

Optimal Modulation and Coding Scheme Selection in Cellular Networks with Hybrid-ARQ Error Control

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Abstract—We propose an optimal modulation and coding scheme (MCS) selection criterion for maximizing user throughput in cellular networks. The proposed criterion adopts both the Chase combining and incremental redundancy based hybrid automatic repeat request (HARQ) mechanisms and it selects an MCS level that maximizes the expected throughput which is estimated by considering both the number of transmissions and successful decoding probability in HARQ operation. We also prove that the conventional MCS selection rule is not optimized with mathematical analysis. Through link-level and system-level simulations, we show that the proposed MCS selection criterion yields higher average cell throughput than the conventional MCS selection schemes for slowly varying channels.

Index Terms—Link adaptation (LA), hybrid automatic repeat request (HARQ), modulation and coding scheme (MCS), expected throughput, Chase combining, incremental redundancy (IR), OFDM, HSDPA.

I. INTRODUCTION

LINK adaptation (LA) techniques significantly increase user throughput by providing efficient ways to maximize spectral efficiency with the instantaneous quality of wireless channels[1][2][3]. Hybrid automatic repeat request (HARQ) techniques accompanied by retransmission improve the throughput performance of the LA techniques by compensating for link adaptation errors caused by inaccurate channel estimation and the channel quality feedback delay[4][5]. In a Chase combining (CC)-based HARQ mechanism, base station (BS) retransmits the same frame as that of the initial transmission and, for decoding, mobile station (MS) uses the energy increased by combining every received frame[6]. Incremental redundancy (IR), which is a more complex HARQ mechanism, sends additional parity bits through retransmitted frames and increases the probability of successful decoding by achieving both signal-to-interference-and-noise-ratio (SINR) gain and coding gain through retransmissions[7][8].

The mapping between the channel quality and modulation and coding scheme (MCS) level is one of the important design issues in the LA techniques[9]. The conventional mapping

design was to choose an MCS level which maximizes the instantaneous data rate within a given constraint of frame error rate (FER)[10]. However, the design did not consider the performance improvement through HARQ operation. Zheng *et al.*[11] proposed an MCS selection criterion considering HARQ operation in which the mapping design is based on maximizing the average user throughput. However, they approximated the user throughput without estimating the exact expected throughput obtained through HARQ operation in retransmission.

In this letter, we investigate how to optimize the selection of MCS levels for maximizing user throughput in cellular networks while taking into account HARQ operation. We consider both the HARQ mechanisms with CC and IR and, for each HARQ mechanism, the proposed mapping design is to select an MCS level which maximizes the expected throughput (ET). Under the time-invariant channel states during retransmissions, the proposed method optimally estimates the expected throughput for a given number of transmissions and successful decoding probability in HARQ operation. We also mathematically prove that the conventional MCS mapping rule proposed in [11] is not optimized with respect to the expected throughput and, through the proof, we find that the proposed exact MCS mapping rule estimates larger or equal throughput to the conventional mapping rule. Through link-level and system-level simulations, we show that the proposed ET-based mapping criterion yields higher average cell throughput than the compared mapping schemes for slowly varying channels.

The rest of this letter is organized as follows. In Section II, we analyze the expected throughput with HARQ for a given MCS level and propose an optimal MCS selection criterion in cellular networks with HARQ error control. In Section III, we compare the performance of the proposed MCS selection criterion with that of the conventional schemes, based on link-level and system-level simulations. Finally, we conclude this letter in Section IV.

II. OPTIMAL MCS SELECTION CRITERION

We present an optimal approach to design the mapping between the channel quality, i.e., SINR and MCS level for maximizing user throughput. In this letter, we assume that a synchronous HARQ scheme is employed for slowly varying channels. Therefore, retransmissions are likely to occur soon after the initial transmission[12] and, the channel state remains constant during retransmissions as that of the initial transmission. If the channel states vary during retransmissions, the expected throughput may be different from the actual

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TABLE I
ACRONYMS

Notation	Definition
LA	Link Adaptation
HARQ	Hybrid Automatic Repeat reQuest
MCS	Modulation and Coding Scheme
SINR	Signal-to-Interference-and-Noise-Ratio
BS	Base Station
MS	Mobile Station
CC	Chase Combining
IR	Incremental Redundancy
FER	Frame Error Rate
ET	Expected Throughput
AUT	Approximated User Throughput

throughput. However, in this case, the proposed MCS selection criterion is still effective because the aggregated SINR value increases as the number of HARQ operations accompanied by retransmissions increases. Once BS selects an MCS level of a given frame, the reselection procedure of MCS level for the frame does not occur until all HARQ operations accompanied by transmissions are completed. Acronyms are listed in Table I.

A. Expected Throughput with HARQ

We first analyze the expected throughput (ET) for a given MCS level, considering HARQ operations accompanied by retransmissions. MCS is one of the schemes made by the combination of various modulation methods such as quadrature phase shift keying (QPSK) and 16 quadrature amplitude modulation (16QAM), and various code rates obtained from puncturing or repetition by a channel encoder. The selection of MCS level for a given frame is performed before the frame is actually transmitted and, according to the objectives of the mapping designs in the LA techniques, MCS levels are differently selected. The proposed mapping design aims at achieving the maximization of user throughput and, for this, the design is to select an MCS level which maximizes the expected throughput. The proposed optimal method for estimating the expected throughput exploits not only the channel quality but also the utilized HARQ operation, which is defined as the following lemma:

LEMMA 1: *The channel state is assumed to be time-invariant during retransmissions. The expected throughput (ET) obtained by adopting the Chase combining (CC)-based*

HARQ mechanism is the summation of the throughput estimated at each (re)transmission. For given MCS i and the maximum number of transmissions N_{\max} , the ET obtained through the CC-based HARQ mechanism with the channel quality, SINR γ , is expressed as (1) where R_i is the data rate of MCS i , $\Pr(S_k|F_1, \dots, F_{k-1})$ denotes the probability that a frame is successfully decoded at the k -th transmission, conditioned on the previous $k-1$ unsuccessful transmissions, and $F_i(\cdot)$ is the associated FER of MCS i with SINR (\cdot) .

PROOF. The throughput at each (re)transmission with HARQ operation is obtained by multiplying the data rate achieved at each (re)transmission with the probability that a frame is successfully decoded at the (re)transmission. If a frame made by MCS i is transmitted k times, the data rate achieved at the k -th transmission is reduced to R_i/k . With a soft-combined frame obtained through the CC-based HARQ mechanism, the SINR used to decode the frame after a retransmission increases to the sum of the SINR corresponding to the original transmission and the subsequent retransmission. Under the time-invariant channel states during retransmissions, the SINR after the k -th transmission is $k\gamma$ when γ is the SINR at the initial transmission. In addition, at the k -th transmission, the FER is retrieved by relating $k\gamma$ to the look-up table of MCS i . Therefore, the throughput with SINR γ at the k -th transmission is expressed as $(R_i/k) \cdot \prod_{m=1}^{k-1} F_i(m\gamma)(1 - F_i(k\gamma))$, which is illustrated in Fig. 1 in detail. Consequently, with the CC-based HARQ mechanism, (1) holds as the sum of the throughput obtained from the initial transmission up to the N_{\max} -th transmission. We will extend (1) in the case of an IR-based HARQ mechanism in Subsection II-C.

On the other hand, Zheng *et al.*[11] also proposed an MCS selection criterion considering HARQ operation in which the mapping design is to choose an MCS level maximizing the approximated user throughput (AUT). For given MCS i and the maximum number of transmissions N_{\max} , the AUT obtained through the CC-based HARQ mechanism with SINR γ is expressed as (2) where the numerator term indicates the average data rate achieved with successful decoding and the denominator terms represent the average number of transmissions with the HARQ operations. However, (2) is not the exact expected throughput and, thus, to prove this, we perform the mathematical analysis which compares (1) with (2) in Subsection II-B.

$$\begin{aligned}
 ET_i(\gamma) &= R_i \Pr(S_1) + \frac{R_i}{2} \Pr(S_2|F_1) + \dots + \frac{R_i}{N_{\max}} \Pr(S_{N_{\max}}|F_1, \dots, F_{N_{\max}-1}) \\
 &= R_i \sum_{k=1}^{N_{\max}} \frac{1}{k} \prod_{m=1}^{k-1} F_i(m\gamma)(1 - F_i(k\gamma))
 \end{aligned} \tag{1}$$

$$AUT_i(\gamma) = \frac{R_i(1 - \prod_{m=1}^{N_{\max}} F_i(m\gamma))}{\sum_{k=1}^{N_{\max}} k \prod_{m=1}^{k-1} F_i(m\gamma)(1 - F_i(k\gamma)) + N_{\max} \prod_{m=1}^{N_{\max}} F_i(m\gamma)} \tag{2}$$

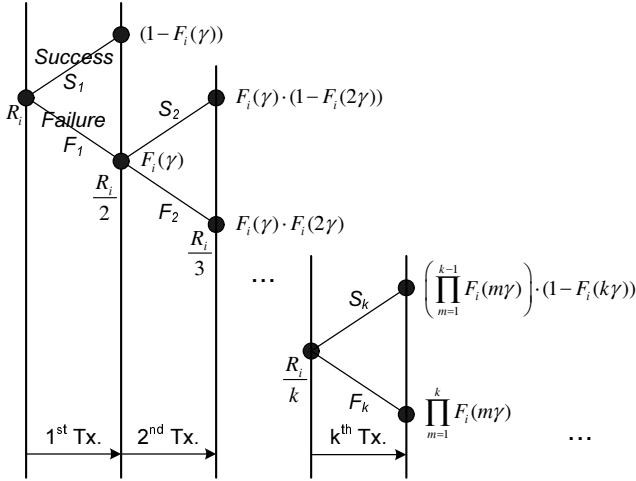


Fig. 1. Expected throughput obtained through the CC-based HARQ mechanism at each (re)transmission.

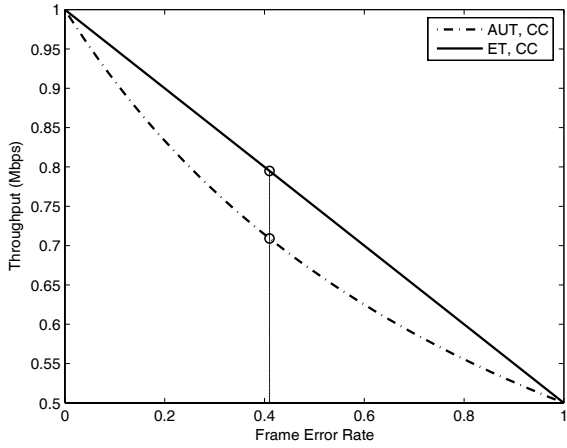


Fig. 2. Comparison between throughput obtained by the ET and AUT where the CC-based HARQ mechanism is employed in both methods.

B. Comparison of Throughput Estimation Methods

We first compare the throughput estimated by (1) in LEMMA 1 and (2) using a simple example. In this example, we assume that BS selects MCS i with SINR γ for transmission of a frame. And, MS successfully decodes a soft-combined frame obtained through the CC at the second transmission. When the data rate of MCS i is assumed to be 1 Mbps, the throughput obtained from (1) is $1 \cdot (1 - F_i(\gamma)) + (1/2) \cdot F_i(\gamma) \cdot 1 = 1 - F_i(\gamma)/2$ Mbps, while the throughput obtained from (2) is $1/(1 + F_i(\gamma))$ Mbps. As shown in Fig. 2, when $0 < F_i(\gamma) < 1$, the throughput from the ET is higher than that from the AUT. It implies that, for a given MCS level, the proposed method yields higher throughput than the AUT for any $F_i(\gamma)$ except the case that $F_i(\gamma)$ is equal to 0 or 1.

Furthermore, we will prove that the throughput obtained from (1) is higher than or equal to the throughput obtained from (2) for any FER, conditioned on a given MCS level and maximum number of transmissions. We first consider a case that a frame is successfully decoded within the maximum N_{\max} transmissions.

THEOREM 1: *If the maximum number of transmissions is*

larger than 1 ($N_{\max} > 1$) and a frame is successfully decoded within N_{\max} transmissions, for a given MCS level, the throughput obtained from (1) is higher than or equal to the throughput obtained from (2) for any FER.

PROOF. If a frame made by MCS i with SINR γ is successfully decoded at the n -th transmission ($F_i(n\gamma) = 0, 2 \leq n \leq N_{\max}$ and $0 < F_i(m\gamma) \leq 1, m = 1, \dots, n-1$), with the data rate of MCS i , R_i , the throughput obtained from (1) at the n -th transmission is expressed as

$$ET_i^n = R_i \left(1 - \sum_{k=2}^n \frac{1}{(k-1)k} \prod_{m=1}^{k-1} F_i(m\gamma) \right) \quad (3)$$

and the throughput obtained from (2) at the n -th transmission is expressed as

$$AUT_i^n = \frac{R_i}{1 + \sum_{k=2}^n \prod_{m=1}^{k-1} F_i(m\gamma)}. \quad (4)$$

The proofs of (3) and (4) are given in Appendices A and B, respectively. Moreover, we set a hypothesis in which THEOREM 1 is true. The hypothesis is given by

$$R_i \left(1 - \sum_{k=2}^n \frac{1}{(k-1)k} \prod_{m=1}^{k-1} F_i(m\gamma) \right) \geq \frac{R_i}{1 + \sum_{k=2}^n \prod_{m=1}^{k-1} F_i(m\gamma)}. \quad (5)$$

(5) is proved by mathematical induction, and the details are described in Appendix C. If the maximum number of transmissions N_{\max} goes to infinity, the decoding is successfully completed. That is, THEOREM 1 is also true when $N_{\max} \rightarrow \infty$.

Second, we consider another case in which a frame is not successfully decoded during N_{\max} transmissions. In this case, we derive the following theorem:

THEOREM 2: *If the maximum number of transmissions is larger than 1 ($N_{\max} > 1$) and the probability that all N_{\max} transmissions of a frame are not successfully decoded is larger than 0, the throughput obtained from (1) is higher than or equal to the throughput obtained from (2) for a given MCS level and any FER.*

PROOF. In this case, for given MCS i achieving the data rate of R_i and SINR γ , the throughput obtained from (1) at the N_{\max} -th transmission is expressed as (6) and the throughput obtained from (2) at the N_{\max} -th transmission is expressed as (7). Both (6) and (7) are easily proved by using (1), (2), and THEOREM 1. Then, we set a hypothesis in which THEOREM 2 is true. The hypothesis is given by

$$R_i \left(1 - \sum_{k=2}^{N_{\max}} \frac{1}{(k-1)k} \prod_{m=1}^{k-1} F_i(m\gamma) - \frac{1}{1 + \sum_{k=2}^{N_{\max}} \prod_{m=1}^{k-1} F_i(m\gamma)} \right) - R_i \left(\frac{1}{N_{\max}} \prod_{m=1}^{N_{\max}} F_i(m\gamma) - \frac{\prod_{m=1}^{N_{\max}} F_i(m\gamma)}{1 + \sum_{k=2}^{N_{\max}} \prod_{m=1}^{k-1} F_i(m\gamma)} \right) \geq 0. \quad (8)$$

In THEOREM 1, we showed the first-line terms in (8) are greater than or equal to zero. In the second-line terms, since $N_{\max} \geq 1 + \sum_{k=2}^{N_{\max}} \prod_{m=1}^{k-1} F_i(m\gamma)$, $\prod_{m=1}^{N_{\max}} F_i(m\gamma) \cdot$

$\left(1/N_{\max} - 1 / \left(1 + \sum_{k=2}^{N_{\max}} \prod_{m=1}^{k-1} F_i(m\gamma)\right)\right) \leq 0$. Therefore, the theorem is proved to be true with the above results.

Through THEOREMS 1 and 2, we can conclude that, for a given MCS level and maximum number of transmissions, the throughput obtained from (1) is higher than or equal to the throughput obtained from (2) for any FER.

C. Optimal MCS Mapping Design

The conventional MCS mapping design in cellular networks is based on maximizing the instantaneous data rate while maintaining a given FER constraint. This criterion is

$$\text{MCS}_{\text{FER}_x}(\gamma) = \arg \max_{i \in M} \{R_i | F_i(\gamma) < x\}, \quad (9)$$

where x is the maximum allowable FER and M represents the set of MCS levels[11].

With the maximum number of transmissions N_{\max} , the proposed criterion based on the CC-based HARQ mechanism chooses an MCS level maximizing (1) and is given by

$$\text{MCS}_{\text{ET}}^{\text{CHASE}}(\gamma) = \arg \max_{i \in M} R_i \sum_{k=1}^{N_{\max}} \frac{1}{k} \prod_{m=1}^{k-1} F_i(m\gamma)(1 - F_i(k\gamma)). \quad (10)$$

The proposed MCS selection achieves the optimal approach by choosing an MCS level which maximizes the expected throughput considering the contributions from the HARQ operations accompanied by future retransmissions.

As proposed in [11], the AUT-based mapping criterion for the HARQ mechanism with CC chooses an MCS level maximizing (2) and is given by (11).

In this letter, we also propose an optimal MCS selection criterion considering an IR-based HARQ mechanism. We assume the conventional IR policy in which the retransmission frame size is restricted to be the same as the initial transmission[5]. Using the conventional IR-based HARQ mechanism, the proposed MCS selection criterion is given by (12). $F_{i,CR_k^i}(\cdot)$ is the associated FER of MCS i at the k -th transmission with SINR (\cdot) , which reflects a different FER function considering the coding gain obtained from each subsequent retransmission. The term α_k^i is the associated SINR gain of MCS i at the k -th transmission.

The above FER function and SINR gain used for decoding at each (re)transmission depend upon the policy of the IR scheme implemented in a system. As mentioned in [11], (11) can be extended to the criterion that adopts the conventional IR-based HARQ mechanism with the above FER function and

SINR gain. This newly derived criterion from (11) is used for performance evaluation of our criterion in Section III.

Based on THEOREMS 1 and 2, we define the following corollary:

COROLLARY 1: *In a conventional IR-based HARQ mechanism where the retransmission frame size is the same as the initially transmitted frame size, the throughput obtained based on the method in (1) is higher than or equal to the throughput obtained based on the method in (2) for a given MCS level and any FER.*

PROOF. Since the size of retransmission frame is the same as that of the initial transmission, the HARQ mode change from the CC to IR only requires different FER functions. Therefore, the above corollary is proved to be true with the following conclusion that THEOREMS 1 and 2 are satisfied in both the CC- and conventional IR-based HARQ mechanisms.

III. PERFORMANCE EVALUATION

We compare the performance of three MCS selection criteria in orthogonal frequency division multiplexing (OFDM)-based high-speed downlink packet access (HSDPA) system[13]: the conventional mapping design with an FER of 10%, named as ‘FER10’, the AUT-based mapping design proposed in [11], named as ‘AUT’, and our ET-based mapping design named as ‘ET’. We adopt 6 MCS levels with data rates of 0.8 Mbps, 1.2 Mbps, 1.6 Mbps, 1.8 Mbps, 2.4 Mbps, and 3.6 Mbps. Specific MCS levels are described in Table II and a turbo encoder with a mother code rate of 1/3 is used in order to obtain the code rate of each MCS level. We use the CC- and conventional IR-based HARQ mechanisms and the maximum number of transmissions N_{\max} is set to 5 in our simulations. Table II lists the operation parameters of the IR scheme for 6 MCS levels where the first field of the table includes the index, the size of information bits, modulation type, and code rate for each MCS level. Policies of the IR scheme employed in our simulations are as follows:

- Each retransmission frame has the same size as the initial transmission frame.
- The SINR gain of MCS i at the k -th transmission is given by

$$\alpha_k^i = \sum_{l=1}^k \frac{L_l^i - P_l^i}{L_1^i}, \quad k = 2, \dots, N_{\max}, \quad (13)$$

where L_l^i is the frame size of MCS i at the l -th transmission and P_l^i is the size of new parity bits, not transmitted to the destination until the $(l-1)$ -th transmission. If the

$$ET_i^{N_{\max}} = R_i \left(1 - \sum_{k=2}^{N_{\max}} \frac{1}{(k-1)k} \prod_{m=1}^{k-1} F_i(m\gamma) - \frac{1}{N_{\max}} \prod_{m=1}^{N_{\max}} F_i(m\gamma) \right) \quad (6)$$

$$AUT_i^{N_{\max}} = R_i \left(\frac{1}{1 + \sum_{k=2}^{N_{\max}} \prod_{m=1}^{k-1} F_i(m\gamma)} - \frac{\prod_{m=1}^{N_{\max}} F_i(m\gamma)}{1 + \sum_{k=2}^{N_{\max}} \prod_{m=1}^{k-1} F_i(m\gamma)} \right) \quad (7)$$

TABLE II

EXAMPLE OF AN OPERATION POLICY OF THE IR SCHEME EMPLOYED IN OUR SIMULATIONS

MCS level	Code rate(s) ($1 \leq k \leq l_k$)	SINR gains ($1 \leq k \leq N_{\max}$)	P_l^i ($2 \leq l \leq l_k$)
1, 1600 QPSK, 1/3	1/3 ($l_k = 1$)	1, 2, 3, 4, 5	0
2, 2400 QPSK, 1/2	1/2, 1/3	1, 3/2, 5/2, 7/2, 9/2	2400 ($l_k = 2$)
3, 3200 16QAM, 1/3	1/3 ($l_k = 1$)	1, 2, 3, 4, 5	0
4, 3600 QPSK, 3/4	3/4, 1/2, 1/3	1, 3/2, 7/4, 11/4, 15/4	2400, 3600 ($l_k = 3$)
5, 4800 16QAM, 1/2	1/2, 1/3	1, 3/2, 5/2, 7/2, 9/2	4800 ($l_k = 2$)
6, 7200 16QAM, 3/4	3/4, 1/2, 1/3	1, 3/2, 7/4, 11/4, 15/4	4800, 7200 ($l_k = 3$)

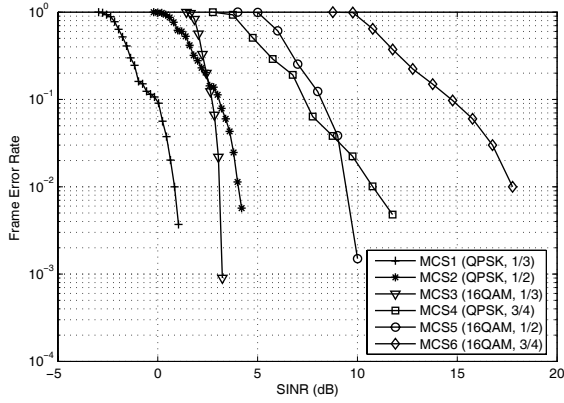


Fig. 3. Link-level FER curves of the 6 MCS levels for the ITU Ped-A 3 km/h channel.

code rate gained by the IR scheme reaches the mother code rate in the l_k -th transmission, $P_{l_k+1}^i, \dots, P_{N_{\max}}^i$ are all zero.

- For each MCS level, the code rate corresponding to the FER function changed at each retransmission is listed in the second field of Table II. If the code rate gained by the IR scheme reaches a mother code rate of 1/3 at the l_k -th transmission, in the remaining transmissions, the FER function used in the l_k -th transmission is applied to obtain the error rate.

We perform link-level simulations to obtain FER look-up tables for 6 MCS levels. We will use FER functions and FER look-up tables interchangeably. The OFDM configuration for the link-level simulations uses the parameter set 2 in [13].

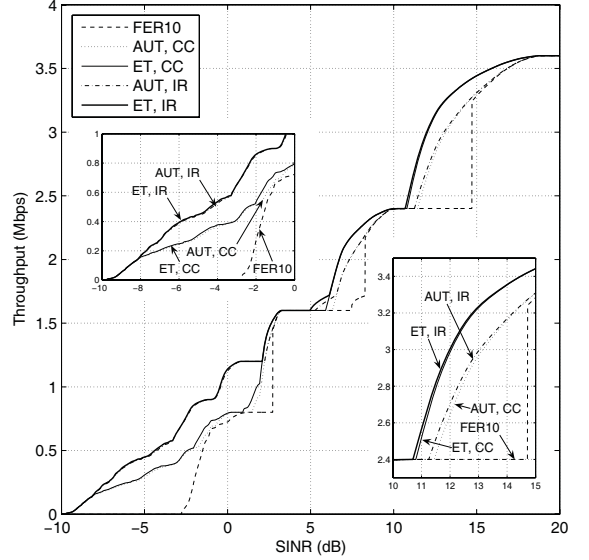


Fig. 4. Comparison of hull curves of the mapping criteria for the ITU Ped-A 3 km/h channel.

Figure 3 shows the link-level FER curves of the 6 MCS levels for the International Telecommunication Union (ITU) Pedestrian-A 3 km/h channel. The link-level FER curves for the additive white Gaussian noise (AWGN) and ITU Ped-B 3 km/h channels are also obtained through the link-level simulations. Figure 4 compares the hull curves of the mapping criteria for the ITU Ped-A 3 km/h channel. In both the CC- and IR-based HARQ mechanisms, the proposed mapping criteria and the criteria in [11] choose MCS levels which achieve higher throughput than the criterion ‘FER10’. Moreover, our two mapping criteria show the hull curve with higher throughput than the AUT-based mapping criteria.

Furthermore, we evaluate the throughput performance of the mapping criteria in terms of the average cell throughput using system-level simulations. Seven cells are deployed with a hexagonal layout where MSs are uniformly distributed within the center cell. We consider full queue traffic and apply a round robin discipline as a scheduling algorithm where the number of MSs scheduled at each TTI is set to 3. Figure 5 shows a comparison result of the average cell throughput for the mapping criteria in the AWGN, ITU Ped-A 3 km/h, and Ped-B 3 km/h channel models. The proposed mapping criteria and the criteria in [11] yield better performance than

$$\text{MCS}_{\text{AUT}}^{\text{CHASE}}(\gamma) = \arg \max_{i \in M} \frac{R_i \left(1 - \prod_{m=1}^{N_{\max}} F_i(m\gamma) \right)}{\sum_{k=1}^{N_{\max}} k \prod_{m=1}^{k-1} F_i(m\gamma) (1 - F_i(k\gamma)) + N_{\max} \prod_{m=1}^{N_{\max}} F_i(m\gamma)} \quad (11)$$

$$\text{MCS}_{\text{ET}}^{\text{IR}}(\gamma) = \arg \max_{i \in M} R_i \sum_{k=1}^{N_{\max}} \frac{1}{k} \prod_{m=1}^{k-1} F_{i, \text{CR}_m}(\alpha_m^i \gamma) (1 - F_{i, \text{CR}_k}(\alpha_k^i \gamma)) \quad (12)$$

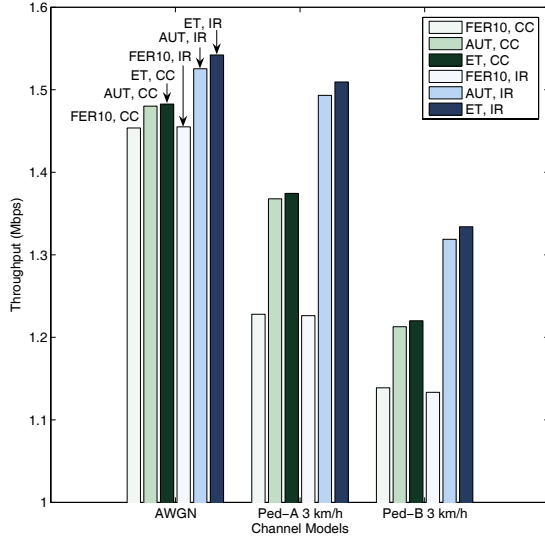


Fig. 5. Comparison of average cell throughput obtained by the mapping criteria for the AWGN, ITU Ped-A 3 km/h, and Ped-B 3 km/h channels.

the criterion of ‘FER10’. Moreover, in both the CC- and IR-based HARQ mechanisms, our mapping criteria achieve higher average cell throughput than the AUT-based mapping criteria for all types of channel models. Compared with the AUT-based mapping criterion adopting the IR-based HARQ mechanism, the proposed ET-based mapping criterion with the IR achieves higher average cell throughput by 16.8 kbps for the AWGN, 16.2 kbps for the Ped-A 3 km/h, and 15.2 kbps for the Ped-B 3 km/h channels.

IV. CONCLUSION

In this letter, we propose an optimal MCS selection rule for maximizing user throughput while taking into account the utilized HARQ operation in cellular networks. We adopt both the CC- and IR-based HARQ mechanisms to our proposed criterion and the MCS selection for the optimal mapping decision is based on maximizing the expected throughput (ET) estimated based on the number of transmissions and successful decoding probability in HARQ operation. We analytically derive the ET under the assumption of time-invariant channel states during retransmissions. And, we prove that the MCS mapping criterion proposed in [11] is not optimized with respect to the expected throughput, by performing the mathematical analysis. Through the analysis, we find that the expected throughput in the proposed mapping criterion is higher than or equal to that in the mapping criterion proposed in [11] for a given MCS level and any FER. Through link-level and system-level simulations performed in the OFDM-based HSDPA system, we find that, in both the CC- and conventional IR-based HARQ mechanisms, the proposed ET-based mapping criteria achieve higher average cell throughput than the compared mapping schemes for slowly varying channels.

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APPENDIX A PROOF OF (3)

$$\begin{aligned}
 R_i & \sum_{k=1}^n \frac{1}{k} \prod_{m=1}^{k-1} F_i(m\gamma)(1 - F_i(k\gamma)) \\
 & = R_i(1 - F_i(\gamma)) + \\
 & \quad \frac{1}{2}F_i(\gamma)(1 - F_i(2\gamma)) + \frac{1}{3}F_i(\gamma)F_i(2\gamma)(1 - F_i(3\gamma)) + \dots \\
 & \quad \frac{1}{n-1} \prod_{m=1}^{n-2} F_i(m\gamma)(1 - F_i((n-1)\gamma)) + \frac{1}{n} \prod_{m=1}^{n-1} F_i(m\gamma) \cdot 1 \\
 & = R_i \left(1 - \left(\frac{1}{2}F_i(\gamma) + \frac{1}{2 \cdot 3} \prod_{m=1}^2 F_i(m\gamma) + \dots \right. \right. \\
 & \quad \left. \left. \frac{1}{(n-1)n} \prod_{m=1}^{n-1} F_i(m\gamma) \right) \right) \\
 & = R_i \left(1 - \sum_{k=2}^n \frac{1}{(k-1)k} \prod_{m=1}^{k-1} F_i(m\gamma) \right).
 \end{aligned}$$

APPENDIX B PROOF OF (4)

If an MS successfully decodes a frame at the n -th transmission, the term $\prod_{m=1}^n F_i(m\gamma)$ is zero ($\because F_i(n\gamma) = 0$). Thus, the throughput obtained from (2) at the n -th transmission is reduced to $R_i / \left(\sum_{k=1}^n k \prod_{m=1}^{k-1} F_i(m\gamma)(1 - F_i(k\gamma)) \right)$. Therefore, (4) holds as

$$\begin{aligned}
 & \frac{R_i}{\sum_{k=1}^n k \prod_{m=1}^{k-1} F_i(m\gamma)(1 - F_i(k\gamma))} \\
 & = \frac{R_i}{1 - F_i(\gamma) + 2F_i(\gamma)(1 - F_i(2\gamma)) + \dots + (n-1) \prod_{m=1}^{n-2} F_i(m\gamma)(1 - F_i((n-1)\gamma))} \\
 & = \frac{R_i}{1 + F_i(\gamma) + \prod_{m=1}^2 F_i(m\gamma) + \dots + \prod_{m=1}^{n-1} F_i(m\gamma)} \\
 & = \frac{R_i}{1 + \sum_{k=2}^n \prod_{m=1}^{k-1} F_i(m\gamma)}.
 \end{aligned}$$

APPENDIX C PROOF OF (5)

We can prove the inequality by mathematical induction. In the basis, when $n = 2$, the left and right terms of (5) are $R_i(1 - 1/2 \cdot F_i(\gamma))$ and $R_i/(1 + F_i(\gamma))$, respectively. Since the difference between these two terms is $R_i \cdot (F_i(\gamma)(1 - F_i(\gamma))/(2 + 2F_i(\gamma)))$ and it is greater than or equal to zero, (5) holds for $n = 2$. Next, in the inductive step, we assume that the following induction hypothesis holds for $n = l$ ($l > 2$):

$$R_i \left(1 - \sum_{k=2}^l \frac{1}{(k-1)k} \prod_{m=1}^{k-1} F_i(m\gamma) \right) \geq \frac{R_i}{1 + \sum_{k=2}^l \prod_{m=1}^{k-1} F_i(m\gamma)} \quad (14)$$

To show that the hypothesis holds for $n = l + 1$, at first, we subtract the term $R_i/(l(l+1)) \cdot \prod_{m=1}^l F_i(m\gamma)$ from the both sides of (14). Then, we obtain the following inequality:

$$\begin{aligned} & R_i \left(1 - \sum_{k=2}^{l+1} \frac{1}{(k-1)k} \prod_{m=1}^{k-1} F_i(m\gamma) \right) \\ & \geq \frac{R_i}{1 + \sum_{k=2}^l \prod_{m=1}^{k-1} F_i(m\gamma)} - \frac{R_i}{l(l+1)} \prod_{m=1}^l F_i(m\gamma). \end{aligned} \quad (15)$$

Next, $R_i / \left(1 + \sum_{k=2}^{l+1} \prod_{m=1}^{k-1} F_i(m\gamma) \right)$ is added / subtracted to / from the right-hand side of (15). With the following results, the left term of (15) is greater than or equal to the term $R_i / \left(1 + \sum_{k=2}^{l+1} \prod_{m=1}^{k-1} F_i(m\gamma) \right)$, then the hypothesis holds for $n = l + 1$. By induction, (5) is proved to be true.

$$\begin{aligned} & R_i \left(1 - \sum_{k=2}^{l+1} \frac{1}{(k-1)k} \prod_{m=1}^{k-1} F_i(m\gamma) \right) \\ & \geq \frac{R_i \prod_{m=1}^l F_i(m\gamma)}{\left(1 + \sum_{k=2}^l \prod_{m=1}^{k-1} F_i(m\gamma) \right) \left(1 + \sum_{k=2}^{l+1} \prod_{m=1}^{k-1} F_i(m\gamma) \right)} \\ & \quad - \frac{R_i}{l(l+1)} \prod_{m=1}^l F_i(m\gamma) + \frac{R_i}{1 + \sum_{k=2}^{l+1} \prod_{m=1}^{k-1} F_i(m\gamma)} \\ & \geq \frac{R_i}{1 + \sum_{k=2}^{l+1} \prod_{m=1}^{k-1} F_i(m\gamma)} \\ & \quad \left(\begin{aligned} & \frac{R_i \prod_{m=1}^l F_i(m\gamma)}{\left(1 + \sum_{k=2}^l \prod_{m=1}^{k-1} F_i(m\gamma) \right) \left(1 + \sum_{k=2}^{l+1} \prod_{m=1}^{k-1} F_i(m\gamma) \right)} \\ & - \frac{R_i \prod_{m=1}^l F_i(m\gamma)}{l(l+1)} \geq 0 \end{aligned} \right). \end{aligned}$$

■

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