MCS Level Selection Methods for Cross-Layered Retransmission in Wireless Networks

by

Kwang-Chun Go

Department of Electrical and Computer Engineering
Graduate School
Ajou University
August, 2015
MCS Level Selection Methods for Cross-Layered Retransmission in Wireless Networks

Principal Advisor: Jae-Hyun Kim

by

Kwang-Chun Go

A Dissertation Submitted to the Graduate School
of Ajou University
in Partial Fulfillment of the Requirements for the Degree of
Doctor of Philosophy

Department of Electrical and Computer Engineering
Graduate School
Ajou University

August, 2015
The doctoral dissertation of Kwang-Chun Go is hereby approved.

Young-Kil Kim, Ph.D.

Byeong-hee Roh, Ph.D.

Sunghyun Cho, Ph.D.

Young-June Choi, Ph.D.

Jae-Hyun Kim, Ph.D. (Principal Advisor)

Graduate School
Ajou University
June 16th, 2015
Abstract

Various retransmission schemes for wireless communication systems have been used to improve performance such as reliability and throughput. Each retransmission scheme is designed to improve the performance according to characteristics of each layer of protocol stacks, such as delay components and error control. Recently, related works exploit the concept of cross-layered design to improve the data transmission performance. The cross-layered retransmission scheme is designed for performance improvement at the wireless access networks. Especially, a cross-layered retransmission scheme has been proposed to maximize the spectral efficiency by combining a retransmission scheme and adaptive modulation and coding (AMC). However, the previous works have not account the end-to-end performance between end-terminals such as user equipment (UE) and application server. Therefore, this dissertation presents advanced cross-layered retransmission schemes considering the end-to-end performance for improving user-perceived performance and wireless resource efficiency.
The first proposed cross-layered retransmission scheme is an application-aware modulation and coding scheme (MCS) level selection method. The application-aware MCS level selection method selects an MCS level depending on the service characteristics. The proposed method adjusts a target PER according to the type of application. To adopt different target PER according to service type, the target PER is derived by using the target packet loss rate (PLR) at the application layer. Simulation results show that the proposed method improves the efficiency of the wireless channel resource in comparison with an existing cross-layered retransmission scheme.

The second proposed cross-layered retransmission scheme is novel MCS level selection method considering the throughput at the transport layer to improve the end-to-end performance. To obtain the end-to-end performance, the analytical model of the delay and the throughput at the transport layer are derived when a system uses a cross-layered retransmission scheme and the TCP as the reliable transmission protocols. The proposed method adopts new criteria for MCS level selection by considering the end-to-end performance. The results of numerical simulations show that the proposed method
improves the throughput at the transport layer as compared with existing ones. This verifies that the existing methods for maximizing wireless channel utilization may be inefficient in terms of the throughput at the transport layer.
Contents

List of Figures xi
List of Tables xiii
Abbreviation xiv

1 Introduction 1
  1.1 Background and Motivation 1
  1.2 Characteristics of Service Classes 4
  1.3 Performance at the Transport Layer 4
  1.4 Contributions 5

2 Related Work 9
  2.1 Adaptive Modulation and Coding 9
  2.2 Retransmission Schemes 13
  2.3 Cross-layered Retransmission Schemes 21

3 Application-aware MCS level selection scheme 27
  3.1 Motivation 27
5 Conclusion

References
## List of Figures

1.1 Overall concept of proposed schemes .................. 6

2.1 MCS level selection procedure of AMC ................. 10

2.2 PER of MCS level ....................................... 11

2.3 Stop-and-wait ARQ ....................................... 14

2.4 Go-back-N ARQ ........................................... 15

2.5 Selective repeat ARQ ..................................... 15

2.6 HARQ Type I ............................................... 16

2.7 HARQ Type II .............................................. 17

2.8 HARQ Type III ............................................. 17

2.9 Congestion window size of TCP Tahoe .................... 19

2.10 Congestion window size of TCP Reno ..................... 20

2.11 System model of the AMC combined with ARQ ........ 23

2.12 System model of the AMC combined with HARQ ....... 24

3.1 Cross layer structure .................................... 29

3.2 MCS level selection procedure of AMS scheme ....... 39

3.3 Average spectral efficiency in AH ...................... 48
List of Tables

1.1 QoS requirements for each service class . . . . . . . . . . 2

2.1 MCS levels in LTE system . . . . . . . . . . . . . . . . . 12

3.1 MCS level parameters for HARQ . . . . . . . . . . . . . 31

3.2 MCS level parameters for ARQ . . . . . . . . . . . . . . 32

3.3 Parameters related to QoS . . . . . . . . . . . . . . . . . . 38

3.4 QCI mapping table in 3GPP LTE . . . . . . . . . . . . . 41

3.5 QoS Requirements . . . . . . . . . . . . . . . . . . . . . . . 45

3.6 System Parameters . . . . . . . . . . . . . . . . . . . . . . . 46

3.7 Minimum SNR boundary . . . . . . . . . . . . . . . . . . . 51

3.8 Trade-off of performance in AMS . . . . . . . . . . . . . 58

4.1 Minimum SNR boundary for packet retransmission . . . 73

4.2 MCS level selection scheme according to service character-

istics . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 95

4.3 Trade-off of performance in TMS . . . . . . . . . . . . . 100
Abbreviation

3GPP 3rd generation partnership project
AA AMC combined with ARQ
AB AMC combined with both HARQ and ARQ
ACK acknowledgement
AH AMC combined with HARQ
AMC adaptive modulation and coding
AMS application-aware MCS level selection
ARQ automatic repeat request
BER bit error rate
BPSK binary phase shift keying
BS base station
CQI channel quality indicator
CRC cyclic redundancy checking
CSI  channel state information

dB  decibel

DTMC  discrete time markov chain

EM  existing method

FEC  forward error correction

FER  frame error rate

FTP  file transfer protocol

GBR  guaranteed bit rate

HARQ  hybrid automatic repeat request

IMS  IP multimedia subsystem

IP  internet protocol

ITU  international telecommunication union

ITU-T  ITU-telecommunication standardization sector

LDPC  low-density parity-check

LTE  long term evolution

LTE-A  LTE-advanced

MAC  medium access control

MCS  modulation and coding scheme

MIMO  multiple-input multiple-output
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS</td>
<td>mobile station</td>
</tr>
<tr>
<td>ms</td>
<td>millisecond</td>
</tr>
<tr>
<td>PDU</td>
<td>protocol data unit</td>
</tr>
<tr>
<td>PELR</td>
<td>packet error loss rate</td>
</tr>
<tr>
<td>PER</td>
<td>packet error rate</td>
</tr>
<tr>
<td>PHY</td>
<td>physical</td>
</tr>
<tr>
<td>PM</td>
<td>proposed method</td>
</tr>
<tr>
<td>QAM</td>
<td>quadrature amplitude modulation</td>
</tr>
<tr>
<td>QCI</td>
<td>QoS class identifier</td>
</tr>
<tr>
<td>QoS</td>
<td>quality of service</td>
</tr>
<tr>
<td>QPSK</td>
<td>quadrature phase shift keying</td>
</tr>
<tr>
<td>RLS</td>
<td>radio link control</td>
</tr>
<tr>
<td>RTT</td>
<td>round trip time</td>
</tr>
<tr>
<td>SNR</td>
<td>signal-to-noise ratio</td>
</tr>
<tr>
<td>TCP</td>
<td>transmission control protocol</td>
</tr>
<tr>
<td>TMS</td>
<td>TCP performance-aware MCS level selection</td>
</tr>
<tr>
<td>TTI</td>
<td>transmission time interval</td>
</tr>
</tbody>
</table>
1

Introduction

1.1 Background and Motivation

In the wireless communication networks, different types of services are available. Each service class is mapped to the QoS requirements according to their characteristics. In the 3GPP LTE system, service types are classified according to minimum service requirements of services [1]. The minimum service requirements for each service class are defined by packet delay budget and packet error loss rate between end terminals. Table 1.1 represents the QoS requirements for each service class based on packet delay budget and packet error loss rate between end terminals. For example, the class 6 includes the TCP-based services and the Buffered video streaming which are characterized by 300 ms of packet delay budget and packet error loss rate of $10^{-6}$.
<table>
<thead>
<tr>
<th>Resource Type</th>
<th>Priority</th>
<th>Packet Delay Budget</th>
<th>Packet Error Loss Rate</th>
<th>Example Services</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guaranteed Bit Rate</td>
<td>2</td>
<td>100 ms</td>
<td>$10^{-2}$</td>
<td>Conversational Voice</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>150 ms</td>
<td>$10^{-3}$</td>
<td>Conversational Video (Live Streaming)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>50 ms</td>
<td>$10^{-3}$</td>
<td>Real Time Gaming</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>300 ms</td>
<td>$10^{-6}$</td>
<td>Non-Conversational Video (Buffered Streaming)</td>
</tr>
<tr>
<td>Non-GBR</td>
<td>1</td>
<td>100 ms</td>
<td>$10^{-6}$</td>
<td>IMS Signalling</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>300 ms</td>
<td>$10^{-6}$</td>
<td>Video (Buffered Streaming) TCP-based (e.g., www, e-mail, ftp, progressive video, etc)</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>100 ms</td>
<td>$10^{-3}$</td>
<td>Voice Video (Live Streaming) Interactive Gaming</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>300 ms</td>
<td>$10^{-6}$</td>
<td>Video (Buffered Streaming) TCP-based (e.g., www, e-mail, ftp, progressive video, etc)</td>
</tr>
</tbody>
</table>
To meet the QoS requirements of users, it is important to improve the efficiency and reliability of packet transmission, and so far, various methods have been proposed for this purpose. Initially, several retransmission schemes have been taken into account to recover a erroneous packet [2, 3]. However, these retransmission schemes are insufficient to improve the transmission efficiency over a wireless channel. To enhance the transmission efficiency, the cross-layered retransmission schemes have been proposed [4–12]. One of a kind of cross-layered retransmission scheme is a retransmission scheme combined with AMC.

In many recent studies, the authors focused on cross-layer design in order to improve the performance of retransmission schemes [4–12]. Cross-layer design allows protocol layers to interact with each other and share information. In particular, in many previous studies cross-layer retransmission schemes that combine a retransmission scheme at the data link layer and AMC at the PHY layer were proposed [4, 5, 8–10]. The authors of [4] and [5] presented an analytical model of the spectral efficiency and PER. Their results showed that cross-layered retransmission schemes achieve a better performance than does a retransmission scheme or AMC because they improve the spectral efficiency and PER by exploiting the adaptability of AMC to the wireless channel conditions and the error-correcting capability of retransmission schemes.

However, the existing cross-layered retransmission schemes focused on the wireless channel state rather than service types and end-to-end performance. Therefore, to improve the end-to-end performance, a study of cross-layered retransmission schemes is necessary.
1.2 Characteristics of Service Classes

Each service class has unique QoS requirements as shown in Table 1.1. Thus, the existing cross-layered retransmission schemes that use the the maximum number of transmissions and the target PER can decrease the channel utilization because the constant values may not be adequate for all service classes. Then the cross-layered retransmission schemes may be a conservative scheme for a service class even though the service class can tolerate more packet loss at the application layer. Nevertheless when the wireless channel can allow more bits, the transmitter modulates data with a low coding rate. This wastes channel resources. On the other hand, the existing schemes may be aggressive for a service class which is more sensitive to the packet loss than other service classes. This may increase the PLR at the application layer and may not guarantee the QoS requirements of the service class. As a result, a discrepancy between the QoS requirements at the application layer and the criterion for MCS level selection at the physical layer can decrease the wireless channel utilization. Therefore, a modified algorithm that can adjust the parameters for selection of an MCS level depending on the type of service should be considered to improve the wireless channel utilization.

1.3 Performance at the Transport Layer

In most previous works, the proposed cross-layered retransmission schemes addressed the wireless channel conditions rather than the performance
at the transport layer \[4\]–\[12\]. The performance at the transport layer in terms of delay, PER, and throughput was not analyzed. It is difficult for a system designer to decide whether the cross-layered retransmission schemes are suitable for each service class. Besides, the performance at the transport layer may be degraded and a mismatch between the QoS requirements of applications and the transmission performance at the data link layer occurs. As a result, it is difficult to optimize the performance at the transport layer when using the schemes that have been proposed in previous works. Therefore, the end-to-end performance analysis and the modified MCS level selection algorithm considering the performance at the transport layer are focused in this dissertation.

1.4 Contributions

The goal of this dissertation is improving user-perceived performance and efficiency of wireless channel resource. As mentioned in above, the end-to-end performance and the QoS requirements of service classes are extremely important to improve the user-perceived performance. Therefore, advanced cross-layered retransmission schemes are proposed and the end-to-end performance is analyzed. The proposed schemes not only improve the user-perceived performance, but also improve efficiency of wireless channel resource. Fig. 1.1 shows the overall concept of existing cross-layered retransmission schemes and proposed schemes. The proposed schemes consider service characteristics and throughput at the application layer and the transport layer, respectively.
Fig. 1.1. Overall concept of proposed schemes
The following are the principle contributions of this dissertation.

- Analytical models to obtain the end-to-end performance are presented. The spectral efficiency at the data link layer and PER, delay, and throughput at the transport layer are modeled. The analytical and numerical results can be used for criteria for selection of an appropriate cross-layered retransmission scheme to guarantee the service quality.

- A novel cross-layered retransmission scheme considering both the QoS requirements of service classes and the wireless channel quality is presented. The proposed scheme adjusts criteria for selection of an MCS level according to service class, thereby resulting in increasing efficiency of wireless channel resource.

- Advanced cross-layered retransmission scheme for improving the performance at the transport layer is presented. The proposed scheme adopts both the throughput at the transport layer and the target PER at the data link layer as criteria for MCS level selection.

- A cross-layered retransmission scheme which employs both HARQ and ARQ is presented. The proposed scheme improves the reliability of a transmitted packet and the throughput at the transport layer when the wireless channel quality is poor.
In the future, the mobile traffic and devices are increased sharply \[13\]. This can cause lack of wireless channel resource. The proposed schemes can improve the efficiency of wireless channel resource as well as user-perceived performance. Therefore, it is expected that the proposed schemes can be applied to future wireless networks and devices.
2

Related Work

2.1 Adaptive Modulation and Coding

In wireless channel, the signal quality varies with many factors such as interference signal and obstacles. To improve the performance for data transmission, link adaptation is used for wireless communications to adapt the signal quality to wireless channel condition. Initially, wireless communication systems have used power control as preferred method for link adaptation [14][15]. Recently, many wireless communication systems adopt AMC scheme to improve the overall system capacity [16][17]. AMC scheme provides the flexibility to sender by adapting MCS level according to the signal quality on the wireless channel. Fig. 2.1 describes the MCS level selection procedure of AMC. When the signal quality is high, sender selects higher order MCS level that allows sender to transmit more information bits per symbol. On the contrary, if the signal quality is poor, lower order MCS level is selected and the code rate per symbol
Fig. 2.1. MCS level selection procedure of AMC

... decreases. To adapt MCS level, sender requires information about the signal quality at the receiver. The signal quality can be measured by the receiver and fed back to the sender. The sender selects an MCS level by comparing the target PER and the measured signal quality.

The target PER is prescribed in wireless communication systems. As it is defined in standards, the sender selects the highest MCS level which could be sustained under the present channel conditions, while simultaneously maintaining a transport block error probability not exceeding the target PER \cite{18,21}. For example, AMC scheme can select an MCS level among the six MCS levels and the PER for each MCS level is as shown in Fig. 2.2. If the target PER is 1% and the signal quality is 5dB, sender selects MCS level 2. Table 2.1 shows the MCS levels with modulation method and spectral efficiency in LTE system \cite{16}. 
Fig. 2.2. PER of MCS level
Table 2.1. MCS levels in LTE system

<table>
<thead>
<tr>
<th>MCS</th>
<th>CQI</th>
<th>Modulation</th>
<th>Spectral efficiency</th>
<th>MCS</th>
<th>CQI</th>
<th>Modulation</th>
<th>Spectral efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2</td>
<td>QPSK</td>
<td>0.2344</td>
<td>16</td>
<td>16</td>
<td>16QAM</td>
<td>2.5684</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td>0.3057</td>
<td>17</td>
<td></td>
<td></td>
<td>2.5684</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td></td>
<td>0.3770</td>
<td>18</td>
<td>10</td>
<td>2.7305</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>0.4893</td>
<td>19</td>
<td></td>
<td></td>
<td>3.0264</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>QPSK</td>
<td>0.6016</td>
<td>20</td>
<td>11</td>
<td>3.3223</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td>0.7393</td>
<td>21</td>
<td></td>
<td></td>
<td>3.6123</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td></td>
<td>0.8770</td>
<td>22</td>
<td>12</td>
<td>3.9023</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
<td>1.0264</td>
<td>23</td>
<td></td>
<td></td>
<td>4.2128</td>
</tr>
<tr>
<td>8</td>
<td>6</td>
<td></td>
<td>1.1758</td>
<td>24</td>
<td>13</td>
<td>4.5234</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
<td></td>
<td>1.3262</td>
<td>25</td>
<td></td>
<td></td>
<td>4.8193</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td>1.3262</td>
<td>26</td>
<td>14</td>
<td></td>
<td>5.1152</td>
</tr>
<tr>
<td>11</td>
<td>7</td>
<td></td>
<td>1.4766</td>
<td>27</td>
<td></td>
<td></td>
<td>5.3349</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>16QAM</td>
<td>1.6953</td>
<td>28</td>
<td>15</td>
<td></td>
<td>5.5547</td>
</tr>
<tr>
<td>13</td>
<td>8</td>
<td></td>
<td>1.9141</td>
<td>29</td>
<td></td>
<td>QPSK</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td></td>
<td></td>
<td>2.1602</td>
<td>30</td>
<td>16</td>
<td>16QAM</td>
<td>Reserved</td>
</tr>
<tr>
<td>15</td>
<td>9</td>
<td></td>
<td>2.4063</td>
<td>31</td>
<td>64</td>
<td>64QAM</td>
<td></td>
</tr>
</tbody>
</table>
2.2 Retransmission Schemes

To meet the QoS requirements of users, it is important to improve the efficiency and reliability of packet transmission, and so far, various methods have been proposed for this purpose. Initially, several retransmission schemes have been taken into account to recover an erroneous packet \[2, 3, 22\text{-}40\]. There have been two different retransmission schemes in wireless networks, ARQ and HARQ, which are defined at the data link layer.

The ARQ has an advantage that the implementation is relatively simple. ARQ can be categorized into three types according to packet scheduling method. One is Stop-and-wait ARQ. Stop-and-wait ARQ transmits a frame at a time, then the sender waits for a certain time to receive a acknowledgement packet for the transmitted frame before transmitting another packet. If the sender can not receive the acknowledgement packet for a certain time, the sender transmits the frame again. Another is Go-back-N ARQ. A sender can transmit frames specified by window size without before receiving a acknowledgement packet. If the sender receives a acknowledgement packet, then window is shifted to the right and the sender can transmit a frame. On the contrary, if the sender can not receive an expected acknowledgement packet for a frame, then the sender retransmits the unacknowledged frame and frames behind the unacknowledged frame. The other is Selective repeat ARQ. Selective repeat ARQ sender transmits a number of frames specified by window size without before receiving a acknowledgement packet. Unlike Go-back-N
ARQ, the sender retransmits an unacknowledged frame. Fig. 2.2, Fig. 2.3, and Fig. 2.4 depict the procedure of frame transmission in each ARQ protocols. ARQ protocols have been widely used on radio communication systems to improve reliability of data transmissions. However, the ARQ can lead to increase of the access delay because of the processing time and the round trip delay.
\textbf{Fig. 2.4.} Go-back-N ARQ

\textbf{Fig. 2.5.} Selective repeat ARQ
The HARQ has been investigated for the fast feedback in access networks [2]. The HARQ adopts soft combining to improve the error correction capability. HARQ can be categorized into three types according to the puncturing pattern. HARQ Type I uses chase combining and HARQ Type II and HARQ Type III use incremental redundancy combining. HARQ Type I retransmits the same packet that contains the same data and parity bits with the transmitted packet initially. On the contrary, HARQ Type II and HARQ Type III retransmit different information by using different puncturing patterns. Thus, a receiver can obtain additional information from a retransmitted packet. This can help improve reliability of data transmission.
Systematic bits
Parity bits
Puncturing
Initial Transmission
Retransmission
Incremental Redundancy Combining

**Fig. 2.7.** HARQ Type II

Systematic bits
Parity bits
Puncturing
Initial Transmission
Retransmission
Incremental Redundancy Combining

**Fig. 2.8.** HARQ Type III
TCP is a transport layer protocol to provide reliable packet transmission, flow control, and congestion control \[41, 42\]. For reliable packet transmission, TCP uses sequence number to identify the order of transmitted data. TCP can detect a packet loss by checking a sequence number of transmitted data. A receiver sends an acknowledgement to confirm that the receiver has received all the preceding packets. Modified TCP adopts four algorithm to avoid network congestion and improve the packet transmission performance, i.e. slow-start, congestion avoidance, fast retransmit, and fast recovery \[43\]. TCP Tahoe adopts slow start, congestion avoidance, and fast retransmit to control congestion window size. TCP Reno enhances the transmission rate by adopting fast recovery. Fig. 2.9 and Fig. 2.10 depict the scaling of congestion window size of TCP Tahoe and TCP Reno, respectively.
Fig. 2.9. Congestion window size of TCP Tahoe
Fig. 2.10. Congestion window size of TCP Reno
2.3 Cross-layered Retransmission Schemes

The cross layer design can improve system performance by allowing sharing of information across protocol layers. To share information between protocol layers, the cross layer design methodology uses adaptivity in designing the communication protocols [44]. There are two types of adaptivities. One is channel adaptivity, which is the ability of the network to adapt to variations in channel conditions, traffic conditions, etc., and the other is QoS adaptivity, which is the ability of the network to respond to different QoS requirements of the services. The cross layer design is widely used to improve the performance such as cell capacity and channel utilization [4–12, 45–70]. To enhance the transmission efficiency, the cross-layered retransmission schemes have been proposed [4–12]. One of a kind of cross-layered retransmission scheme is a retransmission scheme combined with AMC.

A cross-layered retransmission scheme has been proposed using the concept of channel adaptivity. The cross-layered retransmission scheme employs an AMC scheme at the PHY layer and an ARQ scheme at the data link layer together [4]. In the AMC combined with ARQ, the error-correcting capability of ARQ, which depends on the maximum allowable number of retransmissions, can alleviate responsibility for the error control of AMC at the PHY layer. For this reason, the AMC can select an MCS level in which a node can transfer more bits per symbol as the maximum allowable number of retransmissions is increased. Thus, this scheme can maximize spectral efficiency under the prescribed de-
lay and error performance constraints. To verify improved performance of the AMC combined with ARQ, [4] presented a mathematical model and compared the performance in terms of the spectral efficiency among the AMC combined with ARQ, AMC only, and ARQ applied to fixed modulation and coding scheme. Their analytical results showed that the AMC combined with ARQ, as compared to AMC alone, improves the spectral efficiency by about 0.25 bits per transmitted symbol. Another cross-layered retransmission scheme has been proposed in [5]. In [5], the authors proposed a cross layer design that combines AMC with HARQ, and provided an analytical model for average PER, spectral efficiency, and throughput. Moreover, the authors derived the optimal packet size only to achieve higher throughput. The AMC combined with HARQ selects an MCS level by using target BER considering the soft-combining gain of HARQ type II. Thus, the target BER for retransmission of a packet is greater than that for previous transmission of the packet. This can increase the probability that a node selects a high MCS level. Therefore, the AMC combined with HARQ can achieve an improved spectral efficiency by considering the soft-combining gain of HARQ type II. Fig. 2.11 and Fig. 2.12 depict the system model of the AMC combined with ARQ and the AMC combined with HARQ, respectively.
Fig. 2.11. System model of the AMC combined with ARQ
Fig. 2.12. System model of the AMC combined with HARQ
In other studies, the authors focused on adapting the cross-layered retransmission schemes proposed in [4] and [5] to specific systems or networks. Recently, several cross-layered retransmission schemes under various conditions have been proposed [6, 7, 9–12]. In [6], the authors analyzed the system performance such as the PLR and the average spectral efficiency by considering the queuing effects at the data link layer. The joint effects of finite-length queuing and AMC for transmissions are taken into account at the analytical model. In [7], the authors applied the cross-layered retransmission scheme (the AMC combined with HARQ) to the wireless communication system using rate-compatible LDPC codes. The work in [9] presented an AMC algorithm which combines truncated ARQ and packet combining over MIMO Nakagami fading channels. In this work, the authors derived the analytical model and evaluated the link layer performance when the ARQ is used in conjunction with packet combining. In [10], a cross-layered DTMC-based model was developed to obtain closed-form analytical expressions in terms of average packet delay, packet loss rate, and throughput. In [11], the authors modified the MCS level selection method for the AMC combined with ARQ in order to improve the spectral efficiency. To achieve this, the scheme proposed in [11] considers PLR as a constraint for the MCS level selection. The authors have shown that the proposed cross-layered retransmission scheme achieves a considerably higher spectral efficiency when compared to AMC alone. In [12], the authors derived an analytical model and evaluated the performance at the data link layer when a cross-layered retransmission scheme was applied in cognitive radio networks.
Most previous studies addressed the performance at the data link layer and did not take into account the performance at the transport layer. It is difficult to optimize the performance at the transport layer, because cross-layered retransmission schemes select an MCS level regardless of the performance at the transport layer. This may cause degradation of the performance at the transport layer, although the existing methods can improve the link layer performance. For example, maximization of spectral efficiency may increase the error rate of both an HARQ packet and a TCP packet (segment), because in general a TCP segment consists of several HARQ packets. Moreover, the QoS is related more to the performance at the transport layer than that at the data link layer. Thus, maximization of the spectral efficiency may decrease the QoS as a result of the degradation of the error rate performance. Consequently, a novel cross-layered retransmission scheme is required that optimizes the performance at the transport layer.
In this chapter, an application-aware MCS level selection scheme for improving the wireless channel utilization within the QoS requirements is presented. Besides, a method to implement the proposed scheme into a practical system is presented.

3.1 Motivation

Wireless communication systems offer various services to a user and each service class has unique QoS requirements [71]. Thus, the existing cross-layered retransmission schemes that use the constant system parameters such as the maximum number of transmissions and target PER may decrease the channel utilization because the constant system parameters may not be adequate for all service classes. Then the cross-layered re-
transmission schemes may be a conservative scheme for a service class even though the service class can tolerate more packet loss at the application layer. Nevertheless when the wireless channel can allow more bits, the transmitter modulates data with a low coding rate. This wastes channel resources. On the other hand, the existing schemes may be aggressive for a service class which is more sensitive to the packet loss than other service classes. This may increase the PLR at the application layer and may not guarantee the QoS requirements of the service class. As a result, a discrepancy between the QoS requirements at the application layer and the criterion for MCS level selection at the physical layer can decrease the wireless channel utilization. Therefore, a modified algorithm that can adjust the parameters for selection of an MCS level depending on the type of service should be considered to improve the wireless channel utilization.

3.2 System model

In this Section, the system architecture, wireless channel model, and existing MCS level selection schemes of cross-layered retransmission schemes are described.

3.2.1 System Structure

We considered the system structure depicted in Fig. 3.1 which consists of an MS, a BS, a data server, and backbone networks. In wireless access networks, the MS and BS are connected by three protocol layers; the
PHY layer, MAC layer, and RLC layer. Retransmission schemes such as TCP Reno, selective repeat ARQ, and HARQ type II are used at the transport, RLC, and MAC layer, respectively. In the PHY layer, the AMC and the Viterbi decoding algorithm are used for link adaptation and error correction. The LTE system is considered as a wireless access system [72].

### 3.2.2 Wireless Channel Model

We adopted the Rayleigh fading channel as the wireless channel model. In the model, (3.1) is used to describe the probability density of the
received SNR statistically.

\[ p_\gamma (\gamma) = \frac{1}{\bar{\gamma}} \exp \left( -\frac{\gamma}{\bar{\gamma}} \right), \quad (3.1) \]

where \( \gamma \) denotes the received SNR and \( \bar{\gamma} \) denotes the average received SNR. The PER according to the received SNR can be obtain through Monte Carlo simulations and we adopt the curve fitting parameters of the simulated PER as shown in Table 3.1 and Table 3.2 [4, 5].

We assume that the wireless channel is frequency flat fading channel and channel state varies from frame to frame [73]. Therefore, AMC scheme adjusts MCS level on a frame-by-frame. In this dissertation, we assume that the updated MCS level based on measured CSI will be sent back to the transmitter with zero delay through a feedback channel [74]. The effects of estimation error and delay in the feedback path were analyzed in existing work [75]. The results in [75] shown that an estimation error is less than 1 dB and a feedback path delay is negligible compared with Doppler frequency of the fading channel.

We considered some assumptions for the performance analysis.

- Error detection by CRC is perfect.

- CSI is defined by the received SNR at the receiver.

- Perfect CSI is available at the receiver.
### Table 3.1. MCS level parameters for HARQ

<table>
<thead>
<tr>
<th></th>
<th>MCS Level 1</th>
<th>MCS Level 2</th>
<th>MCS Level 3</th>
<th>MCS Level 4</th>
<th>MCS Level 5</th>
<th>MCS Level 6</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Modulation</strong></td>
<td>BPSK</td>
<td>QPSK</td>
<td>QPSK</td>
<td>16-QAM</td>
<td>16-QAM</td>
<td>64-QAM</td>
</tr>
<tr>
<td><strong>Coding rate</strong></td>
<td>1/2</td>
<td>1/2</td>
<td>3/4</td>
<td>9/16</td>
<td>3/4</td>
<td>3/4</td>
</tr>
<tr>
<td><strong>bits/symbol</strong></td>
<td>0.50</td>
<td>1.00</td>
<td>1.50</td>
<td>2.25</td>
<td>3.00</td>
<td>4.50</td>
</tr>
<tr>
<td>$a_n$</td>
<td>1.1369</td>
<td>0.3351</td>
<td>0.2197</td>
<td>0.2081</td>
<td>0.1936</td>
<td>0.1887</td>
</tr>
<tr>
<td>$b_n$</td>
<td>7.5556</td>
<td>3.2543</td>
<td>1.5244</td>
<td>0.6250</td>
<td>0.3484</td>
<td>0.0871</td>
</tr>
</tbody>
</table>
Table 3.2. MCS level parameters for ARQ

<table>
<thead>
<tr>
<th>MCS Level 1</th>
<th>MCS Level 2</th>
<th>MCS Level 3</th>
<th>MCS Level 4</th>
<th>MCS Level 5</th>
<th>MCS Level 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation</td>
<td>BPSK</td>
<td>QPSK</td>
<td>QPSK</td>
<td>16-QAM</td>
<td>64-QAM</td>
</tr>
<tr>
<td>Coding rate</td>
<td>1/2</td>
<td>1/2</td>
<td>3/4</td>
<td>9/16</td>
<td>3/4</td>
</tr>
<tr>
<td>bits/symbol</td>
<td>0.50</td>
<td>1.00</td>
<td>1.50</td>
<td>2.25</td>
<td>3.00</td>
</tr>
<tr>
<td>$f_n$</td>
<td>274.7229</td>
<td>90.2514</td>
<td>67.6181</td>
<td>50.1222</td>
<td>35.3987</td>
</tr>
<tr>
<td>$g_n$</td>
<td>7.9932</td>
<td>3.4998</td>
<td>1.6883</td>
<td>0.6644</td>
<td>0.3756</td>
</tr>
</tbody>
</table>

32
3.2.3 AMC Scheme

For the sake of clarity, we define the PER and the PLR as follows.

- PER is the probability that a packet remains as an erroneous packet after completion of error correction procedures of FEC.

- PLR is the probability which a packet remains as an erroneous packet after completion of retransmission procedures for the packet.

In this section, we discuss the boundary values of the SNR region where an MCS level $n$ is selected by a transmitter based on target PLR for each service class. The PER at the received SNR must be lower than the target PER in order to select an MCS level $n$. The target PER is calculated on the basis of the maximum number of transmissions and target PLR, and is given by

$$P^{N_t} \leq P_{\text{loss}} \rightarrow P \leq (P_{\text{loss}})^{1/N_t} = P_{\text{target}},$$

where $P$, $N_t$, $P_{\text{loss}}$, and $P_{\text{target}}$ denote average PER, the maximum number of transmissions, target PLR, and target PER, respectively. An MCS level can be selected by a different scheme according to the types of retransmission schemes.

The AMC scheme adapts the MCS levels to the wireless channel conditions. Each MCS level can be selected in a corresponding SNR region. In this subsection, we discuss the boundary values of the SNR region.
when an MCS level \( n \) is selected by a transmitter based on a target PER.

### 3.2.3.1 AMC combined with HARQ (AH)

An MCS level \( n \) can be selected for the \( i \)-th transmission attempt when the received SNR is higher than the minimum SNR boundary. The minimum SNR boundary is derived as

\[
\gamma_{n,HARQ}^{(i)} = \frac{1}{b_n} \ln \left( \frac{a_n}{BER_{target}^{(i)}} \right), \quad i = 1, \cdots, N_{l,H}, \quad n = 1, \cdots, N, \quad (3.3)
\]

where \( \gamma_{n,HARQ}^{(i)} \) denotes the SNR boundary for the \( i \)-th transmission attempt when using MCS level \( n \), and \( a_n \) and \( b_n \) are MCS level-dependent constants that can be obtained by fitting the experimental BER values of MCS level \( n \) to an exponential function. \( N_{l,H} \) denotes the maximum number of transmissions in HARQ. Each MCS level \( n \) is selected in the SNR region \([\gamma_n, \gamma_{n+1})\). If the received SNR \( \gamma \) is lower than \( \gamma_1 \), in order to avoid deep channel fades, no payloads bits are sent [4]. In contrast, if the received SNR is higher than \( \gamma_N \), the MCS level \( N \) is selected for packet transmission. \( BER_{target}^{(i)} \) and \( N \) denote the target BER for the \( i \)-th transmission and the number of available MCS levels, respectively. The target BER for an initially transmitted packet and a retransmitted packet can be calculated by using a different approach. First, we can obtain the target BER for the initial transmission [5], which is represented by

\[
BER_{target}^{(1)} = 1 - (1 - PER_{target})^{1/L}, \quad (3.4)
\]
where $PER_{\text{target}}$ and $L$ denote the target PER and the number of transmitted bits in the HARQ packet, respectively. When a packet is retransmitted, the receiver attempts to recover errors by using soft combining. The retransmitted HARQ packet is combined with the corresponding packets received from previous transmissions. For this reason, the BER of the retransmitted packet is not independent of the previously transmitted packet. Therefore, we use a PER upper bound to calculate the target BER for the retransmitted packet. The PER upper bound can be derived under the assumption that the convolutional code with hard-decision Viterbi decoding is used [5]; it is given by

$$P_{\text{upper}}^{(i)} = 1 - (1 - P_{u}^{(i)})^L \geq PER^{(i)}, \quad (3.5)$$

where $P_{\text{upper}}^{(i)}$, $PER^{(i)}$, and $P_{u}^{(i)}$ denote the PER upper bound, the PER, and the union bound of the first-event error probability after decoding of the $i$-th retransmitted packet, respectively. $P_{u}^{(i)}$ is obtained by using the free distance of the convolutional code and the total number of error events with weight $d$; it is given by

$$P_{u}^{(i)} = \sum_{d=d_f^{(i)}}^{\infty} a_d^{(i)} \times p_d^{(i)}, \quad (3.6)$$

where $d_f^{(i)}$ and $a_d^{(i)}$ denote the free distance of the convolutional code and the total number of error events for the $i$-th retransmitted packet, respectively. $p_d^{(i)}$ is the error probability with weight $d$ for the $i$-th retransmitted packet. When the hard-decision Viterbi decoding is applied, $p_d^{(i)}$ can be approximately expressed as [76]

$$p_d^{(i)} \approx 4 \rho^{(i)} \left(1 - \rho^{(i)}\right)^{d/2}, \quad (3.7)$$

35
where $\rho^{(i)}$ is the BER for the $i$-th retransmission. If we let $PER^{(i)} = PER_{\text{target}}$, we can obtain the target BER for retransmission as

$$BER_{\text{target}}^{(i)} = \left[ \frac{1 - (1 - PER_{\text{target}})^{1/L}}{a_{d_f^{(i)}}^{(i)} 2^{d_f^{(i)}}} \right]^{2/d_f^{(i)}} ,$$

(3.8)

where $a_{d_f^{(i)}}^{(i)}$ denotes the total number of error events with the free distance of the convolutional code, $d_f^{(i)}$, at the $i$-th transmission attempt.

### 3.2.3.2 AMC combined with ARQ (AA)

At the RLC layer, the FER of a transmitted frame is independent of the corresponding frames received in previous transmissions. Thus, the transmitter sets the target FER to be the same as that of the previously transmitted frame and selects an MCS level within the target FER. Therefore, the minimum SNR boundary can be derived by using the target FER when MCS level $n$ is used for every transmission:

$$\gamma_{n,\text{ARQ}} = \frac{1}{g_n} \ln \left( \frac{f_n}{FER_{\text{target}}} \right) , \quad n = 1, 2, \cdots, N ,$$

(3.9)

where $f_n$ and $g_n$ denote MCS level-dependent constants, the values of which can be obtained by fitting the experimental FER of MCS level $n$ to an exponential function [4]. $FER_{\text{target}}$ denotes the target FER. When the received SNR is lower than $\gamma_1$ or higher than $\gamma_N$, the AMC scheme operates according to the same policies as AH.
3.3 Proposed AMS Scheme

There is a discrepancy between the QoS requirements of a service class at the application layer and the target PER for the selection of an MCS level at the data link layer. A protocol in each layer transmits data by using different parameters as shown in Table 3.3. Each service class is defined by QoS requirements at the application layer such as packet loss rate and delay. For example, 3GPP LTE system classifies the service types according to minimum service requirements as shown in Table 1.1. In the network layer, an IP datagram can be routed based on the service types that are defined in IP packet header. IntServ and DiffServ were presented to guarantee QoS on networks. However, a frame at the data link layer is transmitted by using the prescribed target PER for MCS level selection regardless of the service types. Target PER is configurable parameter in wireless communication systems to provide an appropriate performance for each service class. However, there is any criteria to set the target PER for each service class. Thus, wireless communication systems using AMC adopt target PER values roughly for voice and data services. For example, the target PER for data services is 1 % in WiMAX system [21]. Thus, the existing AMC scheme may not select an appropriate MCS level for the specific service. For this reason, it is difficult to optimize the wireless channel utilization for the service characteristics.

To reduce the discrepancy, we propose the AMS scheme. The AMS scheme selects an MCS level by adjusting the target PER depending on the service characteristics. Fig. 3.2 describes the MCS level selection
Table 3.3. Parameters related to QoS

<table>
<thead>
<tr>
<th>Layer</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application layer</td>
<td>Packet loss rate, Delay</td>
</tr>
<tr>
<td>Network layer</td>
<td>TOS in IP packet header</td>
</tr>
<tr>
<td>Data link layer</td>
<td>Target PER</td>
</tr>
</tbody>
</table>

procedure of AMS scheme which considers the QoS requirements of service classes. In the AMS scheme, the target PER is calculated by using the target PLR at the application layer. The target PLR is related to the number of transmissions and the target PER at the data link layer as follows [77]:

\[
PLR \leq 1 - (1 - P_t^{N_R})^{N_S},
\]

where \( P_t \) and \( N_S \) denote the target PER and the number of the TCP segments related to an application layer packet, respectively. \( N_R \) denotes the number of the frames related to a TCP segment. From (3.10), we can derive the boundary for the target PER, which is given by

\[
P_t \leq \left(1 - (1 - PLR)^{1/N_S}\right)^{1/N_R}.
\]

In (3.11), the target PER does not include error recovery opportunities through retransmission in the transport layer. In other words, the AMS scheme does not take into account the error recovery by retransmission of the TCP to leave a margin for packet loss at the application layer. However, the AMS scheme can enhance the efficiency of wireless channel
Fig. 3.2. MCS level selection procedure of AMS scheme

resource compared to the existing AMC scheme because the existing AMC scheme does not adapts the target PER for each service class and there is a discrepancy between QoS requirements and the target PER. Consequently, the AMS scheme can reduce the discrepancy between the QoS requirements of a service class at the application layer and the target PER at the data link layer. Therefore, the AMS scheme can enhance the efficiency of wireless channel resource within the QoS requirements.

### 3.4 Implementation of the AMS Scheme

The AMS scheme uses an appropriate target PLR for each service class to select an MCS level in the PHY layer. Thus, the wireless communication systems should classify the traffic flow according to the QoS requirements
in order to apply the AMS scheme to the practical systems.

To classify a traffic flow and manage the traffic flow by different criteria, the wireless communication systems initialize a session for the traffic flow based on the service class and the QoS requirements when the traffic flow occurs. Each session is associated with a parameter such as the QCI as shown in Table 3.4 and the types of data delivery services to determine how it is handled in a BS [78, 79]. A BS performs resource allocation and scheduling based on the class identifier parameter. However, the wireless communication systems cannot distinguish the priority of a packet in a traffic flow. Therefore, the AMS scheme can be applied to the wireless communication systems based on the type of the service class. If it is possible to classify a packet according to the priority, the AMS scheme can also be applied in packet level.
<table>
<thead>
<tr>
<th>QCI</th>
<th>Priority</th>
<th>Packet loss rate</th>
<th>Example service</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>$10^{-2}$</td>
<td>Conversational voice</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>$10^{-3}$</td>
<td>Conversational video</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>$10^{-3}$</td>
<td>Real time gaming</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>$10^{-6}$</td>
<td>Non-conversational video</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>$10^{-6}$</td>
<td>IP multimedia subsystem signaling</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>$10^{-6}$</td>
<td>Video streaming</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>$10^{-3}$</td>
<td>Voice, Interactive gaming</td>
</tr>
<tr>
<td>8, 9</td>
<td>8, 9</td>
<td>$10^{-6}$</td>
<td>FTP, E-mail, Web-browsing</td>
</tr>
</tbody>
</table>
3.5 Performance Analysis

We compare the performance of the existing AMC and that of the AMS scheme in terms of spectral efficiency and transmission delay. We can obtain the average spectral efficiency at the $i$-th transmission attempt, $\overline{S}^{(i)}$, as follows:

$$\overline{S}^{(i)} = \sum_{n=1}^{N} R_n \Pr^{(i)}(n), \quad (3.12)$$

where $\Pr^{(i)}(n)$ and $R_n$ denote the selection probability of the MCS level $n$ at the $i$-th transmission attempt and the number of bits per symbol in MCS level $n$, respectively. The average spectral efficiency can be obtained by using the average PER, and it is given by

$$\overline{S}_{overall} = \sum_{i=1}^{N_t} p_i \cdot \overline{S}^{(i)}, \quad (3.13)$$

where $p_i$ denotes the probability that the $i$-th transmission attempt occurs.

$$p_i = \begin{cases} 
1 & i = 1, \\
\frac{\Pr^{(i-1)}(i-1)}{\text{PER}^{(i-1)} \cdot (1 - \text{PER})} & i = 2, 3, \ldots, N_t,
\end{cases} \quad (3.14)$$

The transmission delay between transport layers of the end-terminals is composed of two delay components, such as a delay in the wireless channel and a delay in the wired backbone networks as shown in Fig. 3.1, and it is expressed as follows:

$$D_{TCP} = D_W + D_B, \quad (3.15)$$
where $D_{TCP}$ denotes the one-way packet delivery time from the server to the end terminal at the transport layer. $D_W$ and $D_B$ denote the delay in the wireless channel and backbone networks, respectively. $D_W$ can be derived from the average number of transmissions, $\bar{N}$, as follows:

$$D_W = d_{\text{oneway}} + d_{\text{round}} \cdot (\bar{N} - 1), \quad (3.16)$$

where $d_{\text{oneway}}$ and $d_{\text{round}}$ denote the one-way delay and the round-trip delay between the terminal and the BS, respectively. In (3.16), $\bar{N}$ is expressed as follows [80]:

$$\bar{N} = \left(1 - \frac{\text{PER}}{N_t}\right) / \left(1 - \text{PER}\right). \quad (3.17)$$

The average transmission delay between application layers of the end-terminals can be derived as follows:

$$\sum_{n=1}^{\infty} P_n \cdot D_n, \quad (3.18)$$

where $P_n$ and $D_n$ denote the probability that the $n$-th transmission attempt for an application layer packet occurs and the elapsed time for $n$-th transmission attempts, respectively. We assume that a TCP segment can be transmitted successfully within fourth transmission attempts. Then, $P_n$ can be derived by using the error rate of a TCP segment ($p$) and the number of TCP segments which compose a packet at the application
layer \( (N_S) \), and it is expressed as follows:

\[
P_n = \begin{cases} 
(1 - p)^{N_S} & n = 1, \\
\sum_{i=1}^{N_S} \binom{N_S}{i} p^i (1 - p)^{N_S-i} & n = 2, \\
\sum_{i=1}^{N_S} \binom{N_S}{i} p^i \sum_{j=1}^{i} \binom{i}{j} p^j & n = 3, \\
\sum_{i=1}^{N_S} \binom{N_S}{i} p^i (1 - p)^{N_S-i} \sum_{j=1}^{i} \binom{i}{j} p^j & n = 4.
\end{cases}
\]  

(3.19)

The value of \( D_n \) can be obtained by using (3.15) and the transmission delay, \( d_t \) which is the amount of time required to push a TCP segment into the network as follows:

\[
D_n = \begin{cases} 
N_S d_t + D_{TCP} & n = 1, \\
\sum_{n=2}^{4} \sum_{i=1}^{N_S} [d_t (N_S + i) + D_{TCP} (2n - 1)] & n = 2, 3, 4.
\end{cases}
\]  

(3.20)

### 3.6 Numerical Results

To evaluate the performance, we adopt the system model shown in Section 3.2 and consider the LTE system as a wireless access system. To simplify the performance evaluation, we make some assumptions. First, error detection by CRC is perfect; second, the CSI is reported to the transmitter without error; third, the transmission delay over the backbone network is 100 ms [81]. We use the three types of traffic models,
Table 3.5. QoS Requirements

<table>
<thead>
<tr>
<th>Traffic model</th>
<th>One-way delay</th>
<th>Information loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>High quality streaming audio</td>
<td>&lt;10s</td>
<td>1%</td>
</tr>
<tr>
<td>Movie streaming</td>
<td>&lt;10s</td>
<td>1%</td>
</tr>
<tr>
<td>Bulk data transfer (FTP)</td>
<td>&lt;15s</td>
<td>Zero ($10^{-6}$)</td>
</tr>
</tbody>
</table>

movie streaming traffic, high quality streaming audio (i.e., music streaming), and FTP as shown in Table 3.5. The target PER is 1 % and 0 % ($\approx 10^{-6}$) for the streaming and FTP, respectively [21, 71]. We assume that the CSI feedback delay is 10 ms [16]. Table 3.6 lists the system parameters for the evaluation [4, 5, 72, 82, 83].
## Table 3.6. System Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>10 MHz</td>
</tr>
<tr>
<td>Frame size</td>
<td>10 ms</td>
</tr>
<tr>
<td>PHY layer PDU size</td>
<td>152, 256, 600, 1192, 1928, 3752 bits</td>
</tr>
<tr>
<td></td>
<td>(MCS level 1-6)</td>
</tr>
<tr>
<td>Frame size</td>
<td>10 ms</td>
</tr>
<tr>
<td>Processing delay (intra-layer)</td>
<td>1 ms</td>
</tr>
<tr>
<td>Processing delay (inter-layer)</td>
<td>3 ms</td>
</tr>
<tr>
<td>Transmission time interval</td>
<td>5 ms</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b$</td>
<td>2</td>
</tr>
<tr>
<td>$a_d^{(2)}, a_d^{(3)}$</td>
<td>2, 5</td>
</tr>
<tr>
<td>$d_f^{(2)}, d_f^{(3)}$</td>
<td>7, 12</td>
</tr>
</tbody>
</table>

### $a_n, b_n$ (HARQ)

<table>
<thead>
<tr>
<th>Level (Modulation, $R_n$)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPSK, $R_n$=0.5</td>
<td>1.1369, 7.5556</td>
</tr>
<tr>
<td>QPSK, $R_n$=1</td>
<td>0.3351, 3.2543</td>
</tr>
<tr>
<td>QPSK, $R_n$=1.5</td>
<td>0.2197, 1.5244</td>
</tr>
<tr>
<td>16QAM, $R_n$=2.25</td>
<td>0.2081, 0.6250</td>
</tr>
<tr>
<td>16QAM, $R_n$=3</td>
<td>0.1936, 0.3484</td>
</tr>
<tr>
<td>64QAM, $R_n$=4.5</td>
<td>0.1887, 0.0871</td>
</tr>
</tbody>
</table>

### $f_n, g_n$ (ARQ)

<table>
<thead>
<tr>
<th>Level (Modulation, $R_n$)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPSK, $R_n$=0.5</td>
<td>274.7229, 7.9932</td>
</tr>
<tr>
<td>QPSK, $R_n$=1</td>
<td>90.2514, 3.4998</td>
</tr>
<tr>
<td>QPSK, $R_n$=1.5</td>
<td>67.6181, 1.6883</td>
</tr>
<tr>
<td>16QAM, $R_n$=2.25</td>
<td>50.1222, 0.6644</td>
</tr>
<tr>
<td>16QAM, $R_n$=3</td>
<td>53.3987, 0.3756</td>
</tr>
<tr>
<td>64QAM, $R_n$=4.5</td>
<td>35.3508, 0.0900</td>
</tr>
</tbody>
</table>
Fig. 3.3 and Fig. 3.4 show the average spectral efficiency of the existing AMC scheme and the proposed AMS scheme where AH and AA are employed as cross-layered retransmission schemes, respectively. From the result, we can see that AMS scheme enhanced the average spectral efficiency for streaming services. Especially, the average spectral efficiency of the movie and music streaming traffic was increased by up to 0.522 bits/symbol for AH and 0.38 bits/symbol for AA. This is because the streaming services can tolerate more packet error at the application layer and the AMS scheme increased the target PER at the data link layer within the QoS requirements of the applications. On the contrary, the average spectral efficiency of the FTP traffic was decreased by up to 0.096 bits/symbol for AH and 0.095 bits/symbol for AA because the FTP traffic requires low packet loss rate at the application layer and the target PER at the data link layer is decreased to guarantee the low packet loss rate at the application layer. Table 3.7 and Fig. 3.5 depict the difference between the EM and PM according to service types in terms of the minimum SNR boundary for selection of an MCS level. From the result, the minimum SNR boundaries for streaming traffic were shifted to lower SNR region in the proposed method and we can infer that the proposed method selects an MCS level more aggressively than existing method. On the other hand, the minimum SNR boundary for FTP traffic were shifted to higher SNR region in the proposed method because the proposed method selects an MCS level by conservative manner for FTP traffic.
Fig. 3.3. Average spectral efficiency in AH
Fig. 3.4. Average spectral efficiency in AA
Fig. 3.5. Minimum SNR boundary for selection of an MCS level
Table 3.7. Minimum SNR boundary

<table>
<thead>
<tr>
<th></th>
<th>AMC combined with HARQ</th>
<th>AMC combined with ARQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Movie/Music streaming</td>
<td>EM: 5.33, 8.46, 12.31, 14.82, 20.83</td>
<td>EM: 4.86, 8.01, 11.77, 14.34, 20.34</td>
</tr>
<tr>
<td></td>
<td>PM: 4.33, 7.41, 11.25, 13.76, 19.76</td>
<td>PM: 3.62, 6.74, 10.45, 13.02, 18.94</td>
</tr>
<tr>
<td>(γ₂, γ₃, γ₄, γ₅, γ₆)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FTP</td>
<td>EM: 5.33, 8.46, 12.31, 14.82, 20.83</td>
<td>EM: 4.86, 8.01, 11.77, 14.34, 20.34</td>
</tr>
<tr>
<td></td>
<td>PM: 5.65, 8.78, 12.63, 15.14, 21.16</td>
<td>PM: 4.89, 8.05, 11.80, 14.37, 20.38</td>
</tr>
<tr>
<td>(γ₂, γ₃, γ₄, γ₅, γ₆)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fig. 3.6 and Fig. 3.7 depict the PER at the application layer. The PER of movie and music streaming service are increased compared with that of the existing AMC scheme. On the contrary, the PER of FTP service is decreased. This is because the streaming services tolerate the packet error and this requirement is adopted for MCS level selection. From the results, we found that the AMS scheme can improve the efficiency of wireless channel resource for error-tolerant service and can guarantee the QoS at the application layer for all service classes.
Fig. 3.7. Packet error rate in AA
Fig. 3.8 and Fig. 3.9 depict the average transmission delay at the application layer. From Fig. 3.8 the AMS scheme combined with AH increased the average transmission delay of the music and movie streaming service compared with that of the existing AMC scheme in lower SNR region. From the results, we can infer that the aggressive manner of the AMS scheme combined with AH increases the PER at the data link layer. This then causes a retransmission and the increased average transmission delay. However, the rate of increase of the average transmission delay is small and does not affect the QoS of the application. On the contrary, the AMS scheme improved the transmission delay performance of the music and movie streaming service when the average SNR is higher than 18 dB and 18.9 dB, respectively. In AMS scheme, we can transmit more bits by using higher order of MCS level in the higher SNR region and it results in the reduced average transmission delay. From Fig. 3.9 we found that the average transmission delay of the AMS scheme combined with ARQ is lower than that of the existing AMC scheme. Thus, the AMS scheme combined with ARQ can improve the average transmission delay of error-tolerant services as well as the efficiency of wireless channel resource. Consequently, the AMS scheme can enhance the efficiency of wireless channel resource within the QoS requirements of an error-tolerant services. Therefore, the AMS scheme may help overcome a paucity of wireless channel resources. For the error-sensitive services, the AMS scheme can guarantee the PLR at the application layer in compensation for the efficiency of wireless channel resource.
Fig. 3.8. Average transmission delay in AH
Fig. 3.9. Average transmission delay in AA
3.7 Summary

In this chapter, we proposed the AMS scheme for the cross-layered retransmission schemes. This scheme uses the target PLR at the application layer to select an MCS level at the physical layer. The AMS scheme reduced the discrepancy between the QoS requirements of an application and the criterion for selection of an MCS level. The AMS scheme enhanced the average spectral efficiency of streaming service compared with that of existing methods. Especially, the AMS scheme combined with AA reduced the average transmission delay at the application layer. We analyzed the AMS scheme and have shown that it can enhance the wireless channel utilization while the end-to-end delay performance satisfies the QoS requirements of a service class.

Table 3.8 depicts the trade-off between the spectral efficiency at the PHY layer and the performance at the application layer. From the results, we can infer that the AMS scheme increases the efficiency of wireless channel resource within the QoS requirements of the error-tolerant services such as movie and music streaming services, and the AMS scheme increases the QoS in compensation for the efficiency of wireless channel resource. Consequently, the AMS scheme can mitigate the discrepancy between QoS requirements at the application layer and performance at the data link layer.
Table 3.8. Trade-off of performance in AMS

<table>
<thead>
<tr>
<th></th>
<th>AH</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Spectral efficiency</td>
<td>Error rate</td>
<td>Delay</td>
<td></td>
</tr>
<tr>
<td>Error-tolerant</td>
<td>Increase</td>
<td>Increase</td>
<td>Increase</td>
<td></td>
</tr>
<tr>
<td>Error-sensitive</td>
<td>Decrease</td>
<td>Decrease</td>
<td>Decrease</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>AA</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Error-tolerant</td>
<td>Increase</td>
<td>Increase</td>
<td>Decrease</td>
</tr>
<tr>
<td>Error-sensitive</td>
<td>Decrease</td>
<td>Decrease</td>
<td>Decrease</td>
<td></td>
</tr>
</tbody>
</table>
In this chapter, we focus on the cross layer design of retransmission schemes with the objective of improving the transport layer performance between end terminals. For that, we present a method for selecting an MCS level that is TCP performance-aware and exploits the cross layer design to improve the performance at the transport layer and the network resource utilization.

4.1 Motivation

In many previous studies, the cross-layered retransmission schemes that combine a retransmission scheme at the data link layer and AMC at the physical layer were proposed [4, 5, 8–10]. Their results showed that the cross-layered retransmission schemes achieve a better performance than
does a retransmission scheme or AMC because they improve the spectral efficiency and PER by exploiting the adaptability of AMC to the wireless channel conditions and the error-correcting capability of retransmission schemes.

However, in most previous works, the existing cross-layered retransmission schemes addressed the wireless channel conditions rather than the performance at the transport layer. Thus, the performance at the transport layer may be degraded and a mismatch between the QoS requirements of applications and the transmission performance at the data link layer occurs. As a result, it is difficult to optimize the performance at the transport layer when using the schemes that have been presented in previous works. In this dissertation, we propose an MCS level selection method for the cross-layered retransmission schemes in which the performance at the transport layer is considered in the selection of an MCS level; that is TCP performance-aware MCS level selection scheme.

4.2 System and Channel Models

To design the system and channel model, we adopt the system architecture, wireless channel model, and existing MCS level selection schemes of cross-layered retransmission schemes described in Chapter 3. In this chapter, we consider the other cross-layered retransmission scheme (i.e., the AMC combined with HARQ and ARQ (AB)) as well as the cross-layered retransmission schemes (i.e., the AMC combined with HARQ (AH) and the AMC combined with ARQ (AA)) considered in Chapter
4.2.1 AMC combined with HARQ and ARQ (AB)

In this part, we present a retransmission strategy that involves AMC combined with HARQ and ARQ. The proposed scheme retransmits a packet at the MAC layer using HARQ and then retransmits a frame at the data link layer using ARQ only if a packet error still remains after the retransmission process of HARQ is complete. In this case, AH is effective only when both HARQ and ARQ are applied, because a frame is composed of several packets, which can cause a mismatch between the wireless channel state and a selected MCS level because of the long transmission time for the packets that compose a frame. Thus, in AB the selection procedure of an MCS level follows the same procedure as that of AH. The thresholds for the selection of an MCS level can be obtained by using (3.3). By using the thresholds, the AMC scheme selects an MCS level $n$ in the SNR region $[\gamma_n, \gamma_{n+1})$. In the SNR region $\gamma < \gamma_1$, in order to avoid deep channel fades, no payload bits are sent. The MCS level $N$ is selected when $\gamma \geq \gamma_N$.

4.3 Proposed TMS Scheme

In most previous works, the existing cross-layered retransmission schemes addressed the wireless channel conditions rather than the performance at the transport layer. Thus, the performance at the transport layer may be degraded and a mismatch between the QoS requirements of applications
and the transmission performance at the data link layer occurs. As a result, it is difficult to optimize the performance at the transport layer when using the schemes that have been presented in previous works. In this section, we propose a TCP performance-aware MCS level selection method to improve the performance at the transport layer. The proposed method considers the TCP throughput in the procedures for MCS level selection. The proposed method derives the SNR regions for each MCS level by using the TCP throughput. The TCP throughput when only a single MCS level is used for packet transmission is saturated as channel conditions improve, because the PER and the transmission delay of a packet both converge to minimum values. Thus, the TCP throughput of an MCS level intersects the TCP throughput of a lower or higher MCS level. Fig. 4.1 depicts the TCP throughput for each MCS level using (4.1). The figure shows that the TCP throughput at an MCS level intersects that at other MCS levels, and the envelope detection of the TCP throughput at the MCS levels is the best method for obtaining the maximum TCP throughput. To achieve a TCP throughput comparable to that obtained using the envelope detection method, we propose an MCS level selection method that considers the intersection points between the graphs of the TCP throughput, as shown in Fig. 4.1. The proposed method adopts the intersection points as the minimum SNR boundary, $\gamma_n$, for selecting an MCS level $n$. For example, the intersection point between the TCP throughput of MCS level 1 and MCS level 2 is the minimum SNR boundary for selecting MCS level 2. We can obtain five intersection points and substitute the minimum SNR boundaries in (3.3)
Fig. 4.1. TCP throughput for each MCS level

and (3.9) with the SNR values at the intersection points.

As described in Chapter 3, AH, AA, and AB select an MCS level using different methods. Therefore, we apply the proposed method to each cross-layered retransmission scheme in a different manner. In AH, an MCS level for a retransmitted packet is selected by considering the combining gain of HARQ. Thus, the existing MCS level selection method decreases the SNR boundary for each MCS level when a packet is retransmitted. This means that a transmitter may select a higher order MCS level under the same channel condition. This can increase the spectral efficiency; however, it can also increase the PER of an HARQ packet.
Thus, the PER of a TCP segment can exponentially increase, because a TCP segment generally consists of several HARQ packets. As a result, the TCP throughput can be decreased. Therefore, the proposed method adopts the intersection points of the TCP throughput for the selection of the MCS level for a retransmitted packet. The proposed method changes the minimum SNR boundaries to the SNR values of the intersection points and selects an MCS level by using the changed SNR boundaries. The proposed method mitigates the effects of the combining gain of HARQ by increasing the minimum SNR boundary for MCS level selection. Consequently, the proposed method selects an MCS level that achieves maximum TCP throughput.

AA selects an MCS level by considering the target PER and the number of transmissions to improve the spectral efficiency. The SNR boundary that is obtained by using the target PER and the number of transmissions is applied for every transmission attempt of a packet. Therefore, we applied the proposed MCS level selection method to every transmission attempt. The proposed MCS level selection method considers both the target PER and the intersection points of the TCP throughput.

In AB, the minimum SNR boundary for MCS level selection is the same as in the above-mentioned AH case, because HARQ is the dominant process for selecting an MCS level.

Algorithm 4.1 captures the procedure of the proposed MCS level selection method in AMC combined with HARQ. The algorithm of PM in AA is similar to Algorithm 4.1 except for the procedure for distinguish-
ing an initial transmission and retransmissions.

\textbf{Algorithm 4.1} MCS level selection method in TMS

1: \textbf{if} HARQ is used \textbf{then}
2: \hspace{1em} \textbf{if} the packet is transmitted initially \textbf{then}
3: \hspace{2em} Select an MCS level by using $P_t$ and the received SNR.
4: \hspace{1em} \textbf{else}
5: \hspace{2em} Calculate $\gamma_{nP_t}$ by using $P_t$ and the combining gain of HARQ.
6: \hspace{2em} Obtain $\gamma_{nTCP}$ based on the TCP throughput.
7: \hspace{1em} \textbf{end if}
8: \textbf{end if}
9: \textbf{if} ARQ is only used \textbf{then}
10: \hspace{1em} Calculate $\gamma_{nP_t}$ by using $P_t$ and the combining gain of HARQ.
11: \hspace{1em} Obtain $\gamma_{nTCP}$ based on the TCP throughput.
12: \textbf{end if}
13: \textbf{if} $\gamma_{nP_t} \neq \gamma_{nTCP}$ \textbf{then}
14: \hspace{1em} $\gamma_{n} = \gamma_{nTCP}$
15: \textbf{end if}
16: Select an SNR region that includes the received SNR.
17: Select an MCS level corresponding to the SNR region.
4.4 Performance Analysis

To obtain the end-to-end performance, we derive the throughput by using the PER of a TCP segment and the transmission delay at the transport layer. We also derive the average spectral efficiency for analyzing the correlation between the wireless channel utilization and the performance at the transport layer. Based on the correlation, we verify that optimization of the spectral efficiency according to the wireless channel conditions cannot guarantee the optimized throughput at the transport layer.

4.4.1 Throughput at the Transport Layer

We adopted TCP Reno as an end-to-end reliable segment transmission protocol. Then, the throughput at the transport layer, $S$, can be approximated by

$$S \approx \frac{1}{RTT \sqrt{\frac{2n_s p}{3}} + T_0 \min \left( 1, 3 \sqrt{\frac{3n_s p}{8}} \right) p \left( 1 + 32p^2 \right)}, \quad (4.1)$$

where $n_s$, $T_0$, and $RTT$ denote the number of segments that are acknowledged by a received acknowledgement (ACK), the transmission timeout duration, and the maximum time gap between the segment transmission time and the ACK received time, respectively. $p$ denotes the TCP segment error rate and can be calculated as

$$p = 1 - (1 - P_{drop})^{N_S}, \quad (4.2)$$

where $N_S$ denotes the number of RLC frames that are segments of a TCP segment and $P_{drop}$ denotes the error probability of a packet after the error
recovery process of a packet is completed. $P_{\text{drop}}$ for each retransmission scheme AH, AA, and AB, can be calculated respectively as

$$P_{\text{drop, AH}} = \overline{\text{PER}}_{\text{AH}}^{(N_t, \text{AH})},$$

$$P_{\text{drop, AA}} = \overline{\text{FER}}_{\text{AA}}^{N_t, \text{AA}},$$

$$P_{\text{drop, AB}} = \overline{\text{FER}}_{\text{AB}}^{N_t, \text{AA}},$$

where $\overline{\text{PER}}_{\text{AH}}^{(N_t, \text{AH})}$ denotes the average PER of a packet after the error recovery process of HARQ is completed, $\overline{\text{FER}}_{\text{AA}}$ and $\overline{\text{FER}}_{\text{AB}}$ denote the average FER of AA and AB, respectively. $P_{\text{drop, AH}}$, $P_{\text{drop, AA}}$, and $P_{\text{drop, AB}}$ denote the packet drop probability in AH, AA, and AB, respectively. $N_t$ denotes the maximum number of transmissions in ARQ. The average PER (i.e., $\overline{\text{PER}}_{\text{AH}}$, $\overline{\text{FER}}_{\text{AA}}$, and $\overline{\text{FER}}_{\text{AB}}$) can be obtained by using a different method according to the retransmission schemes.

### 4.4.1.1 Average PER in AH

To determine the average PER of the HARQ scheme, we must consider all cases including the MCS level and the number of packet transmissions. Then, the average PER is expressed as

$$\overline{\text{PER}}_H = \sum_{n_1=1}^{N_t} \sum_{n_2=1}^{N_t} \cdots \sum_{n_{N_t-H}=1}^{N_t} \int_{\gamma_1}^{\gamma_1(1)} \int_{\gamma_2}^{\gamma_2(2)} \cdots \int_{\gamma_{N_t-H}}^{\gamma_{N_t-H}(1)} \overline{\text{PER}}_{n_1, n_2, \cdots, n_{N_t-H}} \left(\gamma_1, \gamma_2, \cdots, \gamma_{N_t-H}\right) p\left(\gamma_1\right) p\left(\gamma_2\right) \cdots p\left(\gamma_{N_t-H}\right) d\gamma_{N_t-H} \cdots d\gamma_2 d\gamma_1,$$

where $\overline{\text{PER}}_{n_1, n_2, \cdots, n_{N_t-H}}$ denotes the average PER of a packet after the error recovery process of HARQ is completed, and $p\left(\gamma_{n_1, n_2, \cdots, n_{N_t-H}}\right)$ denotes the probability of the MCS level and number of transmissions.
\[ \text{PER}_{n_1,n_2,\ldots,n_{N_t}}(\gamma^{(1)}, \ldots, \gamma^{(N_t,H)}) = P \left\{ \mathcal{F}_{n_1}^{(1)}(\gamma^{(1)}), \ldots, \mathcal{F}_{n_1,n_2,\ldots,n_{N_t,H}}^{(N_t,H)}(\gamma^{(1)}, \gamma^{(2)}, \ldots, \gamma^{(N_t,H)}) \right\}, \]

(4.7)

where \( P \{ \mathcal{F}_{n_1,\ldots,n_i}^{(i)}(\gamma^{(1)}, \ldots, \gamma^{(i)}) \} \) denotes the probability of an error event after \( i \) times transmissions using MCS level \( n_1, \ldots, n_i \) under SNR values equal to \( \gamma^{(1)}, \ldots, \gamma^{(i)} \), respectively [5]. We can calculate \( P \{ \cdot \} \) by using the upper bound [84].

### 4.4.1.2 Average FER in AA

The average FER can be derived when the transmitter uses MCS level \( n \) as [4, 5]

\[
\overline{\text{FER}}_n = \frac{1}{\Pr(n)} \cdot \frac{a_n}{\gamma} \cdot \frac{1}{c_n} \left( \exp(-c_n \gamma_n) - \exp(-c_n \gamma_{n+1}) \right),
\]

(4.8)

where \( c_n = \frac{1}{\gamma} + g_n \) and \( \Pr(n) \) denotes the selection probability of MCS level \( n \) obtained by using the Rayleigh fading channel model. The average FER can be computed as the ratio of the average number of incorrectly received frames to the total average number of transmitted frames, and it is given by

\[
\overline{\text{FER}}_A = \frac{\sum_{n=1}^{N} R_n \Pr(n) \overline{\text{FER}}_n}{\sum_{n=1}^{N} R_n \Pr(n)},
\]

(4.9)

where \( N \) denotes the highest level among available MCS levels [4].

### 4.4.1.3 Average FER in AB

When both HARQ and ARQ are implemented in the system, an ARQ scheme is executed only if a packet error still remains after the HARQ
process. Therefore, the average FER can be computed by using the PER of a packet, and it is given by

$$FER_C = 1 - \left(1 - \overline{PER}_{HARQ}^{(N_{tx,H})}\right)^{N_{packet}},$$

where $FER_C$, $\overline{PER}_{HARQ}^{(N_{tx,H})}$ and $N_{packet}$ denote the average FER, the error probability of a packet after the error recovery process of the HARQ is completed, and the number of HARQ packets that make up an RLC frame, respectively.

### 4.4.2 Average Transmission Delay

The transmission delay at the transport layer is composed of two delay components, such as a delay in the wireless channel and a delay in the wired backbone networks as shown in Fig. 3.1, and it is expressed as follows:

$$D_{trans} = D_W + D_B,$$

where $D_{trans}$ denotes the one-way segment delivery time from the server to the end terminal at the transport layer. $D_W$ and $D_B$ denote the delay in the wireless channel and backbone networks, respectively. $D_W$ can be derived from the average number of transmissions and should be calculated by a different method according to the retransmission schemes. When using the AMC combined with HARQ, the delay at the data link layer, $D_{W,H}$, is described as follows:

$$D_{W,H} = \left(D_{one,P} + D_{round,P} \left(\overline{N}_{tx,H} - 1\right)\right) \cdot N_{packet} + 2D_{proc},$$
where $D_{one,P}$ and $D_{round,P}$ denote the one-way delay and the round-trip delay at the physical layer. $D_{proc}$ is the sum of the intra-layer processing delay and inter-layer processing delay. $\bar{N}_{tx,H}$ denotes the average number of transmissions of an HARQ packet, and it is given by

$$\bar{N}_{tx,H} = \frac{1 - \frac{PER_{HARQ}^{N_{t},H}}{1 - \frac{PER_{HARQ}^{N_{t},H}}}}{1 - \frac{PER_{HARQ}}{1 - \frac{PER_{HARQ}}}},$$  \hspace{1cm} \text{(4.13)}$$

The delay at the data link layer when the wireless communication systems adopt the AMC combined with ARQ, $D_{W,A}$, can be calculated as

$$D_{W,A} = D_{one,D} + D_{round,D} \left( \bar{N}_{tx,A} - 1 \right),$$ \hspace{1cm} \text{(4.14)}$$

where $D_{one,D}$ and $D_{round,D}$ denote the one-way delay and the round-trip delay at the data link layer. $\bar{N}_{tx,A}$ denotes the average number of transmissions of a frame and can be calculated as

$$\bar{N}_{tx,A} = \frac{1 - \frac{PER_{ARQ}^{N_{t},A}}{1 - \frac{PER_{ARQ}}}}{1 - \frac{PER_{ARQ}}},$$ \hspace{1cm} \text{(4.15)}$$

In the proposed scheme, the delay at the data link layer, $D_{W,Comb}$, can be calculated as

$$D_{W,Comb} = (D_{one,P} + D_{W,H}) \cdot N_{packet} + 2D_{proc},$$ \hspace{1cm} \text{(4.16)}$$

The average transmission delay of a TCP segment can be derived as follows:

$$\sum_{n=1}^{\infty} P_n \cdot D_{trans},$$ \hspace{1cm} \text{(4.17)}$$

where $P_n$ denotes the probability that the $n$-th transmission attempt for a TCP segment occurs. We assume that a frame or a packet can
be transmitted successfully within fourth transmission attempt. Then, \( P_n \) can be derived by using the error rate of a frame or a packet and the number of frames related to a TCP segment, and it is expressed as follows:

\[
P_n = \begin{cases} 
(1 - P_{\text{drop}})^{N_f}, & n = 1 \\
\sum_{i=1}^{N_f} \binom{N_f}{i} P_{\text{drop}}^i (1 - P_{\text{drop}})^{N_f-i}, & n = 2 \\
\sum_{i=1}^{N_f} \binom{N_f}{i} P_{\text{drop}}^i \sum_{j=1}^{i} \binom{i}{j} P_{\text{drop}}^j, & n = 3 \\
P_{\text{drop}}^j \cdot (1 - P_{\text{drop}})^{2(i-j)} \sum_{k=1}^{i-j} \binom{i-j}{k} P_{\text{drop}}^k, & n = 4 
\end{cases}
\]  

(4.18)

4.4.3 Average Spectral Efficiency

The average spectral efficiency can be obtained by using the selection probability of MCS level \( n \), and it is given by

\[
\overline{S}^{(i)} = \sum_{n=1}^{N} R_n \Pr(n),
\]

(4.19)

where \( \overline{S}^{(i)} \) and \( \Pr(n) \) denote the average spectral efficiency at the \( i \)-th transmission attempt and the selection probability of MCS level \( n \), respectively. Moreover, \( R_n \) denotes the number of bits per symbol at MCS level \( n \). We can obtain the selection probability of MCS level \( n \) by
using Rayleigh fading as the wireless channel model as follows [84]:

\[
\Pr (n) = \int_{\gamma_n}^{\gamma_{n+1}} p_r (\gamma) d\gamma \\
= \exp \left(-\frac{\gamma_n}{\gamma}\right) - \exp \left(-\frac{\gamma_{n+1}}{\gamma}\right),
\]

(4.20)

where \( \gamma_n \) and \( p_r (\gamma) \) denote the SNR boundary when using MCS level \( n \) and the SNR distribution of the Rayleigh fading channel, respectively. If we know the average PER and spectral efficiency of the \( i \)-th transmitted packet, we can calculate the overall average spectral efficiency as

\[
\overline{S}_{\text{overall}} = \sum_{i=1}^{N_t} P_i \overline{S}^{(i)},
\]

(4.21)

where \( P_i \) denotes the probability that the \( i \)-th transmission attempt occurs. We can calculate \( P_i \) by using the average PER as

\[
P_i = \begin{cases} 
1 & i = 1 \\
\frac{1}{PER^i - 1} (1 - \overline{PER}) & i = 2, 3, \cdots, N_t 
\end{cases}
\]

(4.22)

4.5 Numerical Results

We evaluated the performance of the existing MCS level selection method and the proposed MCS level selection method when a system uses a cross-layered retransmission scheme. We adopt the system parameters listed in Table 3.6. To simplify the performance evaluation, we assumed that the transmission delay over the backbone network is 100 ms [81]. To evaluate the effects of the PM, we compared the performance of the EM and the PM in terms of transmission delay, PER, throughput, and average spectral efficiency.
Table 4.1. Minimum SNR boundary for packet retransmission

<table>
<thead>
<tr>
<th>$\gamma_n$</th>
<th>AH</th>
<th></th>
<th>AA</th>
<th></th>
<th>AB</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Existing</td>
<td>Proposed</td>
<td>Existing</td>
<td>Proposed</td>
<td>Existing</td>
<td>Proposed</td>
</tr>
<tr>
<td>$\gamma_2$</td>
<td>0.177</td>
<td>2</td>
<td>4.859</td>
<td>5</td>
<td>0.177</td>
<td>1.7</td>
</tr>
<tr>
<td>$\gamma_3$</td>
<td>3.235</td>
<td>5</td>
<td>8.015</td>
<td>8.4</td>
<td>3.235</td>
<td>6.6</td>
</tr>
<tr>
<td>$\gamma_4$</td>
<td>7.295</td>
<td>9.3</td>
<td>11.766</td>
<td>12.2</td>
<td>7.295</td>
<td>10.5</td>
</tr>
<tr>
<td>$\gamma_5$</td>
<td>9.917</td>
<td>12.7</td>
<td>14.339</td>
<td>14.8</td>
<td>9.917</td>
<td>13.3</td>
</tr>
<tr>
<td>$\gamma_6$</td>
<td>16.141</td>
<td>18.8</td>
<td>20.342</td>
<td>20.8</td>
<td>16.141</td>
<td>19.1</td>
</tr>
</tbody>
</table>

4.5.1 Minimum SNR Boundary

We compared the minimum SNR boundary for packet retransmission, $\gamma_n$, of the EM and the PM. Fig. 4.2 depicts the difference between the EM and PM in terms of the minimum SNR boundary for a retransmitted packet. The figure shows that the minimum SNR boundaries in the PM are shifted to a higher received SNR than in the EM. From these results, we inferred that the EM is more aggressive than the PM, because the EM can select a higher MCS level under the same wireless channel conditions than can the PM.

Table 4.1 shows the results for the minimum SNR boundary. In a practical system, we can easily use the results of Table 4.1 for MCS level selection.
### Existing method

<table>
<thead>
<tr>
<th>Region 1</th>
<th>Region 2</th>
<th>Region 3</th>
<th>Region 4</th>
<th>Region 5</th>
<th>Region 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCS Level 1</td>
<td>MCS Level 2</td>
<td>MCS Level 3</td>
<td>MCS Level 4</td>
<td>MCS Level 5</td>
<td>MCS Level 6</td>
</tr>
</tbody>
</table>

### Proposed method

<table>
<thead>
<tr>
<th>Region 1</th>
<th>Region 2</th>
<th>Region 3</th>
<th>Region 4</th>
<th>Region 5</th>
<th>Region 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCS Level 1</td>
<td>MCS Level 2</td>
<td>MCS Level 3</td>
<td>MCS Level 4</td>
<td>MCS Level 5</td>
<td>MCS Level 6</td>
</tr>
</tbody>
</table>

Fig. 4.2. Minimum SNR boundary for selection of an MCS level

![Figure 4.2](image-url)
4.5.2 Transmission Delay

Fig. 4.3, Fig. 4.4, and Fig. 4.5 depict the average transmission delay at the transport layer between the server and the end terminal. The average transmission delay of the PM is longer than that of the EM, because the PM uses the conservative method to select an MCS level. Thus, the PM needs to transmit more symbols due to the low information bits per symbol. This can increase the average transmission delay. As shown in Figs. 4.3 - 4.5, the average transmission delay in each cross-layered retransmission scheme, AH, AA, and AB, is increased by a maximum of 10 ms, 3 ms, and 18 ms, respectively. However, the increased delay is less than 10% of the total delay and guarantees that the delay requirement of the service classes that use the TCP protocol is met [71]. Furthermore, we found that the difference in the average transmission delay of the EM and the PM is reduced as the average SNR increases. Therefore, the average transmission delay of the PM may not affect the QoS.
Fig. 4.3. Average transmission delay in AH
Fig. 4.4. Average transmission delay in AA
Fig. 4.5. Average transmission delay in AB
4.5.3 Packet Error Rate

Fig. 4.6, Fig. 4.7, and Fig. 4.8 describe the PER of a TCP segment in each cross-layered retransmission scheme. The figures show that the PM reduces the PER as compared with the EM, because the PM applies the conservative method to select an MCS level. This may decrease the PER of an HARQ PDU. Thus, the PER of a TCP segment can be decreased exponentially. The PER in AH, AA, and AB is decreased by a maximum of $10^{-5}$, $1/5$, and $2 \times 10^{-11}$, respectively. In particular, the PER in AB is very small as a result of the many retransmission opportunities of a PHY packet. The reduction in the PER of a TCP segment may increase the performance in the backbone networks. This can reduce the traffic loads in backbone networks, because the number of retransmissions of a TCP segment can be decreased. Moreover, a sender can push many segments into the networks simultaneously by maintaining a large value of the transmission window size of the TCP protocol. Thus, a sender can transmit data rapidly when the PM is applied for MCS level selection.
Fig. 4.6. TCP segment error rate in AH
Fig. 4.7. TCP segment error rate in AA
Fig. 4.8. TCP segment error rate in AB
4.5.4 Throughput

Fig. 4.9, Fig. 4.10, and Fig. 4.11 depict the throughput at the transport layer. The PM increased the throughput in AH and AA. This is because the PM decreases the PER of a TCP segment, as shown in Figs. 4.6 - 4.7. However, we found that the throughput of the PM is similar to that of the EM when using AB, because the PER of a TCP segment when the EM is used for MCS level selection is sufficiently low to allow a TCP segment to be transmitted without error. Thus, the PM cannot obtain a gain in terms of the throughput at the transport layer. Therefore, the PM is effective when AH and AA are used for MCS level selection.
Fig. 4.9. Throughput at the transport layer in AH
Fig. 4.10. Throughput at the transport layer in AA
Fig. 4.11. Throughput at the transport layer in AB
4.5.5 Average Spectral Efficiency

In this subsection, we analyze the trade-off between the average spectral efficiency at the PHY layer and the throughput at the transport layer.

Fig. 4.12 illustrates the average spectral efficiency in AH. As shown in Fig. 4.12, the average spectral efficiency values of the EM and the PM are similar, because the PM is applied for a retransmitted packet in AH. In the EM and the PM, the spectral efficiency values of a packet at the initial transmission are equal, while the spectral efficiency values for a retransmitted packet are different. AH has a small retransmission opportunity in comparison with AA because of the soft combining gain of AH. Thus, the average spectral efficiency values of the EM and the PM are similar. Fig. 4.13 shows the spectral efficiency for each transmission attempt in AH. The PM selects an MCS level for a retransmitted packet based on the conservative criteria. This can decrease the PER of a TCP segment and enhance the throughput, as shown in Figs. 4.6 - 4.8. However, the spectral efficiency of a retransmitted packet can be decreased in the PM. By simultaneously considering the throughput and the average spectral efficiency, the PM obtains enhanced throughput at the transport layer without the average spectral efficiency being degraded. Consequently, the PM in AH can improve the user-perceived QoS instead of degrading the spectral efficiency of a retransmitted packet.
Fig. 4.12. Average spectral efficiency in AH
Fig. 4.13. Spectral efficiency for each transmission attempt in AH
Fig. 4.14 depicts the average spectral efficiency in AA. The figure shows that the average spectral efficiency of the PM is lower by 0.09 bits/symbol at 19 dB than that of the EM. In our analysis of the effects of the PM, we considered the average spectral efficiency at the PHY layer and the throughput at the transport layer, simultaneously. The PM decreases the average spectral efficiency at the PHY layer; however, the PM can achieve an improved throughput performance at the transport layer, as shown in Figs. 4.10 and Fig. 4.14. The results show that the PM can improve the user-perceived QoS.
Fig. 4.14. Average spectral efficiency in AA
Fig. 4.15 shows the average spectral efficiency in AB. The average spectral efficiency in the PM is lower than that in the EM by 0.19 bits/symbol at 15 dB. Figs. 4.11 and 4.15 show that the PM cannot improve the performance at the transport layer and degrades the average spectral efficiency when AB is applied for MCS level selection. This is because the PER of a TCP segment is sufficiently low to allow the TCP segment to be transmitted without errors when AB is applied for MCS level selection. Thus, the PM cannot improve the performance at the transport layer, except in terms of the PER.
Fig. 4.15. Average spectral efficiency in AB
To summarize the above results, the transmission efficiency over the wireless channel can be decreased in the PM. On the other hand, the PM can improve the performance at the transport layer and reduce the traffic load due to the retransmission of a TCP segment. According to the results, we can conclude that a global optimum may not be achieved by optimizing the spectral efficiency according to the wireless channel conditions.

4.6 MCS Level Selection Scheme for Each Service Class

To improve the QoS, an appropriate MCS level selection scheme is selected based on the end-to-end performance. In this dissertation, two MCS level selection schemes, i.e., AMS scheme and TMS scheme, have been proposed. In this section, we present an appropriate MCS level selection scheme for a service type based on the performance at the transport layer. Fig. 4.16 - 4.18 describe the throughput at the transport layer for each cross-layered retransmission schemes. By using the results, we can present an appropriate MCS level selection scheme according to the service characteristics as shown in Table 4.2. From the results, the throughput of error-tolerant service is maximized where TMS scheme is used for AH and AA and AMS scheme is used for AB. In error-sensitive service, the throughput is maximized where TMS is used for AH and AB and AMS is used for AA.
<table>
<thead>
<tr>
<th>Service type</th>
<th>AH</th>
<th>AA</th>
<th>AB</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Error-tolerant service</td>
<td>TCP Performance-aware</td>
<td>Application-aware</td>
<td>MCS level selection scheme</td>
<td></td>
</tr>
<tr>
<td>Error-sensitive service</td>
<td>TCP Performance-aware</td>
<td>Application-aware</td>
<td>MCS level selection scheme</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2. MCS level selection scheme according to service characteristics
Fig. 4.16. Throughput for AH
Fig. 4.17. Throughput for AA
Fig. 4.18. Throughput for AB
4.7 Summary

In this chapter, we proposed an MCS level selection method that considers the throughput at the transport layer. We presented comparative numerical results for the performance of the existing and the proposed method in terms of the average transmission delay, PER of a TCP segment, throughput at the transport layer, and average spectral efficiency at the PHY layer. According to these results, the proposed method can enhance the performance at the transport layer and network resource utilization by reducing the traffic load due to the retransmission. Consequently, we can assert that the proposed method is effective for error-tolerant services when AH and AA are applied in wireless communication systems. For the error-sensitive services, the proposed method is effective where AH or AB is adopted as a cross-layered retransmission scheme.

Table 4.3 depicts the trade-off between performance metrics. From the results, the TMS scheme deteriorates the performance of the efficiency of wireless channel resource and delay at the transport layer. On the contrary, the TMS scheme improves the performance of the error rate and throughput at the transport layer. Even though the TMS deteriorate the efficiency and delay performance, the TMS scheme can transmit more information to receiver during unit time because the TMS scheme improves the throughput and error rate at the transport layer. Consequently, the TMS scheme can improve the user-perceived performance. In our opinion, the proposed method can be easily implemented in practical wireless communication systems by using the predefined parameters.
**Table 4.3.** Trade-off of performance in TMS

<table>
<thead>
<tr>
<th></th>
<th>AH</th>
<th>AA</th>
<th>AB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource efficiency</td>
<td>Decrease</td>
<td>Decrease</td>
<td>Decrease</td>
</tr>
<tr>
<td>Delay</td>
<td>Increase</td>
<td>Increase</td>
<td>Increase</td>
</tr>
<tr>
<td>Error rate</td>
<td>Decrease</td>
<td>Decrease</td>
<td>Decrease</td>
</tr>
<tr>
<td>Throughput</td>
<td>Increase</td>
<td>Increase</td>
<td>Increase</td>
</tr>
</tbody>
</table>
Conclusion

In this dissertation, MCS level selection methods for the cross-layered retransmission schemes are presented to improve user-perceived performance and network resource efficiency.

The following question is addressed in this dissertation. If an algorithm can optimize the performance at the PHY layer, is it adequate for optimizing the end-to-end performance between end-terminals? We answered the question by evaluating the performance at the transport layer and the application layer. In most previous works, the presented cross-layered retransmission schemes addressed the wireless channel conditions rather than the user-perceived performance. The performance at the transport layer is degraded and a mismatch between the QoS requirements of applications and the transmission performance at the data link layer occurs. Therefore, this dissertation has focused on these problems.

To solve the problems, analytical models, a novel cross-layered retransmission scheme (i.e., AMC combined with HARQ and ARQ), and
two MCS level selection schemes (i.e., Application-aware MCS level selection scheme and TCP performance-aware MCS level selection scheme) are presented. The application-aware MCS level selection scheme reduces the discrepancy between the QoS requirements of an application and the criterion for selection of an MCS level by using the target PLR at the application layer. The TCP performance-aware MCS level selection scheme considers the throughput at the transport layer as criteria for selection of an MCS level. This proposed scheme enhances the performance at the transport layer and network resource efficiency by reducing the traffic load due to the retransmission. This dissertation presents the guideline to design the cross-layered retransmission schemes according to the service characteristics based on the performance evaluation results. This guideline can be used for improving the user-perceived performance and network resource efficiency in wireless networks where a cross-layered retransmission scheme is adopted for retransmission.

Presently, the mobile traffic and wireless communication devices to be sharply increased. Therefore, it is important to improve the efficiency of network resource. The proposed schemes can improve the efficiency and user-perceived performance. It is expected that the proposed schemes can be applied to future wireless networks and devices.
References


[77] A. Goldsmith, *Wireless Communications*. Cambridge University Press. 38


[80] Q. Li and M. van der Schaar, “Providing adaptive qos to layered video over wireless local area networks through real-time retry limit adapta-
tion,” *Multimedia, IEEE Transactions on*, vol. 6, no. 2, pp. 278–290, April 2004. 43

