analysis.

For the homogeneous case in which the average SNRs of all users have the same value (i.e., $\bar{\gamma}_1 = \bar{\gamma}_2 = \dots = \bar{\gamma}_K$), $f_{\gamma_k}(\gamma)$ will be given by the well-known Rayleigh distribution. Therefore, it is straightforward to find the spectral efficiency for the homogeneous case, just by replacing (13) with the PDF of the Rayleigh distribution. Using the PDF (13), the probability that an arbitrary user in the system is subject to the mode n for AMC operation, denoted as $\Pr(n)$, will be given as

$$\Pr(n) = \int_{\gamma_{\text{th}}^{(n)}}^{\infty} f_{\gamma_k}(\gamma) d\gamma = \frac{\bar{\gamma}_{\text{edge}}}{\gamma_{\text{th}}^{(n)}} \left\{ 1 - \exp \left(-\frac{\gamma_{\text{th}}^{(n)}}{\bar{\gamma}_{\text{edge}}} \right) \right\}. \quad (14)$$

Let p_e denote the conditional PER given the AMC mode n . Then, it can be obtained in the following closed form:

$$p_e = \frac{1}{\Pr(n)} \int_{\gamma_{\text{th}}^{(n)}}^{\infty} a_n \exp(-g_n \gamma) f_{\gamma_k}(\gamma) d\gamma$$

$$= \frac{1}{\Pr(n)} \left(\int_{\gamma_{\text{th}}^{(n)}}^{\infty} \frac{a_n \bar{\gamma}_{\text{edge}}}{\gamma^2} \exp(-g_n \gamma) d\gamma \right. \\ \left. - \int_{\gamma_{\text{th}}^{(n)}}^{\infty} \frac{a_n \bar{\gamma}_{\text{edge}}}{\gamma^2} \exp \left(-\left(g_n + \frac{1}{\bar{\gamma}_{\text{edge}}} \right) \gamma \right) d\gamma \right. \\ \left. - \int_{\gamma_{\text{th}}^{(n)}}^{\infty} \frac{a_n}{\gamma} \exp \left(-\left(g_n + \frac{1}{\bar{\gamma}_{\text{edge}}} \right) \gamma \right) d\gamma \right)$$

$$= \frac{a_n}{\Pr(n)} \left(\bar{\gamma}_{\text{edge}} \left(\frac{\exp(-g_n \gamma_{\text{th}}^{(n)})}{\gamma_{\text{th}}^{(n)}} + g_n \text{Ei}(-g_n \gamma_{\text{th}}^{(n)}) \right) \right. \\ \left. - \bar{\gamma}_{\text{edge}} \left(\frac{1}{\gamma_{\text{th}}^{(n)}} \exp(-b_n \gamma_{\text{th}}^{(n)}) + b_n \text{Ei}(-b_n \gamma_{\text{th}}^{(n)}) \right) \right. \\ \left. + \text{Ei}(-b_n \gamma_{\text{th}}^{(n)}) \right). \quad (15)$$

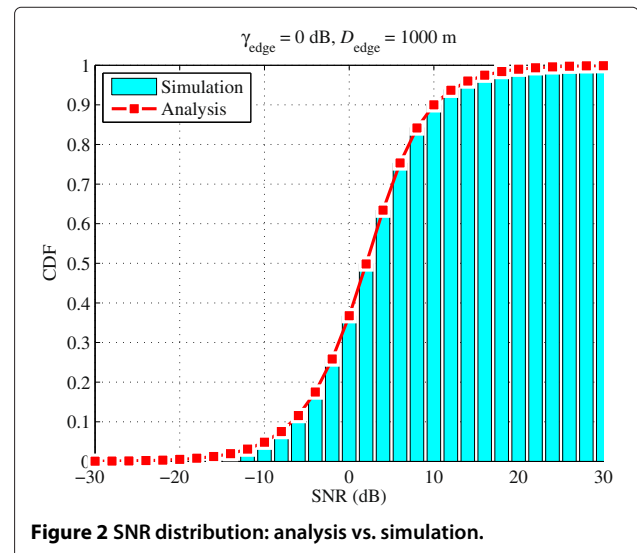


Figure 2 SNR distribution: analysis vs. simulation.

where $b_n \triangleq g_n + 1/\bar{\gamma}_{\text{edge}}$ and $\text{Ei}(x)$ is the exponential integral function. Note that additional encoded packets are required until the frame reception becomes successful for each user. Let $p_r(L)$ be the probability that the frame reception is terminated with L additional encoded packets at each of the user side. It depends on the PER in (15), such that $p_r(L)$ is given as

$$p_r(L) = \begin{cases} \binom{M+L-1}{L} p_e^L (1-p_e)^M, & L = 0, 1, \dots, L_{\max}-1 \\ \binom{M+L-1}{L} p_e^L (1-p_e)^{M-1}, & L = L_{\max}. \end{cases} \quad (16)$$

Meanwhile, the base station continues the encoded packet transmission until all users receive the same video frame successfully. Let $p_t(L)$ be the probability that the frame transmission is terminated with exactly L additional encoded packets at the base station. As it depends on the number of users in the given AMC mode, let K_n denote the average number of users in AMC mode n , i.e., $K_n = K \cdot \text{Pr}(n)$, then $p_t(L)$ is given as

$$p_t(L) = \begin{cases} \left(\sum_{\ell=0}^L p_r(\ell) \right)^{K_n} - \left(\sum_{\ell=0}^{L-1} p_r(\ell) \right)^{K_n}, & L = 0, 1, 2, \dots, L_{\max}-1 \\ 1 - \sum_{\ell=0}^{L-1} p_t(\ell), & L = L_{\max} \end{cases} \quad (17)$$

The average spectral efficiency for AMC mode n in our scheme, denoted as η_n , is given by data rate of AMC mode n^* probability that a user employs AMC mode n^* transmission efficiency where transmission efficiency is governed by the average number of packet transmissions required until terminated. More specifically, transmission efficiency is given as a ratio of the number of packets to transmit (M) to the average number of packet transmissions required until terminated ($\sum_{\ell=0}^{L_{\max}} (M+\ell) p_t(\ell)$), i.e.,

$$\eta_n = R_n \cdot \text{Pr}(n) \frac{M}{\sum_{\ell=0}^{L_{\max}} (M+\ell) p_t(\ell)} \quad (18)$$

Without common feedback, the probability that the frame transmission is terminated with redundant packets at the base station is 1. Therefore, the average spectral efficiency is given by

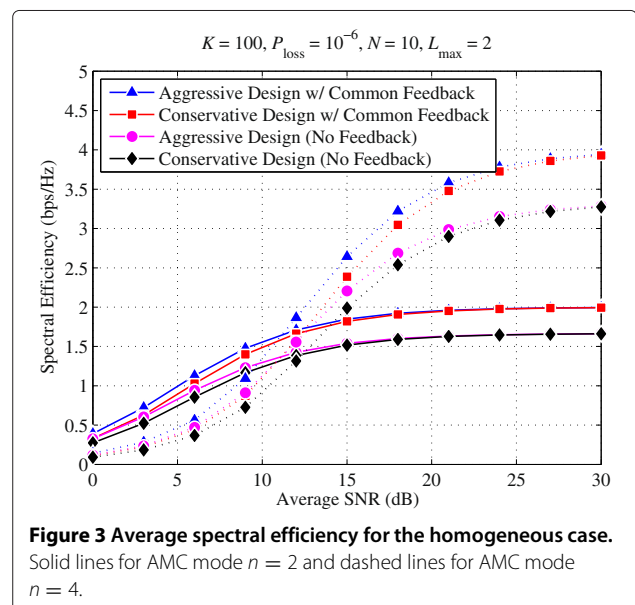
$$\eta_n = R_n \cdot \text{Pr}(n) \cdot \frac{M}{M+L_{\max}} \quad (19)$$

5 Numerical results

In this section, we compare the average spectral efficiencies for the different AMC designs, in order to illustrate

how much additional gain can be achieved by the aggressive AMC design subject to the target frame error rate requirement when random network coding is applied to a multicast video transmission system with a delay constraint. In the current analysis, we also consider the performance gain obtained by the common feedback channel, which will be compared to that without the common feedback channel, in which the prescribed number of redundant packets is always transmitted for each packet, as the success of reception cannot be known to the transmitter. Furthermore, the current numerical analysis considers the five different AMC modes in Table 1. As the coverage for each AMC mode varies with the AMC design approach, with a lower AMC threshold corresponding to larger coverage, we investigate the average spectral efficiency of individual AMC modes, given by Equation 19.

First, we present the numerical results for the homogeneous case in Figure 3, while varying the average SNR with a target FLR requirement of $P_{\text{loss}} = 10^{-6}$ for 100 users ($K = 100$), $N = 10$, and $L_{\max} = 2$. Two different cases, one for AMC mode $n = 2$ and the other for AMC mode $n = 4$, are shown in Figure 3. In this homogeneous case, the average spectral efficiency for each AMC mode is mainly governed by the average SNR. The theoretical spectral efficiency of 4 bps/Hz for AMC mode $n = 4$ in Table 1 can be achieved when the average SNR is sufficiently large, when a common feedback channel is employed. As shown in Figure 3, however, the maximum efficiency can never be achieved without the feedback channel, leaving a significant gap in performance compared with the common feedback



channel. The performance gap is mainly attributed to the L_{max} redundant transmissions, which always reduce the spectral efficiency, when there is no feedback channel. Such a gap will be more conspicuous as L_{max} increases. Due to the QoS-specific optimized nature of the aggressive AMC design, its advantage is clear for any case. As observed in previous studies [1,2], the performance difference between the aggressive and conservative AMC designs turns out to be rather marginal in this homogeneous case, especially when L_{max} is not too large.

In Figure 4, the performance of the aggressive AMC design with the common feedback improves as the maximum allowable delay L_{max} is increased, allowing for more aggressive transmission. L_{max} does not affect the performance of the conservative AMC design, even with the common feedback channel, since the advantage of possible transmission opportunities in the future is not taken into account. This implies that the proposed AMC design with the common feedback deals with the best trade-off performance between the allowable delay and the service coverage by optimizing the AMC threshold.

Figure 5 shows that the aggressive AMC design with the common feedback channel always outperforms for the different target FLR requirements. The aggressive design becomes more advantageous with a more stringent FLR requirement. This is attributed to the fact that a target PER for each transmission is set as a target FLR in the conservative design, which excessively enforces QoS. Therefore, the performance of the conservative design is relatively more sensitive to the target FLR. Combining all the effects of Figures 4 and 5, the aggressive design becomes more advantageous, allowing more

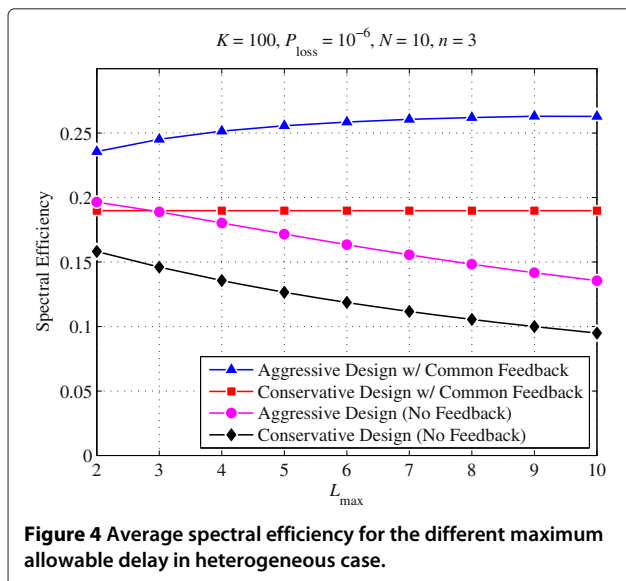


Figure 4 Average spectral efficiency for the different maximum allowable delay in heterogeneous case.

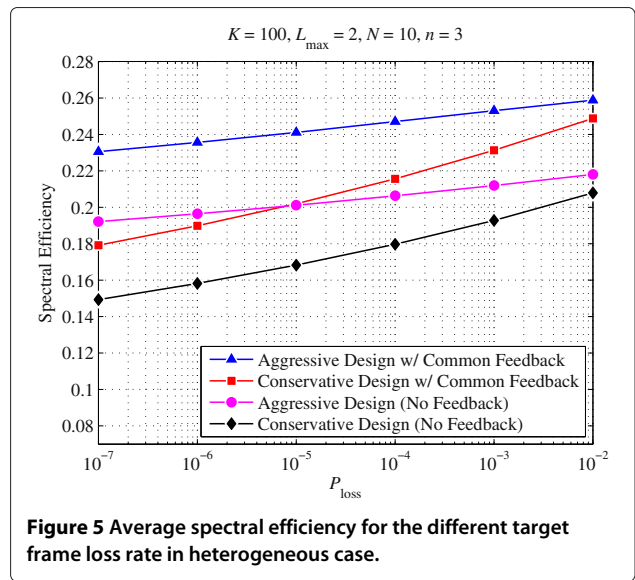


Figure 5 Average spectral efficiency for the different target frame loss rate in heterogeneous case.

redundant transmission while requiring a stricter FLR constraint.

6 Conclusions

We have developed an aggressive AMC design approach for an SVC-layered multicast/broadcast system with random network coding. It is a cross-layer design approach to optimize the SNR threshold of the given AMC mode in the physical layer, which determines the specific coverage area for the individual SVC layer in the multicast/broadcast network, while satisfying the given target frame loss rate under the delay constraint of the real-time streaming services. Our analysis has demonstrated that the proposed design can provide significant spectral efficiency enhancement. Furthermore, it has been shown that a common feedback channel is essential for ensuring the bandwidth efficiency of random network coding in the multicast/broadcast system. In this paper, however, we have not addressed how the different AMC mode is selected for each SVC layer, which is beyond our current work. If the notion of quality of experience (QoE) can be quantified by defining a utility function associated with an individual SVC layer of the video stream, the current design approach can be extended to maximize the total system utility rather than bandwidth efficiency subject to the given QoE requirement. To this end, the frame loss rate and delay constraint under consideration must be properly translated into QoE. The QoE-specific cross-layer design will be useful for the SVC-based multicasting technology to implement real-time video streaming applications, such as mobile IPTV services in a mobile WiMAX network.

Competing interests

The authors declare that they have no competing interests.

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