Cross-Layer Design of Adaptive Wireless Multicast Transmission with Truncated HARQ

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Abstract—This paper presents a cross-layer design of adaptive modulation and coding (AMC) with truncated hybrid automatic repeat request (HARQ) for one-to-many multicast transmission, in order to increase the spectral efficiency under the quality-of-service (QoS) constraints. For adaptive transmission over the channel common to the multicast group users, the AMC mode is chosen with the minimum SNR among the users to guarantee the target performance of all users. In the meanwhile, the minimum SNR required to support an AMC mode is aggressively designed by allowing retransmission with HARQ schemes. For the proposed design, we derive the average packet error rate, average number of transmission, and spectral efficiency and provide the performance numerically obtained. Numerical results show that the cross-layer design for multicast provides a significant performance gain at a small number of retransmissions as in unicast. In particular, it is observed that AMC design with HARQ is more beneficial in the low SNR region where multicast performs worse than unicast.

I. INTRODUCTION

Recently, one-to-many multicast transmission has been introduced in various wireless networks such as cellular systems and wireless local area networks (WLANs) for more efficient delivery of multimedia streaming services [1][2]. Initial study on multicast has been focused on higher layer issues such as efficient design of routing protocols. Multicast protocols have been shown to considerably reduce the bandwidth and power consumption compared with unicasting counterparts [3]. For further enhancement of overall throughput, lower layers are also required to efficiently combat the adverse fading effect on multicast transmission.

Most of multicast approaches in currently deployed wireless networks resort to the diversity techniques to mitigate the fading effect since it is not easy to adapt to all the channel states of multicast users when a multicast group size is large [1]. If a multicast group size is not so large and the mobility of users is low, adaptive transmission methods developed for unicast could be used for multicast with some modifications. Those adaptive methods typically include adaptive modulation and coding (AMC) at the physical layer [4][5] and automatic repeat request (ARQ) protocol at the data link layer [6]. For further performance enhancement, hybrid ARQ (HARQ) integrating the ARQ with channel coding could be applied at the cost of complexity [7][8].

Traditionally, the parameters of AMC and ARQ are designed separately to meet the requirement of the layer where each method is implemented. However, many of recent works reveal that cooperation of two or more layers improves resource utilization. In particular, [9] has combined AMC and truncated ARQ by designing the SNR regions for AMC modes taking into consideration the effect of retransmission under the prescribed delay and error performance constraints. The work of [9] has been extended with truncated HARQ [10]. The results of [9] and [10] show that the cross-layer design approaches significantly improve the spectral efficiency. Those approaches could be also applied to multicast while the performance would depend on the number of users in the multicast group.

In this paper, we consider a cross-layer design approach combining AMC with truncated HARQ for multicast to meet the target packet loss rate under the delay constraint which is typically given to the streaming services. Different from the unicast counterpart, adaptive transmission for multicast is performed with the channel state information (CSI) of all the users in the group sharing the physical channel. In this paper, we provide an AMC design to meet the QoS requirements of all users when the number of retransmission for HARQ is given. With the cross-layer design for multicast, we derive the average packet error rate (PER) of the multicast group and the number of retransmissions, from which the spectral efficiency is obtained for comparison with the unicast alternatives.

The remaining of the paper is organized as follows. Section II presents the system model of multicast transmission based on which the cross-layer design of AMC with truncated HARQ is provided in Section III. Throughput analysis on the proposed method is provided in Section IV, followed by numerical results in Section V. Finally, conclusions of the paper are provided in Section VI.

II. SYSTEM MODEL

Consider a cellular system with one base station (BS) and $K$ users joined in a multicast group as shown in Fig. 1. The system model for adaptive multicast transmission is shown in Fig. 2, where HARQ and AMC modules are included as a cross-layer design approach. For transmission of multicast
data using AMC, the system provides \( M \) modulation and coding schemes which leads to \( M + 1 \) data rates including no transmission. The normalized data rate of AMC mode \( m \) is given by \( R_m \) bps/Hz for \( m = 0, 1, \ldots, M \) with \( R_0 = 0 \) bps/Hz. For a proper choice of an AMC mode, each user in the multicast group estimates the received SNR \( \gamma_k \) and sends the SNR to the BS via the feedback channel. Then the BS decides the AMC mode of a multicast data based on the SNR vector \( \gamma = [\gamma_1 \gamma_2 \cdots \gamma_K] \) of the multicast group. To satisfy the QoS of all users in the multicast group, the AMC mode is chosen by \( \gamma_{\text{min}} = \min_k \gamma_k \).

III. CROSS-LAYER DESIGN OF AMC WITH TRUNCATED HARQ

The AMC and HARQ parameters for adaptive multicast transmission should be designed to satisfy the QoS requirements of higher layers as in unicast transmission [9]. The QoS of multimedia services is typically given by the packet loss rate \( P_{\text{loss}} \) and the delay constraint. The delay constraint determines \( N_{\text{max}} \) in the truncated HARQ. For given \( N_{\text{max}} \), we determine the SNR regions of AMC modes to meet the packet loss rate under the following assumptions: i) the channel remains invariant during the initial transmission and retransmissions of a data packet so that the AMC mode is selected packet-by-packet, ii) perfect CSI is available at both the transmitter and receivers, and iii) packet error detection with CRC is perfect.

When the CSI from the users is given as \( \gamma \), the AMC mode \( m \) should satisfy the following packet loss rate criterion after \( N_{\text{max}} + 1 \) transmissions:

\[
\prod_{n=1}^{N_{\text{max}}} P_{m,n}^{gr}(\gamma) \leq P_{\text{loss}}, \text{for all } k,
\]

where \( P_{m,n}^{gr}(\gamma) \) is the PER at the \( n \)th transmission when AMC mode \( m \) is chosen for the given SNR \( \gamma \) and \( P_{m,n}^{gr}(\gamma) \) is the probability that at least one of multicast users detects a packet error at the \( n \)th transmission (thereby requesting retransmission) as follows.

\[
P_{m,n}^{gr}(\gamma) = 1 - \prod_{k=1}^{K} [1 - P_{m,n}(\gamma_k)].
\]

It should be noted that multicast is different from unicast since the retransmission process terminates only when all users send ACK message. Thus, we call \( P_{m,n}^{gr}(\gamma) \) the PER of the multicast group.

It should be noted that (1) is satisfied by all users if and only if it is satisfied by the user with the minimum SNR. In addition, \( P_{m,n}^{gr}(\gamma) \) is approximately given by

\[
P_{m,n}^{gr}(\gamma) \approx P_{m,n}(\gamma_{\text{min}})
\]

since the PER of the user with the minimum SNR dominates the performance. Thus, we choose the AMC mode \( m \) if \( \Gamma_m \leq \gamma_{\text{min}} < \Gamma_{m+1} \), where \( \Gamma_0 = -\infty \), \( \Gamma_{M+1} = \infty \), and \( \Gamma_m \) satisfying

\[
N_{\text{max}} + 1 \prod_{n=1}^{N_{\text{max}}} P_{m,n}(\gamma_{\text{min}}) \leq P_{\text{loss}}.
\]

On the other hand, the instantaneous PER \( P_{m,n}(\gamma_k) \) is approximately given by [9]

\[
P_{m,n}(\gamma_k) = a_{m,n}e^{-g_{m,n} \gamma_k} \;
\]

where \( a_{m,n} \) and \( g_{m,n} \) are determined by the modulation scheme, the channel coding scheme, and the HARQ scheme applied: \( a_{m,n} = a_{m,1} \) and \( g_{m,n} = g_{m,1} \) with \( a_{m,1} \) and \( g_{m,1} \) determined by the AMC mode as in [9] if the conventional ARQ scheme is applied, \( a_{m,n} = a_{m,1} \) and \( g_{m,n} = n g_{m,1} \) if the type-I HARQ is applied, and \( a_{m,n} \) and \( g_{m,n} \) are obtained.
by fitting the approximated PERs to the exact PERs as in [10] if type-II HARQ is applied. By incorporating (5) into (1), we have
\[
\Gamma_m = \frac{1}{\sum_{n=1}^{N_{\text{max}}+1} g_{m,n}} \ln(\prod_{n=1}^{N_{\text{max}}+1} a_{m,n}), \text{ for } 1 \leq m \leq M.
\] (6)

IV. ANALYSIS ON SPECTRAL EFFICIENCY

In this section, we derive the average PER and the spectral efficiency of the proposed multicast method when the users experience independent and identically distributed Rayleigh fading. With the fading assumption, the probability density function (pdf) of the SNR vector \( \gamma \) is given by
\[
f_2(\gamma) = \prod_{k=1}^{K} f_1(\gamma_k),
\] (7)
where \( f_1(\gamma_k) = \rho^{-1} e^{-\gamma_k/\rho} \) with the average received SNR \( \rho \) at the user.

Let \( S_c \) be the data received in unit time and unit frequency (bps/Hz) via the multicast channel per user. The spectral efficiency of the multicast transmission is given by
\[
S_m = K \times S_c,
\] (8)
since \( K \) users receive the same amount of data at the same time via the common multicast channel. For the truncated (H)ARQ, \( S_c \) is given by [9]
\[
S_c = \frac{\pi_m R_m}{N},
\] (9)
where \( \pi_m \) is the probability that AMC mode \( m \) is chosen and \( N \) is the average number of transmissions per packet. Since the AMC mode is chosen based on the minimum SNR \( \gamma_{\text{min}} \) among the users, \( \pi_m \) is obtained as
\[
\pi_m = \int_{\Gamma_m}^{\Gamma_{m+1}} f_{\gamma_{\text{min}}}(x) dx,
\] (10)
where the pdf \( f_{\gamma_{\text{min}}}(x) \) of \( \gamma_{\text{min}} \) is given by applying order statistics [11] as
\[
f_{\gamma_{\text{min}}}(x) = \frac{K}{\rho} e^{-Kx/\rho}.
\] (11)

On the other hand, the average number of transmissions per packet is given by
\[
N = 1 + \sum_{j=1}^{N_{\text{max}}} \prod_{n=1}^{j} \bar{P}_{gr,n}^m
\] (12)
where \( \bar{P}_{gr}^m \) is the average PER of the multicast group at the \( n \)th transmission such that
\[
\bar{P}_{gr}^m = \frac{\sum_{m=1}^{M} \pi_m \bar{P}_{gr,n}^m}{\sum_{m=1}^{M} \pi_m}.
\] (13)
Here, \( \bar{P}_{gr,n}^m \) is the average PER of the multicast group at the \( n \)th transmission when the AMC mode \( m \) is chosen. It is obtained by averaging \( P_{gr,n}^m(\gamma) \) over the region \( A_m \) of \( \gamma \) leading to the AMC mode \( m \) as follows.
\[
\bar{P}_{gr,n}^m = \int_{2 \in A_m} P_{gr,n}^m(\gamma) f_2(\gamma) d\gamma,
\] (14)
where the conditional pdf \( f_2(\gamma) \) conditioned on the AMC mode \( m \) is given by
\[
f_2(\gamma) = \left\{ \begin{array}{ll} f_1(\gamma), & \text{if } \gamma \in A_m, \\ 0, & \text{otherwise}. \end{array} \right.
\] (15)
It should be noted that \( A_m = \bigcup_{j=1}^{K} A_{m,j} \) where \( A_{m,j} = \{ \gamma_j = \min_k \gamma_k, \Gamma_m \leq \gamma_j \leq \Gamma_{m+1} \} \). Since the regions \( \{ A_{m,j} \}_{j=1}^{K} \) are mutually exclusive and the pdf \( f_2(\gamma) \) and \( f_{\gamma_{\text{min}}}(x) \) are symmetric over the regions, we have
\[
\bar{P}_{gr,n}^m = 1 - \frac{K}{\pi_m} \int_{\Gamma_m}^{\Gamma_{m+1}} [1 - P_{m,n}(\gamma_j)] \left[ \prod_{k \neq j} \int_{\Gamma_m}^{\Gamma_{m+1}} [1 - P_{m,n}(\gamma_k)] f_1(\gamma_k) d\gamma_k \right] f_1(\gamma_j) d\gamma_j.
\] (16)

With (5) for the instantaneous PER, the closed form of \( \bar{P}_{gr,n}^m \) can be obtained as
\[
\bar{P}_{gr,n}^m = 1 - \frac{K}{\pi_m \rho} \sum_{k=0}^{K-1} \frac{(K-1)}{(k+1)g_{m,n}} e^{-\left(\frac{K}{\rho} + (k+1)g_{m,n}\right)\Gamma_m} \left[ a_{m,n} \Gamma_m + e^{-\left(\frac{K}{\rho} + k g_{m,n}\right)\Gamma_m} \right] \left[ a_{m,n} \Gamma_m + e^{-\left(\frac{K}{\rho} + k g_{m,n}\right)\Gamma_m} \right]^{-1}.
\] (17)

V. NUMERICAL RESULTS

We evaluate the spectral efficiency of the proposed multicast transmission using the set of AMC modes with \( M = 4 \) in Table I. The channel coding and modulation schemes are the same as in [10]. The SNR thresholds \( \{ \Gamma_m \} \) are different according to \( N_{\text{max}}, P_{\text{loss}}, \) and ARQ schemes applied. In the table, we provide the SNR thresholds when \( N_{\text{max}} = 2 \) and \( P_{\text{loss}} = 10^{-3} \) for two types of HARQ.

Firstly, we show the validity of the AMC thresholds designed in the paper by evaluating the actual packet loss rate in Fig. 3. In the figure, we apply type-I HARQ for adaptive multicast when \( K = 2 \) and \( P_{\text{loss}} = 10^{-3} \) for different \( N_{\text{max}} \). For \( N_{\text{max}} = 0, 1, \ldots, 3 \), the packet loss rate after

<table>
<thead>
<tr>
<th>AMC Modes</th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>Mode 3</th>
<th>Mode 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation</td>
<td>QPSK</td>
<td>QPSK</td>
<td>16QAM</td>
<td>16QAM</td>
</tr>
<tr>
<td>Code Rate</td>
<td>1/2</td>
<td>2/3</td>
<td>1/2</td>
<td>2/3</td>
</tr>
<tr>
<td>Data Rate</td>
<td>4/3</td>
<td>1.2765</td>
<td>1.2765</td>
<td>1.2765</td>
</tr>
<tr>
<td>( P_{\text{loss}} ) (dB) for HARQ-I</td>
<td>2.0667</td>
<td>5.5786</td>
<td>7.5765</td>
<td>11.3163</td>
</tr>
<tr>
<td>( P_{\text{loss}} ) (dB) for HARQ-II</td>
<td>-0.2377</td>
<td>1.3993</td>
<td>5.1642</td>
<td>6.6635</td>
</tr>
</tbody>
</table>
$N_{\text{max}} + 1$ transmissions are always less than the target value $P_{\text{loss}} = 10^{-3}$. Thus, the AMC design with HARQ satisfies the packet loss requirement under different delay constraints. In addition, it is observed that the packet loss rate decrease rapidly in the high SNR region, which implies that the spectral efficiency can be increased further by adopting more AMC modes of higher data rate.

In Fig. 3, the actual packet loss rate of the adaptive multicast method using type-I HARQ when $K = 2$ and $P_{\text{loss}} = 10^{-3}$.

Fig. 4 shows the probability that AMC mode $m$ is chosen when $K = 2$ and $N_{\text{max}} = 2$ for different multicast methods: ‘Mul-AMC-HARQ’, ‘Mul-AMC-ARQ’, and ‘Mul-AMC’ denote the adaptive multicast method with truncated type-I HARQ, the method with truncated ARQ, and the method without ARQ, respectively. We consider two AMC modes with the highest data rate (mode 4) and the lowest data rate (mode 1). By designing AMC with ARQ and HARQ, the probability that the highest AMC mode is chosen increases at the same average SNR. On the other hand, the SNR value where the lowest AMC mode is more likely to be chosen becomes the smallest with HARQ. This figure implies that the throughput could be increased by designing AMC with truncated (H)ARQ methods also in multicast as well as in unicast.

Fig. 5 compares the average spectral efficiency of the proposed adaptive multicast methods with different ARQ schemes when $K = 2$, $N_{\text{max}} = 2$, and $P_{\text{loss}} = 10^{-3}$. In addition, we also provide the performance when multicast data are transmitted in a unicast (one-to-one) manner (‘AMC-HARQ’, ‘AMC-ARQ’, and ‘AMC’). As in unicast transmission, AMC combined with truncated ARQ remarkably improves the performance of adaptive multicast transmission when compared with the AMC only scheme. By applying the HARQ instead of ARQ, we can also leverage the spectral efficiency in the low SNR region. It is also observed that the multicast methods outperform the unicast methods in the high SNR region while they exhibit some performance loss in the low SNR region. However, the cross-over SNR becomes smaller by designing adaptive multicast transmission with ARQ or HARQ by allowing transmission delays.

The effect of $K$ on the spectral efficiency is shown in Fig. 6 for adaptive multicast transmission. It is observed that a significant throughput gain is obtained by using ARQ and HARQ and the gain becomes larger as $K$ increases. Especially, by applying type-II HARQ in adaptive multicast transmission, the performance in the low SNR region is remarkably improved. If the performance of the multicast methods with $K = 5$ is compared with that of their unicast alternatives ($K = 1$), the cross-over SNR over which multicast outperforms unicast is about 14 dB with AMC only while it is about 5 dB with the design of AMC using type-II HARQ. Thus, we can see that multicast exploits the benefit of cross-layer design of AMC and HARQ much better than unicast.
VI. Conclusion

In this paper, we apply a cross-layer design of AMC and truncated HARQ to wireless multicast transmission. For multicast where the data rate is determined by the channel states of multiple users in the group, we obtain the SNR regions for AMC mode operation. For spectral efficiency, we also obtain the average PER of the multicast group and the closed-form of the spectral efficiency. The numerical results show that the proposed design can provide a significant throughput enhancement while satisfying the QoS requirements. In particular, a larger gain is observed when the SNR is low, the number of users in the multicast group increases, and type-II HARQ instead of ARQ or type-I HARQ is applied.

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