MCS Selection for Throughput Improvement in Downlink LTE Systems

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***Abstract*—In this paper, we investigate *resource block* (RB) assignment and *modulation-and-coding scheme* (MCS) selection to maximize downlink throughput of *long-term evolution* (LTE) systems, where all RB's assigned to the same user in any given *transmission time interval* (TTI) must use the same MCS. We develop several effective MCS selection schemes by using the effective packet-level SINR based on *exponential effective SINR mapping* (EESM), arithmetic mean, geometric mean, and harmonic mean. From both analysis and simulation results, we show that the system throughput of all the proposed schemes are better than that of the scheme in [7]. Furthermore, the MCS selection scheme using harmonic mean based effective packet-level SINR almost reaches the optimal performance and significantly outperforms the other proposed schemes.**

I. Introduction

Key features of wireless communication channels are with frequency-selective fading and time varying. In order to match these features, *adaptive modulation and coding* (AMC) has been proposed to enhance system throughput in [1]-[3]. Its basic idea is to select an optimal combination of *modulation and coding scheme* (MCS) according to channel quality so that high rate data can be transmitted when channels are in good condition and low rate data is transmitted to guarantee reliability when channel quality is poor. AMC has been widely adopted for many wireless communication systems or standards, such as 3GPP *long-term evolution* (LTE) [4], IEEE 802.16 WiMAX [5], and IEEE 802.11n [6]. In this paper, we will focus on MCS selection in the downlink transmission of LTE systems.

In the downlink transmission of LTE systems, only *channel quality indicator* (CQI) corresponding to a *resource block* (RB) or multiple RB's in the form of MCS index is fed back to the *base station* (BS). RB in LTE systems is the smallest resource unit and consists of 12 adjacent sub-carriers and 6 or 7 consecutive OFDM symbols [4]. Based on the MCS index fed back from mobile terminals, BS will allocate RB's to users and select an appropriate MCS. Different from the general AMC schemes [1]-[2], LTE specification requires that all RB's allocated to the same user in any given *transmission time interval* (TTI) must use the same MCS. A key issue is which MCS should be selected for each user. In order to guarantee *block-error rate* (BLER) performance of the RB with the poor channel condition, it has been proposed in [7] to select a MCS for the RB's belonging to the same user in any TTI according to the poor channel quality. The scheme in [7] is further extended to proportional fair multiuser scheduling in [8]. Such schemes are too conservative and result in a throughput loss for those RB's with better channel condition. However, if too aggressive, the BLER is too large, which may not have a high throughput either.

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In this paper, we will investigate MCS selection to maximize the system throughput. We will develop effective MCS selection schemes that not only ensure the BLER performance of the RB with poor channel condition but also make full use of the RB's with good channel condition.

The rest of this paper is organized as follows. Section II introduces the MCS feedback model and presents the optimization objective function for the downlink transmission of LTE systems. In Section III, suboptimal RB assignment and MCS selection are proposed. Simulation results are presented in Section IV to demonstrate performance improvement of the proposed schemes and conclusions are drawn in Section V.

II. System Model

In this section, we introduce the MCS feedback model in LTE dowlink and then formulate the optimization problem for RB assignment and MCS selection.

A. MCS Feedback

In LTE downlink, CQI in form of MCS index is very important feedback information, which can be used to assign RB's and determine modulation order and coding rate [4]. Each RB in LTE systems includes multiple subcarriers and their channel gains are different. To determine MCS index, an effective block-level *signal-to-interference-plus-noise ratio* (SINR) mapping method has been proposed in [9]-[13] to collect all channel information and select an appropriate MCS for each RB, which is also called *exponential effective SINR mapping* (EESM). It has been shown that the effective block-

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TABLE I
MCS FEEDBACK TABLE IN LTE DOWNLINK

CQI Index	Modulation Order	Code Rate $\times$ 1024	Rate r [14] (bits/symbol)	β_m [12]	SINR threshold Γ w/ 10% BLER (dB)
0	out of range				
1	QPSK	78	0.1523	1.00	-9.478
2	QPSK	120	0.2344	1.40	-6.658
3	QPSK	193	0.3770	1.40	-4.098
4	QPSK	308	0.6010	1.48	-1.798
5	QPSK	449	0.8770	1.50	0.399
6	QPSK	602	1.1758	1.62	2.424
7	16QAM	378	1.4766	3.10	4.489
8	16QAM	490	1.9141	4.32	6.367
9	16QAM	616	2.4063	5.37	8.456
10	64QAM	466	2.7305	7.71	10.266
11	64QAM	567	3.3223	15.5	12.218
12	64QAM	666	3.9023	19.6	14.122
13	64QAM	772	4.5234	24.7	15.849
14	64QAM	873	5.1152	27.6	17.786
15	64QAM	948	5.5547	28.0	19.809

level for a given MCS can be defined as

$$\overline{\gamma}(\beta_m) = -\beta_m \ln\left(\frac{1}{N_{sb}}\sum_{i\in\mathcal{N}_{sb}}\exp\left(-\frac{\gamma_i}{\beta_m}\right)\right), \qquad (1)$$

where $\mathcal{N}_{sb}$ is the set of subcarriers in a RB, $N_{sb} = |\mathcal{N}_{sb}|$ is the number of subcarriers in the RB, γ_i is the SINR at the ith subcarrier, and β_m, is an adjusting factor and depends on a specific MCS. For LTE systems, the relationship between the MCS index, m, and the adjusting factor, β_m can be found in Table I. In fact, the effective block-level SINR changes slightly with the adjusting factor and with the MCS index since it essentially reflects the average of SINR's on all subcarriers for each RB no matter which adjusting factor is used.

Let switching threshold, Γ_m, be the SINR with 10% BLER for the MCS m. For a given set of SINR's corresponding to subcarriers of a RB, $\{\gamma_i\}_{i\in\mathcal{N}_{sb}}$, the MCS index can be obtained by

$$m = \max\{i|\ \Gamma_i \le \overline{\gamma}(\beta_i),\ \text{for } i = 1, ..., M.\ \}, \qquad (2)$$

where M is the total number of MCS's and is 15 in the current LTE specification. The MCS index of each RB for each user is then fed back to the BS, where resource allocation, including RB assignment and MCS selection, is performed.

Once the MCS index information is obtained at the BS by feedback, the effective SINR corresponding to each RB of each user can be well approximated by

$$\overline{\gamma} \approx \Gamma_m + \Delta\Gamma,\ \text{for } m = 1, ..., M, \qquad (3)$$

where $\Delta\Gamma$ is a positive offset value over the switching SINR, Γ_m, and is determined by the two adjacent switching thresholds. Based on such approximate block-level SINR, we will perform RB assignment and MCS selection to maximize system throughput.

B. Problem Formulation

We focus on the downlink transmission of LTE systems with N_{rb} RB's and K active users, and the CQI information in the form of MCS index for all RB's of each user is assumed to accurately feed back to the BS without delay. With the MCS index, the corresponding effective block-level SINR and transmission rate will be well estimated. We assume that N_k RB's are allocated to user k in a given TTI and all transmitted data blocks of each user in the given TTI are combined into a data packet. Then, the packet throughput corresponding to user k can be expressed as

$$T_{m_k}(\zeta_{k,m_k}) = R_{m_k}(1 - P_{m_k}(\zeta_{k,m_k})), \qquad (4)$$

where m_k is the MCS index of user k, R_{m_k} is the transmission rate determined by the modulation order and code rate and can be found in Table I for LTE systems, and $P_{m_k}(\zeta_{k,m_k})$ is the packet-error rate of the data packet corresponding to user k, which can be obtained according to [11], [12]. In addition, ζ_{k,m_k} is an effective EESM based packet-level SINR for user k and is determined by the SINR's at all subcarriers of the packet and the MCS index, which can be expressed as

$$\zeta_{k,m_k} = -\beta_{m_k} \ln\left(\frac{1}{N_k N_{sb}}\sum_{n\in\mathcal{N}_k}\sum_{i\in\mathcal{N}_{sb}}\exp\left(-\frac{\gamma_{k,n,i}}{\beta_{m_k}}\right)\right), \qquad (5)$$

where $\mathcal{N}_k$ is the set of RB's allocated to user k and $\gamma_{k,n,i}$ is the SINR at the ith subcarrier of RB n for user k.

With the SINR's on the subcarriers of all users, we can assign RB's to users, obtain the corresponding packet-level SINR of each user, and select the MCS. To achieve the highest system throughput, the BS will optimize the RB assignment and select the most appropriate MCS for each user based on the effective packet-level SINR. Mathematically, we can formulate the joint optimization problem of RB assignment and MCS selection as

$$\underset{\{\mathcal{N}_k,\ m_k\}}{\arg\max} \sum_{k=1}^{K} T_{m_k}(\zeta_{k,m_k}), \qquad (6a)$$

subject to

$$\mathcal{N}_i \cap \mathcal{N}_j = \phi,\ \text{for } i \ne j, \qquad (6b)$$

$$\mathcal{N}_1 \cup \mathcal{N}_2 \cup \cdots \cup \mathcal{N}_K = \mathcal{N}_{rb}, \qquad (6c)$$

$$m_k = 0, 1, ..., M, \qquad (6d)$$

where $\mathcal{N}_{rb}$ is the set of all RB's. The constraint in (6b) guarantees that each RB can be allocated to only one user, the constraint in (6c) ensures that all available RB's can be allocated to the users, and the constraint in (6d) means that MCS of each user must be selected from the given MCS set in Table I.

The above optimization problem uses the effective packet-level SINR for each user, which is determined by SINR's of all subcarriers in the packet of each user and the MCS index. However, the only feedback information in LTE systems is the MCS index for each RB of each user, which can be used to evaluate the effective block-level SINR for each RB. In the following sections, we will investigate how to use the approximate effective block-level SINR's belonging to each user to estimate the effective packet-level SINR for resource allocation and develop the MCS selection schemes.

III. Heuristic Schemes

To simplify the optimization problem, we separate RB assignment and MCS selection. We first assign appropriate RB's to users and then select the MCS based on the effective packet-level SINR estimated by different ways.

A. Principle

We will first relax the MCS constraint for each user and then develop a heuristic solution to maximize the system throughput. We know that T_{m_k} in (4) always monotonically increases with SINR. Therefore, if the MCS constraint for each user is ignored, then each RB should be allocated to the user with the highest SINR so that highest MCS can be used to maximize the system throughput, which can be directly expressed as

$$\mathcal{N}_k = \{n : \overline{\gamma}_{n,k} > \overline{\gamma}_{n,l} \text{ for } \forall k \neq l \text{ and } 1 \leq n \leq N_{rb}\}, \quad (7)$$

where $\overline{\gamma}_{n,k}$ is the effective block-level SINR of RB n for user k at the BS based on the MCS index feedback. If several users have the same channel quality or the same MCS index at the same RB, then such a RB will be randomly assigned to arbitrary one of these users.

This RB assignment scheme is very simple since it only needs to compare the SINR of all different users on each RB. However, the RB assignment scheme is suboptimal since the constraint on MCS selection is not considered here. We will further optimize the system throughput by the MCS selection in the following.

Once RB assignment is completed, we will find the best-estimated packet-level SINR to obtain the best MCS for each user. The optimization problem in this case can be expressed as

$$\arg\max_{0 \leq m_k \leq M} T_{m_k}(\zeta_{k,m_k}). \quad (8)$$

For such an optimization problem, we can obtain the optimal solution of MCS selection by an exhaustive search algorithm if the accurate effective packet-level SINR is known. However, only MCS index of each RB is available at the BS in practical LTE systems. Therefore, we will propose some heuristic schemes of MCS selection to deal with this issue.

B. Packet-Level SINR Estimation

A very natural ideal is to use the EESM method to estimate the effective packet-level SINR from the approximation effective block-level SINR's for each user. In this case, the effective packet-level SINR can be estimated as

$$\widetilde{\zeta}_{k,m}^{EESM} = -\beta_m \ln\left(\frac{1}{N_k}\sum_{n \in \mathcal{N}_k} \exp\left(-\frac{\overline{\gamma}_{n,k}}{\beta_m}\right)\right). \quad (9)$$

If accurate block-level SINR's at all RB's belonging to user k are known and they all are calculated by the same adjusting factor, β_m, then we have $\widetilde{\zeta}_{k,m}^{EESM} = \zeta_{k,m}^{EESM}$. Otherwise, they are different.

Besides EESM based estimation, we can exploit *arithmetic mean* (AM), *geometric mean* (GM), and *harmonic mean* (HM) of the approximate block-level SINR's on the RB's for each user to obtain estimated packet-level SINR's, which can be expressed as

$$\widetilde{\zeta}_k^{AM} = \frac{1}{N_k}\sum_{n \in \mathcal{N}_k} \overline{\gamma}_{n,k}, \quad (10)$$

$$\widetilde{\zeta}_k^{GM} = \left(\prod_{n \in \mathcal{N}_k} \overline{\gamma}_{n,k}\right)^{1/N_k}, \quad (11)$$

and

$$\widetilde{\zeta}_k^{HM} = \frac{N_k}{\sum_{n \in \mathcal{N}_k} \frac{1}{\overline{\gamma}_{n,k}}}, \quad (12)$$

respectively.

With these estimation, the corresponding MCS for each user to transmit the data packet can be easily determined by

$$m_k = \begin{cases} 0, & \widetilde{\zeta}_k < \Gamma_1, \quad i = 0, \\ i, & \Gamma_i \leq \widetilde{\zeta}_k < \Gamma_{i+1}, \quad i = 1, ..., M-1, \\ M, & \Gamma_M \leq \widetilde{\zeta}_k, \quad i = M. \end{cases} \quad (13)$$

Compared with the exhaustive search scheme, they can significantly reduce the complexity. For different ways of estimating the effective packet-level SINR, the impact of each RB is different. For the AM based scheme, the estimated effective packet-level SINR is mainly dominated by the RB with the maximum SINR. For the GM based scheme, it fairly considers the impact of all the RB's belonging to the same user. While for the HM based scheme, it is mainly decided by the RB's with the minimum SINR. The difference will result in different throughputs.

MCS selection could be also based on the minimum or maximum effective SINR among the set of effective block-level SINR's belonging to the same user, which are called minimum MCS selection scheme [7] and maximum MCS selection scheme, respectively. Obviously, the former one is too conservative while the later one is too aggressive. They will result in a throughput loss.

According to the relationship among AM, GM, and HM, we have the following inequalities

$$\overline{\gamma}_k^{min} \leq \widetilde{\zeta}_k^{HM} \leq \widetilde{\zeta}_k^{GM} \leq \widetilde{\zeta}_k^{AM} \leq \overline{\gamma}_k^{max}, \tag{14}$$

where $\overline{\gamma}_k^{min}$ and $\overline{\gamma}_k^{max}$ is the minimum and maximum block-level SINR among all block-level SINR's belonging to user k. The selection schemes based on the effective packet-level SINR in (14) from left to right gradually change from the conservative to the aggressive. The conservative scheme ensures the reliability at the cost of low transmission rate while the aggressive one improves transmission rate, however, results in a high packet-error rate. The system throughput is not high in either case. In practice, the system packet-error rate is mainly affected by the RB's with the poor channel condition. The scheme based on ζ_k^{HM} exactly considers this point so it can determine a more appropriate MCS and obtain higher throughput compared with the other schemes besides the optimal one.

From a simple mathematical derivation, we also have

$$\overline{\gamma}_k^{min} \leq \widetilde{\zeta}_k^{EESM} \leq \widetilde{\zeta}_k^{AM} \leq \overline{\gamma}_k^{max}, \tag{15}$$

which means that the EESM based scheme is more conservative than the AM based scheme. However, there is no analytical relationship between the EESM, the GM, and the HM based the schemes which can be only compared by computer simulation in the next section.

C. Implementation

In the above, we present RB assignment and MCS selection schemes and compare the propose MCS selection schemes with the existing MCS selection scheme in [7]. In this section, the implementation of the proposed schemes can be summarized into the following steps:

- First assign RB to the user with the best channel quality according to (7). If several users have the same channel quality at the same RB, the RB will be randomly assigned to arbitrary one of these users.
- Then obtain the effective packet-level SINR for each user according to (9), (10), (11), or (12).
- Finally determine the most appropriate MCS according to the SINR thresholds using (13).

IV. Simulation Results

In this section, we compare performance of the proposed schemes with the optimal scheme based on exhaustive search and the existing scheme based on minimum MCS in [7] by computer simulation. For the scheme in [7], after RB's are assigned to all users, all RB's belonging to the same user select the minimum MCS for transmission. For the optimal scheme, the effective packet-level SINR is first determined by the EESM using SINR's of all subcarriers allocated to each user and then the MCS index is selected by exhaustive search. The optimal scheme can only be used as a performance bound and is impractical in LTE systems. Besides its high complexity, only the MCS indices of the RB's are available in LTE specification and the SINR's of all subcarriers are unknown at the BS. In our simulations, the corresponding simulation parameters are listed in Table II and *hybrid automatic repeat request* (HARQ) is exploited. In addition, all simulation curves are obtained by averaging over 1000 channel realizations.

TABLE II
SIMULATION PARAMETERS

Carrier frequency: 2GHz	Sampling frequency: 7.68MHz
TTI duration: 1ms	OFDM symbols per frame: 14
FFT size: 512	Subcarrier spacing: 15kHz
System bandwidth: 5MHz	Antenna configure: 1×1
HARQ	Type: Chase combining
	Maximum retransmission number: 2
Channel model [15], [16]	Type: ITU Ped-B
	Speed: 3km/h

Figures 1 and 2 demonstrate the average throughput and the average MCS index versus the average SINR for different schemes, respectively. From Figure 1, the proposed scheme with HM based MCS selection obtains almost the same average MCS index as the optimal one while others are either too conservative or too aggressive compared with the optimal one. Therefore, the proposed scheme with HM based MCS selection will obtain almost the same throughput as the optimal one and outperform the rest, which can be verified in Figure 2.

In Figures 3 and 4, we give the average MCS index and the average throughput versus the number of users for various resource allocation schemes, respectively. From these figures, we find that the proposed scheme with HM based MCS selection also has almost the same average MCS as the optimal scheme and achieves the higher throughput compared with the proposed schemes with AM, GM, and EESM based MCS selection as well as the existing scheme in [7]. Furthermore, we have also found that the throughput of the proposed scheme with HM based MCS selection is improved by 18% compared that in [7] when the number of users is 4 and $SINR = 10\ dB$.

V. Conclusions

In this paper, we present novel adaptive block-level RB assignment and MCS selection schemes for the downlink transmission of LTE systems. In these schemes, we first assign RB's to the user with the best channel quality and then select an appropriate MCS according to several effective packet-level SINR estimations. In particular, the scheme with HM based MCS selection reaches a good tradeoff between data transmission rate and packet-error rate. Consequently, it achieves almost the same performance as the optimal one and outperforms the rest. The proposed schemes are very easy to implement in the downlink transmission of LTE systems to improve system throughput.

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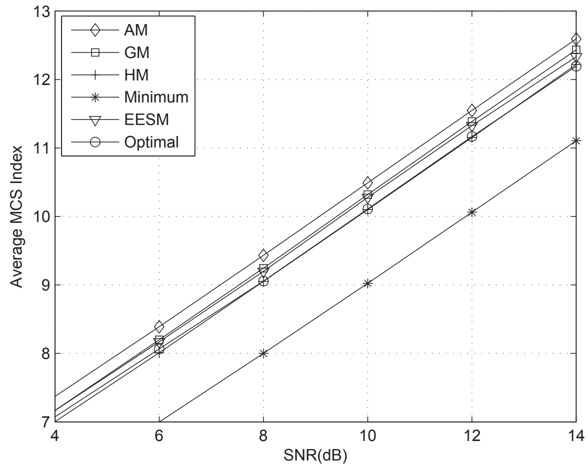

Fig. 1. Average MCS index versus SINR for the proposed schemes, the optimal scheme, and an existing scheme with minimum MCS selection in [7].

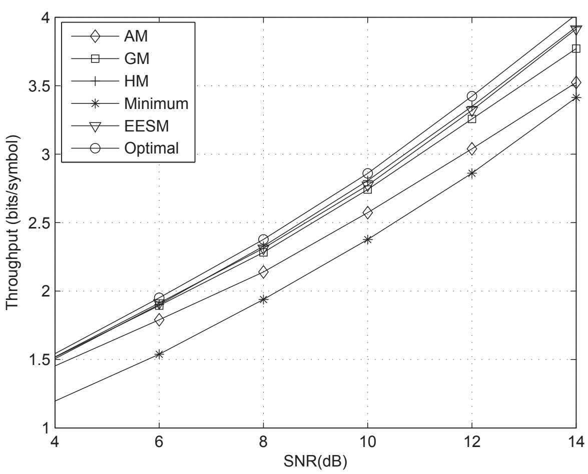

Fig. 2. Average throughput versus SINR for the proposed schemes, the optimal scheme, and an existing scheme with minimum MCS selection in [7].

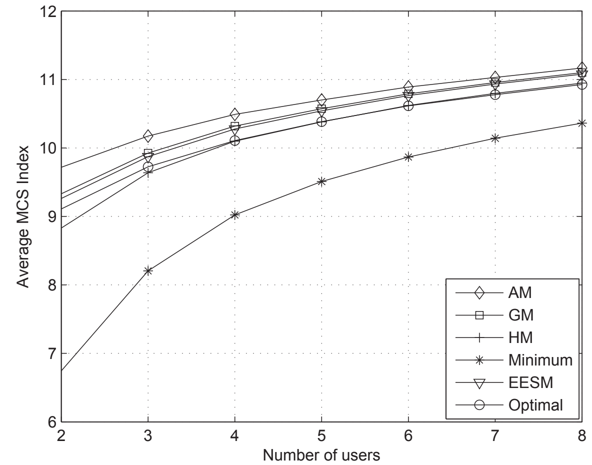

Fig. 3. Average MCS index versus number of users for the proposed schemes, the optimal scheme, and an existing scheme with minimum MCS selection in [7].

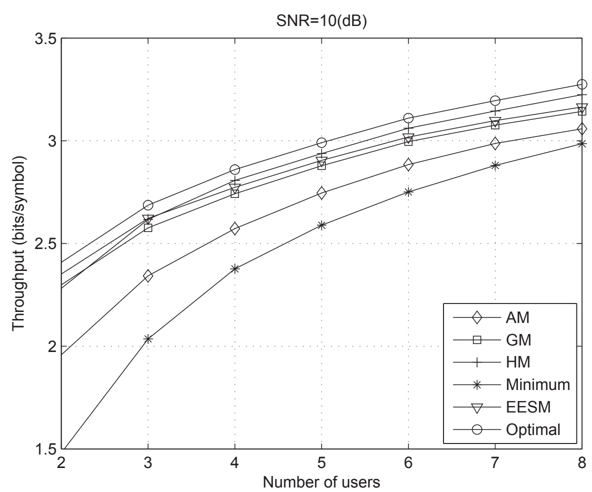

Fig. 4. Average throughput versus number of users for the proposed schemes, the optimal scheme, and an existing scheme with minimum MCS selection in [7].

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