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Research Article

Joint NC-ARQ and AMC for QoS-Guaranteed Mobile Multicast

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In mobile multicast transmissions, the receiver with the worst instantaneous channel condition limits the transmission data rate under the desired Quality-of-Service (QoS) constraints. If Automatic Repeat reQuest (ARQ) schemes are applied, the selection of Adaptive Modulation and Coding (AMC) mode will not necessarily be limited by the worst channel anymore, and improved spectral efficiency may be obtained in the efficiency-reliability tradeoff. In this paper, we first propose a Network-Coding-based ARQ (NC-ARQ) scheme in its optimal form and suboptimal form (denoted as Opt-ARQ and SubOpt-ARQ, resp.) to solve the scalability problem of applying ARQ in multicast. Then we propose two joint NC-ARQ-AMC schemes, namely, the Average PER-based AMC (AvgPER-AMC) with Opt-ARQ and AvgPER-AMC with SubOpt-ARQ in a cross-layer design framework to maximize the average spectral efficiency per receiver under specific QoS constraints. The performance is analyzed under Rayleigh fading channels for different group sizes, and numerical results show that significant gains in spectral efficiency can be achieved with the proposed joint NC-ARQ-AMC schemes compared with the existing multicast ARQ and/or AMC schemes.

1. Introduction

Radio transmission is broadcasting in nature; therefore, wireless multicasting is more efficient than unicasting in providing group-oriented mobile applications like multi-player mobile gaming, mobile TV, mobile commerce, and remote education. However, the time-varying channel seen by each mobile receiver and the channel diversity among the receivers in a multicast group make the design of an efficient multicast strategy technically challenging.

We consider a wireless single-hop cellular network where one transmitter sends a data stream carrying multimedia content (e.g., video) to a group of receivers via a multicast channel. The transmitter can utilize both the Physical Layer (PHY) and the Data-Link Layer (DLL) approaches to maximize the spectral efficiency of this multicast channel under certain Quality of Service (QoS) constraints. As previous work [1, 2] revealed, when the error-performance constraint is instantaneous (e.g., the instantaneous PHY layer Bit Error Ratio (BER)), the transmitter has to adjust the transmission parameters according to the worst channel of the group members. If this instantaneous error-performance constraint can be relaxed, more spectral efficiency may be exploited in the efficiency-reliability tradeoff. For example, if a given DLL Packet Error Ratio (PER) is demanded from upper layers for a multicast service, such a PER constraint becomes a residual PER constraint after retransmissions in a system with ARQ [3]. Therefore, the instantaneous error-performance limit for the first transmissions may be relaxed if the PHY AMC and DLL ARQ can be jointly designed.

The main problem of applying ARQ to multicast is scalability [4]; assume that the channel fading of each receiver is independent and identically distributed (i.i.d). If the expected average PER for one receiver is P, then in a multicast channel with N receivers, the probability of requesting retransmission for a multicast packet is $1-(1-P)^N$, since any receiver that has lost this packet would request a retransmission. When N is large, retransmissions would be requested frequently, reducing the overall spectral efficiency. For example, with the broadcast/multicast ARQ scheme in

[5], the average throughput per receiver decreases when N increases beyond 10.

Network Coding (NC) is a recent field in information theory which has attracted a lot of research interests. The original idea of NC is to allow the information received from multiple senders to be combined at some intermediate nodes for subsequent transmissions, and the combined information can be extracted separately at different receivers with the help of *a priori* knowledge. The fundamental concept of NC was introduced for satellite communications in [6]. The concept was fully developed in [7] with the formal term *network coding* with analysis based on graph theory. NC has been investigated and widely adopted in wired networks, adhoc networks, and mesh networks, mainly in multihop transmissions and/or routing issues [8–14], but not much in single-hop cellular networks.

Larsson and Johansson had proposed in [15] to use network-coding-based ARQ in multiuser case for multiple unicast links. In [15], the transmitter puts multiple retransmission packets requested by different receivers into one Combined Packet (CP) using network coding and retransmits the CP only. Then, each receiver can extract its own expected retransmitted packet from the CP by performing XOR between the CP and the stored correct packets of other receivers. However, this scheme requires that each receiver overhears the transmissions to other receivers and stores their packets. As a result, the power consumption of each receiver will be significantly increased.

This drawback does not exist in the multicast case. For example, if each of the N receivers of a multicast group has a $1/N$ PER for a given transmission rate, then after N transmission bursts, each receiver will have one packet lost on average. The network-coding-based CP for the $(N+1)$th transmission burst is given by

$$D_{N+1} = D_1 \oplus D_2 \oplus \cdots D_k \oplus \cdots \oplus D_N, \tag{1}$$

where D_k represents the kth multicast data packet, and "$\oplus$" denotes the XOR operation. Consequently, each receiver will be able to extract its lost packet by performing XOR between D_{N+1} and the stored $N-1$ correctly received packets.

A more systematic packet-combining method is the packet level Reed-Solomon coding [16, 17], where K consecutive packets are put into a packet-based encoder, which outputs L $(L > K)$ packets, including the K original packets and $L-K$ parity packets. These L packets are sent as a *Transmission Group (TG)*. Hybrid ARQ (HARQ) schemes based on packet level Reed-Solomon codes were proposed in [18] for downlink multicast in the Universal Mobile Telecommunications Systems (UMTS). It has been concluded in [18] that these proposed HARQ schemes are more robust against an increasing number of multicast users than single-packet ARQ.

A cross-layer design that combines AMC and truncated ARQ protocol was proposed in [3] for unicast links. With only one retransmission, this cross-layer scheme outperforms AMC without ARQ in spectral efficiency by about 0.25 bits/symbol, but more retransmissions provide only diminishing gains. Sun et al. [19] considered an imperfect channel state information and adaptive pilot symbol-assisted modulation in cross-layer combining of ARQ and AMC for unicast links, making the performance analysis more practical.

In order to solve the scalability problem for applying ARQ to mobile multicast, we develop network-coding-based ARQ (NC-ARQ) schemes in which multiple retransmission packets are combined together and propose an AMC scheme being aware of the NC-ARQs. The proposed joint NC-ARQ-AMC strategies are then compared with the existing multicast strategies, such as AMC without ARQ and ARQ-AMC without NC design.

The remainder of the paper is organized as follows. We explain the cross-layer design framework in Section 2. Our multicast NC-ARQ design and the joint NC-ARQ-AMC schemes are proposed in Section 3. The performance evaluation of these schemes is presented in Section 4. Conclusions are given in Section 5.

2. System Model and Forumlation

2.1. System Model. We consider a mobile multicast system with one base station (BS) multicasting to a group of N mobile receivers. The system architecture between the BS and one of the receivers is illustrated in Figure 1.

It is assumed that the BS is equipped with both AMC and ARQ functionalities, which is common in contemporary wireless systems (e.g., UMTS High-Speed Downlink Packet Access (HSDPA), IEEE 802.11 a, b, and g). We also assume that instantaneous and perfect Channel State Information (CSI) is fedback from the mobile receivers to the BS (i.e., the CSI feedback link between the PHY layer of receiver i and the BS in Figure 1), which is a common assumption in the radio resource allocation study for providing broadcast/multicast Service in contemporary cellular systems [20–25]. The work in [20–22] utilizes the channel adaptive video-coding techniques based on the channel quality feedback. In [23], the authors consider sending multiresolution video streams in HSDPA systems based on the user-reported Channel Quality Indicator (CQI) in the uplink. The authors of [25] assumed the 3GPP Long-Term Evolution (LTE) uplinks for Multimedia Broadcast Multicast Service (MBMS) users to report SINR periodically, thereby enabling the RNC to allocate power efficiently and dynamically. Uplink for the ARQ request is also included in our proposed architecture. Though the ARQ may cause feedback explosion problem in multicast, such problem can be solved by setting a short round-trip time delay and adopting appropriate feedback suppression algorithm. That is, ARQ is still feasible for real-time video streaming, as suggested in [18, 26, 27].

The system in Figure 1 works in the following process: based on the CSI reported by all receivers, the AMC selector at the BS determines the AMC mode. A packet from the input buffer is sent to the PHY layer, and a copy of it is stored in the ARQ buffer. Each transmitted data packet includes both error detection (ED) coding and forward error correction (FEC) coding. If an error packet cannot be recovered with FEC decoding at a receiver, an ARQ request will be sent to the ARQ controller at the BS via a feedback channel. The ARQ controller at the BS then arranges retransmission of the requested packet, which is stored in the ARQ buffer. If a certain packet is not requested to be resent by any of the receivers, it will be removed from the ARQ buffer. If a packet is requested by all the receivers, it will be pushed down from the ARQ buffer to the PHY for retransmission immediately.

Constant transmission power is assumed to reduce the cross-layer design complexity. The channels are assumed to be frequency-flat block-fading channels. The Signal-to-Interference-and-Noise-Ratio (SINR) of receiver i (for $i = 1, \dots, N$), denoted by γ_i, does not change during the transmission time of a DLL Packet Data Unit (PDU). The Probability Density Functions (PDFs) of γ_i (for $i = 1, \dots, N$) are independent and identically distributed and are denoted by $p(\gamma_i)$, respectively. The random vector $\overrightarrow{\gamma} := (\gamma_1, \gamma_2, \dots, \gamma_N)$ represents the SINRs of the whole multicast group, with the combined PDF $p^*(\overrightarrow{\gamma}) = \prod_{i=1}^{N} p(\gamma_i)$.

The available modulation and FEC code combinations (referred to as AMC modes) are the same as in the HIPERLAN/2 and IEEE 802.11a standards [28], as shown in Table 1. While the exact closed-form PER expressions for the AMC modes in Table 1 are not available, a tight PER approximation has been provided in [3] as

$$\mathrm{PER}_m(\gamma) \approx \begin{cases} a_m \exp(-g_m \gamma), & \text{if } \gamma \geq \Gamma_m, \\ 1, & \text{if } 0 \leq \gamma < \Gamma_m, \end{cases} \tag{2}$$

where m is the index of the AMC modes ($m \in \{1, \dots, M\}$, and M is the total number of AMC modes); γ is the SINR of a receiver; a_m and g_m are parameters that depend on m, which are obtained by fitting (2) to the exact PER curves [3]; Γ_m is the mth SINR threshold, that is, in a typical unicast AMC scheme,

$$\text{AMC mode } m \text{ is chosen, given } \gamma \in [\Gamma_{\mathrm{m}}, \Gamma_{\mathrm{m+1}}). \tag{3}$$

The values of Γ_m (for $m = 1, \dots, M$) may vary according to the target packet loss ratio P_{loss}, and the SINR distribution $p^*(\overrightarrow{\gamma})$.

2.2. Problem Formulation. The optimization target is to maximize the average spectral efficiency per multicast receiver, subject to the following constraints.

(1) *Constraint 1.* The maximum allowed number of retransmissions for each packet is $T_r^{\max}$.

In a practical system, the number of retransmissions has to be limited due to the delay constraints. In this work, $T_r^{\max}$ is set to 1, since the results in [3] have shown that the spectral efficiency gain from cross-layer ARQ diminishes with $T_r^{\max} > 1$.

(2) *Constraint 2.* The residual PER after $T_r^{\max}$ retransmissions is no greater than P_{loss}.

For video transmissions, though it is hard to map the required BER bounds directly to PER bounds for coded transmissions, P_{loss} has been suggested to be between .1 and 0.001 [3]. Without loss of generality, in the performance analysis hereafter, we set $P_{\mathrm{loss}} = .01$.

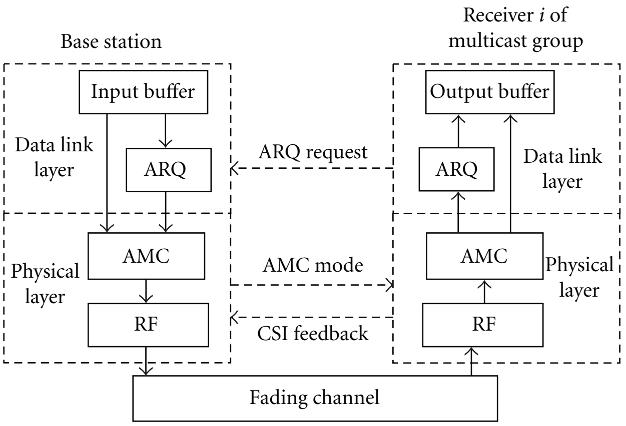

Figure 1: Multicast system model.

For unicast transmissions without ARQ, the AMC thresholds can be derived from (2) as

$$\Gamma_m = \frac{1}{g_m} \ln\left(\frac{a_m}{P_{\mathrm{loss}}}\right). \tag{4}$$

If ARQ is used in the unicast transmissions, set the instantaneous PER constraint for the AMC mode selection as P_0, and $\mathrm{PER}_{T_r^{\max}+1}$ represent the residual packet loss ratio after one original transmission plus $T_r^{\max}$ retransmissions for a specific packet, then *Constraint 2* leads to

$$\mathrm{PER}_{T_r^{\max}+1} \leq {P_0}^{T_r^{\max}+1} \leq P_{\mathrm{loss}}. \tag{5}$$

In this case, the AMC thresholds can be rewritten as

$$\Gamma'_m = \frac{1}{g_m} \ln\left(\frac{a_m}{P_0}\right). \tag{6}$$

Since $0 < P_0 < 1$ and $0 < P_{\mathrm{loss}} < 1 \Rightarrow P_0 > P_{\mathrm{loss}}$, we have $\Gamma'_m < \Gamma_m$, which indicates that higher data rates can be allocated under the threshold Γ'_m than under Γ_m. To exploit this benefit, we set

$$P_0 := {P_{\mathrm{loss}}}^{1/(T_r^{\max}+1)}. \tag{7}$$

The expected spectral efficiency on the transmitter side is the instantaneous spectral efficiency averaged over all possible SINR states and is given by

$$\mathrm{SE}_{Tx} = \sum_{m=1}^{M} R_m P_r(m), \tag{8}$$

where SE_{Tx} is the expected spectral efficiency at the transmitter; R_m is the number of bits per symbol in the mth AMC mode; $P_r(m)$ is the probability of $\overrightarrow{\gamma}$ staying in the mth SINR state. At the receiver side, the expected spectral efficiency SE_{Rx} is affected by the PER of each SINR state. If *Constraint 2* on P_{loss} is guaranteed, there should be

$$\mathrm{SE}_{Rx} \geq \mathrm{SE}_{Tx} \cdot (1 - P_{\mathrm{loss}}). \tag{9}$$

Table 1: Transmission AMC modes with convolutional-coded modulation [28].

Modulation	Mode 1 BPSK	Mode 2 QPSK	Mode 3 QPSK	Mode 4 16-QAM	Mode 5 16-QAM	Mode 6 64-QAM
Coding rate	1/2	1/2	3/4	9/16	3/4	3/4
Rate (bits/symbol)	0.5	1.0	1.5	2.25	3.0	4.5
a_m	274.7229	90.2514	67.6181	50.1222	53.3987	35.3508
g_m	7.9932	3.4998	1.6883	0.6644	0.3756	0.0900

Therefore, we take SE_{Tx} as the optimization target for simplicity and refer to it as SE hereafter. Whether the SINR threshold relaxation in (6) will lead to higher spectral efficiency or not depends on the comparison between

$$\mathrm{SE}(1) = \sum_{m=1}^{M} R_m P_r(m), \tag{10}$$

$$\mathrm{SE}(T_r^{\max} + 1) = \frac{1}{E[T]} \sum_{m=1}^{M} R_m P_r'(m). \tag{11}$$

where SE(1) is the spectral efficiency without retransmission; $\mathrm{SE}(T_r^{\max} + 1)$ is the one with at most $T_r^{\max}$ retransmissions; $P_r(m)$ is the probability of $\gamma \in [\Gamma_m, \Gamma_{m+1})$; $P_r'(m)$ is the probability of $\gamma \in [\Gamma_m', \Gamma_{m+1}')$; $E[T]$ is the expected number of transmissions per packet. The general form of $E[T]$ is given by

$$E[T] = 1 + P + P^2 + \cdots + P^{T_r^{\max}}. \tag{12}$$

In the special case $T_r^{\max} = 1$, $E[T] = 1 + P$ under *Constraint 1*. For a given SINR distribution, if $\mathrm{SE}(T_r^{\max} + 1) > \mathrm{SE}(1)$, then cross-layer AMC offers improved spectral efficiency at the cost of possibly longer packet delays.

3. Joint NC-ARQ-AMC Design

3.1. Network-Coding-Based ARQ. We analyze our multicast ARQ design in two phases which are the original data transmission phase and the retransmission phase, namely, the first phase and the second phase, respectively. In the first phase, a large number of data packets are transmitted, that are sufficient for probabilistic analysis of packet loss ratio. The packet loss of each User Equipment (UE) in the first phase will be reported to the BS. In the second phase, the BS selects the most efficient way to combine *multiple lost packets* into a CP using *XOR* operations and sends the CP. This ARQ method is named as *Network-Coding-based ARQ* (NC-ARQ).

In our proposed NC-ARQ scheme, if a packet is received correctly by all users (i.e., $L = 0$, where L is the number of users who lose the packet), it is removed from the ARQ buffer. If a packet is lost by all users ($L = N$), it will be retransmitted immediately and removed from the ARQ buffer. If a packet is lost by n users ($L = n,\ 1 \le n \le N - 1$), then it will be kept in the ARQ buffer to be combined with other lost packets into a CP for retransmission. Packets that can be combined into one CP are to be *match packets* to one another. As the number of packets in the ARQ buffer increases, the BS transmitter will find match packets for the first packet in the queue, combine them into a CP, and remove these packets once the CP is sent. There are two lemmas for the network-coding process:

Lemma 1. *For an arbitrary packet D_k, its match packets exist if and only if $1 \le L(D_k) \le N - 1$ (assuming an infinitely large ARQ buffer), and its match packets are not unique.*

Lemma 2. *A subset of lost packets $\{D_1', \ldots, D_k', \ldots,\}$ can form a CP if and only if $1 \le L(D_k') \le N - 1$ for each D_k' and $L(D_1') + \cdots + L(D_k') + \cdots \le N$, and each multicast receiver has at most one lost packet in this subset of packets.*

Let $\Pr(L)$ denote the probability of L users losing an arbitrary packet, and $\eta(L)$ represent the expected number of retransmissions, then the expressions of $\Pr(L)$ and $\eta(L)$ corresponding to the three packet-loss cases described above given by the following.

Case 1. $L = 0$,

$$\begin{aligned} \Pr(L = 0) &= (1 - P)^N, \\ \eta(L = 0) &= 0. \end{aligned} \tag{13}$$

Case 2. $L = N$,

$$\begin{aligned} \Pr(L = N) &= P^N, \\ \eta(L = N) &= 1. \end{aligned} \tag{14}$$

Case 3. $L = n, (1 \le n < N)$,

$$\begin{aligned} \Pr(L = n) &= \binom{N}{n} P^n (1 - P)^{N-n}, \\ \eta(L = n) &= \frac{1}{(\text{Number of data packets per CP})}. \end{aligned} \tag{15}$$

3.2. Opt-ARQ and SubOpt-ARQ. Since the match packets for a lost packet are not unique, we propose the optimal NC-ARQ scheme and one suboptimal scheme for selecting and combining retransmission packets into CPs.

3.2.1. Optimal Network-Coding-Based ARQ (Opt-ARQ). For the first packet in the ARQ buffer with $L = n$, the most efficient approach is to select $N - n$ lost packets from the rest of the buffer, each of which was lost by only one user. According to the definition of η, this approach minimizes

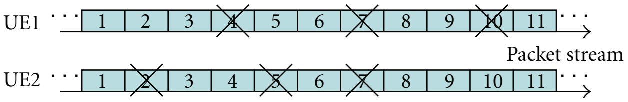

Figure 2: Multicast packet-loss pattern for 2 UEs.

η and $E[T]$, so as to maximize $\mathrm{SE}(T_r^{\max}+1)$ in (11). This selected subset of lost packets form an *optimal combination set*, with

$$\begin{aligned}\eta(L=n) &= \frac{1}{N-n+1},\\ E[T]_{\mathrm{opt}} &= 1+\sum_{n=1}^{N}\eta(L=n)\Pr(L=n)\\ &= 1+\sum_{n=1}^{N}\frac{1}{N-n+1}\binom{N}{n}P^n(1-P)^{N-n}.\end{aligned} \tag{16}$$

3.2.2. Suboptimal Network-Coding-Based ARQ (SubOpt-ARQ). It may take long to wait until all $N-n$ match packets for the *optimal combination set* appear in the ARQ buffer. Hence, we also propose a suboptimal combination scheme, where a lost packet with $L=n$ only needs to be combined with another lost packet with $L=n'$, as long as $n+n'\le N$ and the two lost packets are not lost by the same user. Consequently,

$$\begin{aligned}\eta(L=n) &= \frac{1}{2},\\ E[T]_{\mathrm{SubOpt}} &= 1+P^N+\frac{1}{2}\sum_{n=1}^{N-1}\binom{N}{n}P^n(1-P)^{N-n}.\end{aligned} \tag{17}$$

3.3. Special Case: $N=2$. In this subsection, we give an example of the proposed NC-ARQ in a special case where the number of multicast group members is $N=2$, in which the SubOpt-ARQ is the same as the Opt-ARQ.

In a multicast group with two receivers, UE1 and UE2, a packet-loss pattern in the first phase is illustrated in Figure 2. For data packets D_2, D_4, D_5, and D_{10}, each is lost only by one user; the BS can combine two of these lost packets into the CPs as long as they are not lost by the same user, for example, $\mathrm{CP}_1 = D_2 \oplus D_4$, $\mathrm{CP}_2 = D_5 \oplus D_{10}$. By using previously correctly received packets, UE1 can get D_4 from $D_2 \oplus \mathrm{CP}_1 = D_4$, and UE2 can obtain D_2 from $D_4 \oplus \mathrm{CP}_1 = D_2$. For D_7, since both users lost it, it cannot be combined with any other lost data packet in the retransmission; otherwise, there will be at least one user who cannot detect it. For an arbitrary packet, the number of transmissions per packet when NC-ARQ is adopted is given by

$$T = 1+\eta(L=n), \tag{18}$$

where $n = 1, 2$, $\eta(L=1)=1/2$, and $T=3/2$ for packets D_2, D_4, D_5, and D_{10} while $\eta(L=2)=1$ and $T=2$ for packet D_7.

The expected number of transmissions for an arbitrary packet is given by

$$E[T] = 1+\sum_{n=1}^{2}\eta(L=n)\Pr(L=n). \tag{19}$$

3.4. AMC Design. With the help of ARQ, the instantaneous PER constraint of the worst-channel receiver can be temporarily violated, and the lost packets of the worst-channel receiver can be retransmitted to keep its residual PER below P_{loss}. Thus, we propose an Average PER-based AMC (AvgPER-AMC) scheme to be implemented with the NC-ARQ.

The data rate is chosen such that the corresponding average PER of all multicast group members is the closest to the instantaneous PER constraint P_0.

```
for all AMC mode $m \in \{1, \ldots, M\}$ do
    $\overline{\mathrm{PER}}_m = \frac{1}{N}\sum_{i=1}^{N}\mathrm{PER}_m(\gamma_i)$
    (where $\mathrm{PER}_m(\gamma_i)$ is given in (2))
end for
if $m_{\mathrm{opt}} = \arg\min_{m}|\overline{\mathrm{PER}}_m - P_0|$ then
    AMC mode $m_{\mathrm{opt}}$ is chosen
end if
```

The idea behind this design is that the AMC mode chosen should make the resulting average PER of all receivers as close to P_0 as possible. If the average PER of all receivers is much less than P_0, then the selected AMC mode does not fully exploit the channel capacity; if the average PER is much higher than P_0, the number of receivers that lose packets during each transmission is large, making it hard to find match packets that satisfy Lemma 2, and the advantage of using NC-ARQ in spectral efficiency will be lost.

The above proposed AMC scheme is combined with our NC-ARQ schemes to form two joint NC-ARQ-AMC algorithms, which are

1. AvgPER-AMC with Opt-ARQ, and
2. AvgPER-AMC with SubOpt-ARQ.

4. Performance Evaluation

In this section, the performance of the proposed two joint NC-ARQ-AMC schemes are compared with two typical link adaptation strategies: Minimum SINR AMC (Min-AMC) combined with and without single-packet ARQ (Single-packet ARQ refers to the ARQ without NC design.). In Min-AMC, the data rate has to satisfy the instantaneous PER constraint of the worst SINR receiver, that is,

$$\text{AMC mode } m \text{ is chosen if} \min\{\gamma_1, \gamma_2, \ldots, \gamma_N\} \in [\Gamma_m, \Gamma_{m+1}) \tag{20}$$

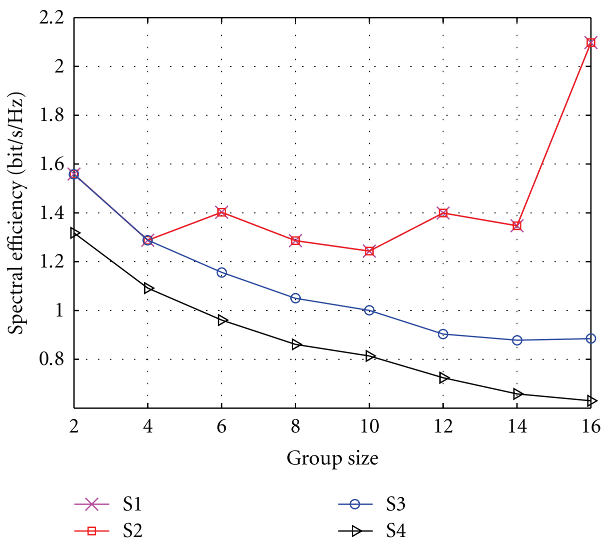

Figure 3: Spectral efficiency of the first transmission.

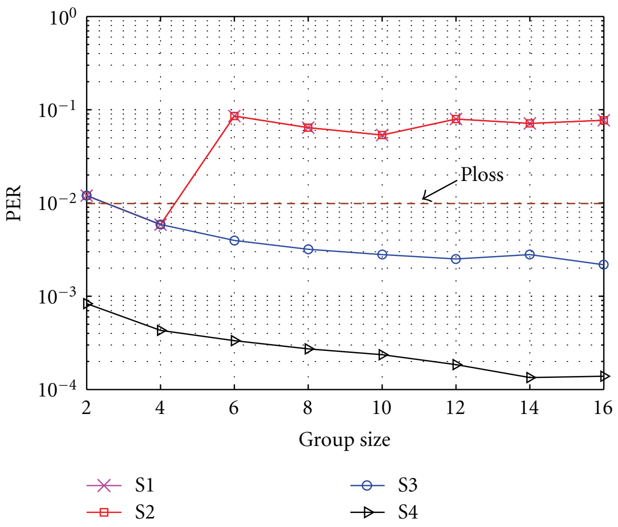

Figure 4: Packet error ratio of the first transmission.

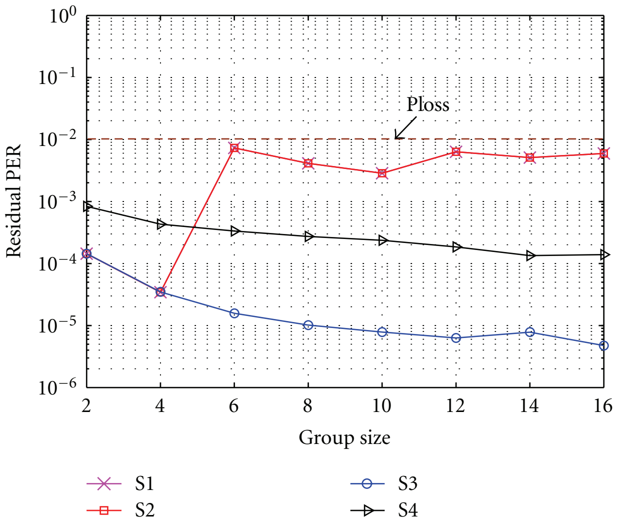

Figure 5: Residual packet error ratio.

For notational convenience, we label the four different schemes included in the performance comparisons as S1 to S4, respectively, as follows:

(i) S1: AvgPER-AMC with Opt-ARQ,

(ii) S2: AvgPER-AMC with SubOpt-ARQ,

(iii) S3: Min-AMC with single-packet ARQ,

(iv) S4: Min-AMC without ARQ.

The Monte-Carlo method is adopted to numerically evaluate the performance of different ARQ-AMC strategies under Rayleigh fading channels, with the average SINR set to 10dB. For the implementation of the AMC schemes, we set

$$P_0 = \begin{cases} P_{\text{loss}}^{1/2}, & \text{when ARQ is adopted, for S1, S2, and S3,} \\ P_{\text{loss}}, & \text{otherwise, for S4.} \end{cases} \tag{21}$$

The spectral efficiencies of the first transmission stage are depicted in Figure 3, and the PERs of the first transmission are presented in Figure 4.

After the retransmissions, the residual PERs are shown in Figure 5. Figure 6 illustrates the overall spectral efficiencies.

In Figure 3, it can be observed that S1 and S2 achieve the best spectral efficiencies in the first transmission stage, since they are not limited by the receiver with the worst SINR. The spectral efficiency of S3 is higher than that of S4, because S4 has a much more stringent P_0 according to (21). S1 and S2 outperform S3 when $N > 4$, and the performance gain increases as the group size gets larger, from about 0.2 bit/s/Hz at $N = 6$ to 1.4 bits/s/Hz at $N = 16$. The reason is that, as the group size increases for the AvgPER-AMC, there is a higher probability that the worst PER can be averaged out by the PERs of other group members, so that the average PER of the whole multicast group allows a higher rate assignment. When $N \leq 4$, the spectral efficiencies of S1 and S2 before ARQ are almost the same as S3. This is because the group size is too small and the worst PER caused by the minimum SINR receiver dominates the rate assignment.

From Figure 4, we can see that S1 and S2 exploit the efficiency-reliability tradeoff extensively, where the PERs of them are close to 10^{-1} (i.e., the value of their P_0) when $N > 4$. On the other hand, $\text{PER}_{S3} < 10^{-2}$ while $P_{S3} = 10^{-1}$, and $\text{PER}_{S4} < 10^{-3}$ while $P_{S4} = 10^{-2}$, indicating that S3 and S4 achieve much higher reliability than that required but lose spectral efficiency.

This phenomenon can also be observed in Figure 5, where the residual PERs of S1 and S2 are within and close to the P_{loss} constraint when $N > 4$, while the residual PERs of S3 and S4 are much lower than it.

Figure 6 shows that S1 is the best scheme in terms of overall spectral efficiency after retransmissions. S1 outperforms S2 by up to 0.44 bit/s/Hz when $N = 16$. This

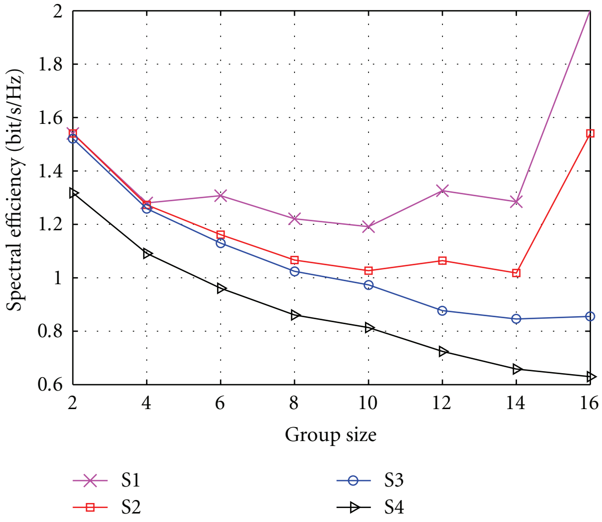

Figure 6: Overall spectral efficiency of ARQ-AMC schemes versus group sizes.

performance advantage of S1 over S2 is because Opt-ARQ is much more efficient than SubOpt-ARQ in retransmissions of lost packets. Even the advantage of AMC with single-packet ARQ over that without ARQ in multicast is also significant.

Comparing S3 and S4 in Figure 6, both of which adopt Min-AMC, we can see that S3 always outperforms S4 by 0.2 to 0.24 bit/s/Hz in its overall spectral efficiency. From Figure 3 to Figure 6, we can conclude that S1 and S2 favor a large group size, because they exploit the user diversity in their SINRs and corresponding PERs.

Last but not least, we have assumed that perfect and instantaneous CSI feedbacks are available for the AMC function in the BS. In reality, the CSI feedbacks must be delayed and may include errors. There could also be scalability problems with the CSI feedbacks when the group size is large. That is, the spectral efficiencies of the proposed joint NC-ARQ-AMC schemes are expected to decrease with imperfect CSIs as compared to the current results with perfect CSIs.

It has also been assumed that PDU-level feedbacks are available for the ARQ function in the BS. Since feedbacks for the ARQ function are simply ACK/NACK messages, which require rather low data rates and can be transmitted with the most robust AMC mode, it is reasonable to assume correct PDU-level feedbacks unless the feedback channel is in temporarily deep fading.

5. Conclusion and Future Work

In this paper, we have proposed an innovative Network-Coding-based ARQ approach for mobile multicast in its optimal and suboptimal forms, which are named as Opt-ARQ and SubOpt-ARQ, respectively. This approach utilizes the network coding of PDUs to reduce the number of retransmissions in order to solve the scalability problem of multicast ARQs. We adopt the proposed Opt-ARQ and SubOpt-ARQ in a cross-layer design framework, which allows the instantaneous PER constraint to be relaxed and the spectral efficiency to be improved. An average-PER-based (averaged over instantaneous PERs of all group members) rate adaptation algorithm has also been developed within this cross-layer framework and is then combined with the proposed Network-Coding-based ARQ schemes. Numerical evaluation of the algorithms has shown that the proposed joint NC-ARQ-AMC schemes with cross-layer design can achieve significant gains in average spectral efficiency for multicast groups of different sizes, while keeping the residual PER constraint inviolate.

In the downlink of a cellular network, SubOpt-ARQ might be preferred to Opt-ARQ, since it should introduce less delay, as explained in Section 3.2. Our results have shown that the spectral efficiency advantage of AvgPER-AMC with SubOpt-ARQ over Min-AMC with single-packet ARQ is still significant. In our future work, a detailed delay analysis for the proposed joint NC-ARQ and AMC schemes is planned.

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References

[1] H. Wang, H. P. Schwefel, and T. S. Toftegaard, "History-based adaptive modulation for a downlink Multicast channel in OFDMA systems," in *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC '08)*, pp. 1588–1592, March 2008.

[2] H. Wang, H. P. Schwefel, and T. S. Toftegaard, "The optimal joint power and rate adaptation for mobile multicast: a theoretical approach," in *Proceedings of the IEEE Sarnoff Symposium (SARNOFF '08)*, Princeton, NJ, USA, April 2008.

[3] Q. Liu, S. Zhou, and G. B. Giannakis, "Cross-layer combining of adaptive modulation and Coding with truncated ARQ over wireless links," *IEEE Transactions on Wireless Communications*, vol. 3, no. 5, pp. 1746–1755, 2004.

[4] S. Sesia, G. Caire, and G. Vivier, "On the scalability of H-ARQ systems in wireless multicast," in *Proceedings of the IEEE International Symposium on Information Theory (ISIT '04)*, pp. 321–321, 2004.

[5] J. Peng, "A new ARQ scheme for reliable broadcasting in wireless LANs," *IEEE Communications Letters*, vol. 12, no. 2, pp. 146–148, 2008.

[6] R. W. Yeung and Z. Zhang, "Distributed source coding for satellite communications," *IEEE Transactions on Information Theory*, vol. 45, no. 4, pp. 1111–1120, 1999.

[7] R. Ahlswede, N. Cai, S.-Y. R. Li, and R. W. Yeung, "Network information flow," *IEEE Transactions on Information Theory*, vol. 46, no. 4, pp. 1204–1216, 2000.

[8] Y. Wu, P. A. Chou, and S. Y. Kung, "Information exchange in wireless networks with network coding and physical-layer broadcast," in *Proceedings of the 39th Annual Conference on Information Sciences and Systems (CISS '05)*, Baltimore, Md, USA, March 2005.

[9] C. Fragouli, J.-Y. Le Boudec, and J. Widmer, "Network coding: an instant primer," *ACM SIGCOMM Computer Communication Review*, vol. 36, no. 1, pp. 63–68, 2006.

[10] S. Katti, H. Rahul, W. Hu, D. Katabi, M. Médard, and J. Crowcroft, "XORs in the air: practical wireless network coding," in *Proceedings of the IEEE Conference on Applications, Technologies, Architectures, and Protocols for Computer Communications (SIGCOMM '06)*, pp. 243–254, Pisa, Italy, September 2006.

[11] S. Sengupta, S. Rayanchu, and S. Banerjee, "An analysis of wireless network coding for unicast sessions: the case for coding-aware routing," in *Proceedings of the 26th IEEE International Conference on Computer Communications (INFOCOM '07)*, pp. 1028–1036, Anchorage, Alaska, USA, May 2007.

[12] C. Fragouli, J. Widmer, and J.-Y. Le Boudec, "A network coding approach to energy efficient broadcasting: from theory to practice," in *Proceedings of the 25th IEEE International Conference on Computer Communications (INFOCOM '06)*, Barcelona, Spain, April 2006.

[13] J. Widmer, C. Fragouli, and J. Y. LeBoudec, "Low-complexity energy efficient broadcasting in wireless ad hoc networks using network coding," in *Proceedings of the 1st Workshop on Network Coding, Theory, and Applications (NetCod '05)*, Riva del Garda, Italy, April 2005.

[14] J. Widmer and J.-Y. Le Boudec, "Network coding for efficient communication in extreme networks," in *Proceedings of the Workshop on Delay Tolerant Networking and Related Networks (WDTN '05)*, pp. 284–291, Philadelphia, Pa, USA, August 2005.

[15] P. Larsson and N. Johansson, "Multi-user ARQ," in *Proceedings of the IEEE 63rd Vehicular Technology Conference (VTC '06)*, Melbourne, Australia, May 2006.

[16] C. Huitema, "The case for packet level FEC," in *Proceedings of the IFIP 5th International Workshop on Protocols for High Speed Networks (PsHSN '96)*, Inria, France, October 1996.

[17] J. Nonnenmacher, E. W. Biersack, and D. Towsley, "Parity-based loss recovery for reliable multicast transmission," *IEEE/ACM Transactions on Networking*, vol. 6, no. 4, pp. 349–361, 1998.

[18] F. Fitzek, M. Rossi, and M. Zorzi, "Error control techniques for efficient multicast streaming in UMTS networks," in *Proceedings of the Systemics, Cybernetics and Informatics (SCI '03)*, Orlando, Florida, USA, 2003.

[19] S. Jun, Y. Dongfeng, and T. Mathiopoulos, "Adaptive PSAM in cross-layer combining of AMC and ARQ," in *Proceedings of the 1st International Workshop on Cross Layer Design (IWCLD '07)*, pp. 125–128, Jinan, China, September 2007.

[20] B. Girod, J. Chakareski, M. Kalman, Y. J. Liang, E. Setton, and R. Zhang, "Advances in network-adaptive video streaming," *Wireless Communications and Mobile Computing*, vol. 2, no. 6, pp. 549–552, 2004.

[21] U. Horn, K. Stuhlmüller, M. Link, and B. Girod, "Robust internet video transmission based on scalable coding and unequal error protection," *Signal Processing: Image Communication*, vol. 15, no. 1, pp. 77–94, 1999.

[22] T. Stockhammer, H. Jenkač, and C. Weiß, "Feedback and error protection strategies for wireless progressive video transmission," *IEEE Transactions on Circuits and Systems for Video Technology*, vol. 12, no. 6, pp. 465–482, 2002.

[23] A. M. C. Correia, J. C. M. Silva, N. M. B. Souto, L. A. C. Silva, A. B. Boal, and A. B. Soares, "Multi-resolution broadcast/multicast systems for MBMS," *IEEE Transactions on Broadcasting*, vol. 53, no. 1, pp. 224–233, 2007.

[24] C. Suh and J. Mo, "Resource allocation for multicast services in multicarrier wireless communications," *IEEE Transactions on Wireless Communications*, vol. 7, no. 1, pp. 27–31, 2008.

[25] A. Alexiou, C. Bouras, V. Kokkinos, and E. Rekkas, "Optimal MBMS power allocation exploiting MIMO in LTE networks," in *Proceedings of the IEEE 69th Vehicular Technology Conference (VTC '09)*, pp. 1–6, April 2009.

[26] G. D. Papadopoulos, G. Koltsidas, and F.-N. Pavlidou, "Two hybrid ARQ algorithms for reliable multicast communications in UMTS networks," *IEEE Communications Letters*, vol. 10, no. 4, pp. 260–262, 2006.

[27] S. Makharia, D. Raychaudhuri, M. Wu, H. Liu, and D. Li, "Experimental study on wireless multicast scalability using merged hybrid ARQ with staggered adaptive FEC," in *Proceedings of the IEEE International Symposium on Wireless, Mobile and Multimedia Networks (WoWMoM '08)*, pp. 1–12, June 2008.

[28] A. Doufexi, S. Armour, M. Butler et al., "A comparison of the HIPERLAN/2 and IEEE 802.11a wireless LAN standards," *IEEE Communications Magazine*, vol. 40, no. 5, pp. 172–180, 2002.